IUPAP

INTERNATIONAL UNION OF
PURE AND APPLIED PHYSICS

Physics 2000

as it Enters a New Millenium

A compendium of reviews by leading physicists in the International Union of Pure and Applied Physics

Edited by

Paul Black
Gordon Drake
Leonard Jossem

I.U.P.A.P. – 36

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Editorial Introduction

Paul J. Black, Gordon W.F. Drake, E. Leonard Jossem

The preparation of this collection arose out of discussions at a meeting of the Council of the International Union of Pure and Applied Physics in 1998. The Commission on Physics Education, C14, had raised the question of whether IUPAP would arrange any special activity to celebrate the millennium. Various grand ideas, for example a special millennium conference or a substantial book on the state of physics, were dismissed on the grounds that they would involve a great deal of effort in organisation, and yet would not be attractive. They would only add to the pressures on busy physicists who might prefer to spend their time on moving ahead rather than one more millennium celebration.

So it was decided to prepare a modest publication by asking the chair of each of the commissions to contribute an article of about 2000 words about the field of physics covered by that commission. One of us - Paul Black - agreed to start the task of collection, and Gordon Drake and Len Jossem subsequently agreed to help.

The editorial invitation asked that a member of the commission should contribute a document " to explain the major advances in their field in the last part of the century, and to make predictions about how they expect it to develop, and what it might achieve in (say) the next 10-20 years (for it would be crazy to try to look farther ahead) ". The main purpose for the collection of such documents was that they would serve as background briefing for any physicist who might be giving a lecture during the year 2000 on the state of, and prospects for, physics in the new millennium. Indeed, the IUPAP Council expressed the hope that a general lecture of this kind should feature in the otherwise specialist programmes of the many and varied international conferences which will be sponsored by the IUPAP, on the recommendation of its member commissions, in 2000.

We asked each author to write for physicists who are not specialists in their commission's field. We also suggested including high school teachers in this category. The results form this volume. They have been only lightly edited, and it will be clear that they vary in the demands that they make on the reader's knowledge of physics.

They also vary in length, but here again the editors felt that, with a few extreme exceptions which were referred back to their authors, they should leave the pieces as their authors thought fit to present them. The strength of this collection is that each piece is authoritative — written by a recognised international expert in the field with a passion for his particular part of it, and we thank each of the authors for their willingness to contribute to the collection.

The pieces are presented in the order in which the IUPAP commissions happen to be ordered. It would be possible to re-order them so that related fields are grouped together. The cross-links are multiple, so no one sequence could be ideal. There is overlap between them, and in some cases, notably between Commission 17 on Quantum Electronics and Affiliated Commission 1 on Optics, the overlap is considerable. Such features might be a stimulus for IUPAP to look again at the structure of its commissions. It should be noted that Commission 1 deals with Finances of the Union and so does not feature here.

All three of us have enjoyed these pieces. Whilst none of us would claim to have understood all parts of all of them, they have expanded our vision and given us a lively picture of physics. They show that the subject is very much alive, and still full of intriguing surprises and fascinating promise.. We hope that other readers will share this experience.

Symbols, Units, Nomenclature and Fundamental Physical Constants

Where We Are and Where We Are Going

Commission 2
Brian W Petley

1. Introduction

This field cuts across the whole of physics in a particular way and hence the likely future developments will be apparent from a study of the future developments in the whole of physics.

The subject is a pragmatic one and use is made of the best measure available. This both builds on and helps provide the most stringent tests of our understanding of physics and it is therefore very difficult to predict these in advance. We therefore tend to concentrate on those aspects that will not be highlighted in the other chapters of this book.

It should be emphasised that, although a wide range of talents can be accommodated, the physics in this general area is just as intellectually demanding as is any other part of physics. Although often frustrating, physics in the last decimal place has a beauty of its own, as those who practice it will confirm. We are taught to do our physics by isolating the variables. In the last decimal place, however, one never knows what other physics will intrude on this sound principle. Physicists come into the field, some stay, others move on - some collecting their Nobel Prize as they do so. It is not necessary to be obsessive about accuracy. The interest is stimulated by the observation by eminent physicists that "God is in the detail" (as also is the Devil). The metrologist must have a general interest in physics as well as in measuring things accurately - and that is part of the interest in the subject.

In order to communicate the discoveries of physics and in order to compare theory with experiment, it is necessary to have an internationally agreed vocabulary, a system of quantities, a method of conveying how well the measurement has been made, and a correspondingly well defined system of units. This enables others to relate our work to their own.

Vocabulary, quantities, units, and uncertainties are therefore even more an essential part of modern physics than they were in the past. It is, of course, salutary but rather irksome to have a colleague point out that we have not paid sufficient attention to this aspect of our work

In physics we tend to match our terminology to fit the particular purpose, for we would obviously expect to pay more care when working to a large number of decimal places than if we were performing a yes/no type of measurement. The terminology of physics, the units of measurement and the associated uncertainty statements must all be capable of use to the highest accuracy and to whatever degree of sophistication the circumstances demand. Since the accuracy of scientific measurements is being improved all the time so too must the measurement system in which they are discussed.

2. Vocabulary and code of accuracy.

Physicists do not work in isolation, so even greater problems are to be surmounted for successful two-way communication of ideas and data between physics and other branches of science and technology. We also have to be able to communicate (i) with the man and woman in the street who, one way or another, ultimately play a major part in paying for our work, and (ii) the next generation of physicists who are still in the classroom. All of these aspects, although sometimes irksome, are essential to modern physics. As physics moves to ever higher accuracy, so too the requirements for a stable and agreed platform for our work become ever more important.

Many aspects of our system of units (for example its dimensionality, and the vocabulary of measurement) are made for science, technology and every-day purposes, and our ideas evolve in response to fresh discoveries. Despite our strong instincts that it should do, Nature has not so far provided us with any unique *natural* units of length, mass, and time, and there are many possibilities based on combinations of the fundamental physical constants: the electron and proton masses, the Planck constant, the elementary charge, the speed of light, the Newtonian constant of gravitation, and so on.

3. The SI units

Physicists will always need their own *local* units in order to discuss particular problems. There is often a group vocabulary which is used for abbreviated communication of ideas within the group but which can leave the outsider baffled. There is therefore a requirement for a universal system comprehensible to all. The International System of units (SI) provides a common system of units for science and technology. Although they may like their local units, it is recommended that physicists give their results in terms of the SI units the first time that they are used, so that everyone knows exactly what is being said or written. During its nearly forty years of use, the SI has been modified as science and technology have advanced. To the great satisfaction of most physicists, the artefact standards are being replaced by units and standards that are based on atomic and quantum phenomena. The process seems likely to continue for the next few decades, reflecting the fact that nature does not provide a unique set of natural units.

The second and time measurement

Once measurement accuracy surpassed the part per million level, the earth proved an increasingly poor timekeeper. The second was first defined by the Conférence Générale des Poids et Mesures (CGPM 1968) in terms of the frequency associated with a specified microwave hyperfine energy transition in the ground state of the caesium l33 atom. Today the accuracy is such that a general relativistic correction must be made to the measured caesium frequency in order to allow for the frequency shift associated with the black-body radiation associated with room temperature apparatus, and for the effects of altitude. Such gravitational and other corrections will be of even greater importance in the future.

Precision timing techniques have been used to measure the distance of the moon with centimetre accuracy and satellite navigation systems should soon tell us our position in space, in the air, sea, or on the surface of the earth with comparable 0.1 nanosecond timing accuracy, or better.

The developments in our ability to laser cool atoms has led to caesium fountain atomic clocks, whereby caesium atoms move a few tens of centimetres vertically before falling back through the same microwave cavity - thereby permitting the observation of very narrow optical (Ramsey) fringes. These have increased our ability to realise and measure time with very high accuracy. There are other systems which are ideal secondary standards, including mercury and rubidium ions, room temperature and cryogenic hydrogen masers, and very high Q microwave cavities.

Extremely narrow resonances have been observed in the visible region of the spectrum and beyond, and one or more of these may well prove to provide more accurate frequency standards or clocks in the future. The definition of the second in terms of the hyperfine transition in caesium may well be replaced in the next thirty years or so.

The metre

Laser technology enabled the metre to be defined in terms of time and an agreed value for the speed of light. The consequence of this is that in principle the metre is realisable with the same accuracy as the second. The development of the necessary enabling technology makes this possibility an increasing reality. However, the accuracy of length measurement has not yet quite caught up with the accuracy of time measurement.

Ion and atom traps enable very narrow transitions to be studied in the visible region and even higher frequencies. As above, the measurement accuracy is advancing very rapidly and one day may lead to an optical transition being used to define the second. The ls-2s transition in atomic hydrogen is already part of the *mise en pratique* for the definition of the metre.

The volt and ohm

Low temperature solid-state physics has led to the use of the Josephson effects of Brian Josephson, and the Quantised Hall Resistance of Klaus von Klitzing to maintain very stable units of potential and resistance respectively. The Josephson effects particularly may be capable of refinement to even greater accuracies in the future. There is rather less accuracy in hand with the present generation of measurements of the quantised Hall resistance. There may well be other solid state measurements in the future which permit other combinations of the fine structure constant and the impedance of space, rather than with the quantised Hall resistance.

In the past our knowledge of physics has so often been shown to be but an approximation to the truth. The future will provide increasingly stringent tests of the underlying theory of both of these effects as part of this process.

The kilogram

The accuracy achieved by the prototype kilogram is well within the sights of metrologists. They have an alternative method which is based on the realisation of the electrical watt, and as soon as the accuracy reaches the next decimal place they should be able to see drifts in the realised mass unit. We have been accustomed to a measurement system derived from units of mass length and time, and one can already speculate on how we might replace our definition of the kilogram by some type of *atomic* mass definition. There are several related possibilities, including an agreed value for the Avogadro constant. It is conceivable, but unlikely, that the watt might even become a base unit, and the kilogram a derived unit. However it seems much more likely at present that this will happen in an equivalent way, much as the ohm was once suggested as the base electrical unit but is implicit in the definition of the ampere. The solution adopted will depend on the views of the scientific, technological, commercial, and other communities, and will only be arrived at after the widest possible consultation.

The kelvin

Our unit of temperature is currently based on the triple point of water. It is not very clear what is intended by the term *water*, for there are marked differences between the triple points of water containing deuterium and that containing hydrogen. The deuterium content of water varies according to the water source. Consequently, although the isotopic composition of the water is not specified at present, this will gradually become more important as demands for higher accuracy temperature measurements develop in science and technology. In the longer term it is likely that a definition based in some way on the Boltzmann constant (or, equivalently, the molar gas constant, rather than the triple point of water, will be increasingly discussed and brought to fruition in the next twenty years or so.

The candela

The candela is very much a physiological unit, for it is strongly based on properties of the human eye. It is a unit that is essential to the very important cinema, illumination, photographic, television, and other allied industries. Our increasing ability to measure optical energies with high accuracy by substituting an equivalent electrical energy in a cryogenic radiometer suggests that the lumen might be a better long term choice as the base optical unit - but only if that is what the majority of people want. Certainly for many purposes the watt is more often used to express the power of lasers than the candela is used to express their luminous intensity. The unit is currently realised to better than 0.1%

4. The mole

This quantity is central in modern chemistry and in the parts of physics which overlap with it. The mole is often not properly understood by physicists. This spills over to the Avogadro constant and to other physics constants involving the mole, such as the Faraday constant and the molar gas constant. Many of these problems reflect the continued use of the centimetre, gram, second unit system and the misconception that the SI is simply derived from it. In some respects it is, but in others there are important differences, particularly where the mole is involved.

The Avogadro constant is implicit in the definition of the mole but its value must be obtained experimentally. It is an important part of the relationship between units and measurements based on atomic mass and atomic energy quantities and measurements based on the corresponding SI units. Its measurement is therefore related to our knowledge of the atomic mass unit, the Planck constant, and so on, and with the realisation of the kilogram which are discussed above.

5. The fundamental physical constants.

The experimental confirmation of the existence of a group of invariant quantities in nature led to a variety of methods of measuring their values experimentally. There were soon more measurements than constants, so statistical methods had to be developed to find a set of values consistent with the bulk of the data. This process was pioneered by R. T. Birge and continues today under the Committee on Data for Science and Technology (CODATA) — Task Group on Fundamental Physical

Constants. The extent to which values from different parts of physics agree, or disagree, provides a stringent test of our understanding of the phenomena concerned as well as the accuracy of the associated experiments. Such comparisons have sometimes led to new discoveries.

The accuracies of the evaluated values of many of these constants have advanced tenfold every fifteen years or so and this process is likely to continue. This has been made possible in part by our ability to make accurate measurements at ever higher frequencies and our ability to reduce thermal noise and Doppler motion by working at ever lower temperatures.

We do not attempt to give here a detailed listing of the likely future accuracies of many of the fundamental constants as they are increasingly interdependent. This reflects our understanding of the physics of the last decimal place. There will, of course, be an ultimate accuracy for all measurement but in many areas of physics we are still some way from the ultimate frontier.

Atomic Masses

These are a sub-set of the fundamental constants and the accuracies of the measurements of atomic masses have similarly been making spectacular advances. This applies not only to the masses of the stable nuclides, but also to those far from stability, and to measurements of the masses of the new trans-fermium elements. The island of stability in the region of element 114 is a particular area of interest and effort is likely to be devoted to the production of elements in this region.

Ion traps have been used to make very accurate measurements of the atomic masses of the proton, silicon, and caesium ions in terms of carbon-12. These masses are simply corrected to the corresponding atomic masses by correcting for the mass and binding energy of the electron removed in the ionisation process. Ion traps are likely to be used increasingly with other ions in order to build up our understanding of the properties of the elements, and the formidable progress in this field will be into improved tables of atomic masses.

6. The fine structure constant.

The quantity known as the fine structure constant plays a deep role in physics and also in metrology, particularly in our choice of suitable units in which to express our measurements. In consequence we need to know this constant as accurately as possible. Because it is so universal, being particularly important in the field of quantum electrodynamics, it provides an opportunity to check the accuracy of our understanding of physics in markedly different areas.

The availability of laser cooled atoms is already being used to improve our knowledge of this constant via improved measurements of the Compton wavelengths of heavy atoms such as caesium, a process likely to continue. However, other spectroscopic measurements provide important information as exemplified by the accurate measurements of the anomalous magnetic moments of the leptons, and the von Klitzing resistance.

7. The measurement of the Planck constant

If we rely on the theory of the Josephson and von Klitzing effects, the accuracy of the Planck constant, and of many other constants, is limited by our knowledge of the SI watt. For much of the twentieth century this was realised using the ampere and ohm. However a new method was developed by Bryan Kibble and others which enables much greater accuracy to be obtained via an absolute realisation of the watt. This realisation may then be compared with the one that is maintained via the Josephson volt and von Klitzing ohm. In this way the accuracy with which we know many fundamental constants has already advanced by a factor of about five, depending on the constant. It seems that the accuracy of the method is capable of further refinement, possibly to the extent of allowing the replacement of the kilogram. One can therefore look forward to the day when the values of many of the constants are really constant when expressed in SI units - much as the speed of light is already fixed by its involvement in the definition of the metre. This method of deducing fundamental physical constants currently looks more promising than the alternative route involving deducing the Avogadro constant from a measurement of the lattice parameter and density of silicon. However, the future will decide, for physics is ever full of surprises.

8. Conclusion.

The area covered by Commission C 2 is an important part of the engine house of physics and in helping physics to be applied to the benefit of mankind. This brief survey illustrates that the whole area covered by the title is making spectacular advances. These advances both build on those made elsewhere in physics and help to make them possible. Further advances are predictable for some time to come.

Statistical Physics at the Turn of the XXth Century

Commission 3
Kurt Binder and Pierre C. Hohenberg

Introduction

Statistical mechanics is that branch of physics that tries to make a connection between the physics of atoms (Angstrom scale), the properties of matter on a macroscopic scale, and all related mesoscopic and macroscopic phenomena. Given the knowledge of the forces between atoms, the problem consists in dealing with the large number of these to calculate all quantities of interest (note that one cm^3 of condensed matter contains on the order of 10^{22} atoms). If this task is accomplished one not only understands the principles of thermodynamics, but one also creates a basis for applications in many other fields, such as engineering, materials science, and physical chemistry.

This concept of statistical physics as sketched above is now about 100 years old. It dates back to Ludwig Boltzmann, J. Willard Gibbs and many contemporary scientists at the turn of the XIXth century. Thus it is interesting to ask where we stand now in this branch of physics after 100 years, and what are the milestones marking the progress along the road that had been taken. Simultaneously we will attempt to identify the fundamental questions that remain unanswered, and to look ahead to the next few decades and speculate where the future emphasis will be.

Problems with the basic foundations

Perhaps surprisingly, even the most basic foundations of statistical mechanics are still areas of active research. Let us briefly sketch these problems. As is well known, on the scale of elementary particles and atoms the basic equations describe the evolution of the system in time. Also when we consider the limiting case where the equations of motion reduce to the simple Newtonian equations of classical mechanics, it is the time evolution of the entire state of the system that is described. Consequently it would be natural to describe any observable of a macroscopic system (which we assume to be at rest in thermal equilibrium) as a time average along the trajectory of the system in phase space (in classical statistical mechanics, phase space for a system of N atoms is the 6N-dimensional space of all the co-ordinates and momenta of the particles).

Now the ergodicity hypothesis of statistical mechanics implies that this time average can be replaced by an average over a suitable statistical ensemble, describing the probability distribution of these points in phase space. For example in a "closed" system (i.e., completely isolated from its environment) energy is conserved, so the trajectory of the system must lie on the energy hypersurface in phase space. According to the microcanonical ensemble of statistical mechanics, all regions at this energy hypersurface are equally probable, and a corresponding average can then be deduced from the principle that the (statistically definable) entropy of the system is maximal. Of course, it is highly nontrivial that the time average along the trajectory and this ensemble average over the energy hypersurface are equivalent, for it is then implied that the trajectory on the hypersurface is sufficiently chaotic that it comes close enough to any point on the hypersurface in a short enough time. It has been a challenging problem to make these conditions (which we could state only very vaguely here) as precise as possible, and to understand which properties of a system are responsible for ensuring that the ergodicity hypothesis will hold, as well as why it does not hold in the case of a few rather special counter-examples.

A related problem is irreversibility: Newton's equations of motion of classical mechanics are perfectly reversible in time - how can we then derive from them the second law of thermodynamics, stating that the entropy of a closed system, that is not yet in equilibrium, will always increase and never decrease with time (apart from statistical fluctuations which are absolutely negligible in the thermodynamic limit) ?

Both problems, ergodicity and irreversibility, are rather subtle and the answers that can be given are fairly mathematical. So we do not attempt to describe them here, but we emphasise that the understanding of both problems has profited a lot from a refined insight into non-linear problems in classical mechanics, in "non-linear dynamics" and in the science of chaotic motions. The progress that has been achieved is documented by Boltzmann medals awarded to D. Ruelle (1986), Y. Sinai (1986) and J. L. Lebowitz (1992). Still, the roundtable discussion on irreversibility held at the last STATPHYS conference (Paris 1998) is a vivid testimony that there continue to exist conflicting views, and this situation will no doubt persist in the next decades. We also wish to emphasise that these controversial issues mostly concern matters of fundamental principles, they do not matter so much for practical computations, including irreversible phenomena: in fact, the small deviations from equilibrium are very conveniently handled with linear response theory (Boltzmann medal for R. Kubo 1977) and many further related developments, while phenomena far from thermal equilibrium still pose important problems to our fundamental understanding, as will be discussed below.

Theories of critical phenomena

When we deal with equilibrium statistical mechanics, the formulation of the various statistical ensembles (microcanonical, canonical, grand-canonical) provides in principle a precise connection between the Hamiltonian describing the atoms and their interactions with the macroscopic properties of matter in equilibrium. However, working out this connection in practice is simple only for rather trivial systems (ideal gases, dilute solutions, harmonic oscillators and systems that can be described by them, e.g. crystals at low temperatures, ideal paramagnets, etc.). These are the systems which are extensively described in the various standard textbooks of statistical mechanics, while everything else still is the subject of active research! For example, let us recall the well known example of dense fluids undergoing gas-liquid condensation: while a qualitative description in terms of van der Waals' theory is also about 100 years old, and we have known for more than 50 years from experiment that this theory fails to describe correctly the vicinity of the critical point (e.g. it implies there a simple parabolic shape of the gas-liquid coexistence curve, i.e. an order parameter critical exponent $b = 1/2$ instead of, what we know now, $b \approx 0.325$), quantitatively accurate descriptions of liquid-gas coexistence have emerged only in the last few decades. A very important step was the understanding of critical phenomena in general: examples of important questions are:

• How it can happen that near a critical point the order parameter (the density difference between liquid and gas in the above example) can be arbitrarily small and nevertheless the free energy cannot be expanded in a Taylor series, as assumed in Landau's theory?
• How are the critical singularities of various physical quantities related i.e. what are the scaling laws between the critical exponents characterising them?
• How can we understand the physical basis for the universality of critical phenomena, why the critical exponents at the gas-liquid critical point are the same as those of binary liquid mixtures, anisotropic magnets, and certain order-disorder transitions in binary alloys such as ß-brass?

It has been one of the greatest successes of the last four decades that these aspects of critical phenomena have been clarified. The Boltzmann medals for Fisher (1983), Kadanoff (1989) and Widom (1998) honour in particular the developments of scaling laws, universality etc., but the particularly outstanding achievements is the development of the renormalization group theory, pioneered by Wilson (Boltzmann medal 1977, Nobel Prize 1982). This theory allows one to understand which properties define a universality class, i.e. it clarifies the properties on which critical exponents and related universal quantities (such as scaling functions and universal amplitude ratios) depend, and on which properties they do not depend.

Numerical methods

It must be emphasised, however, that no model (apart from the rather trivial "spherical model" that can be solved in any space dimension) is known that can be solved exactly in three space dimensions and yields a critical point. For the study of critical phenomena and phase diagrams, in three dimensions, the development of numerical methods has been very valuable, such as the Monte Carlo method (Metropolis et al. 1953) and the method of Molecular Dynamics simulations (where one simply solves Newton's equations of motion on a high speed computer). These techniques have become a most important tool of statistical mechanics in the last few decades only, although some important discoveries by computer simulation (e.g. the solid-fluid transition of hard spheres) were made quite early. Note that while renormalization group techniques yield accurate estimates for universal quantities such as critical exponents, they do not predict non-universal quantities such as critical temperature and critical density of a fluid, or the absolute magnitude of critical amplitudes. Such tasks can now be solved satisfactorily with the Monte Carlo method, using suitable analytic input from the theory of finite size scaling for the appropriate analysis of the computer simulation results (note that in practical simulations N is not 10^{22} but on the order 10^2 to 10^8 only, and using the variation of N as a control parameter is a most useful tool).

Since computer simulations can implement many concepts of statistical mechanics in a rather straightforward manner (linear response concepts such as switching on and off various perturbations, and analysis of small subsystems of a larger system) and computers are now easily accessible for every scientist on the desktop, unlike thirty years ago, this development of computer simulation as a standard tool to solve the tasks of statistical mechanics is a fairly recent development, and far from being fully exploited. It is clear that these methods will continue to find broad application, but it is also clear that the interplay with both analytical theory and experiment is indispensable if their full potential is to be achieved. We also note that there are important problems that are not solved - both molecular dynamics and Monte Carlo methods in their original forms deal with classical statistical mechanics, and though there exist some extensions to deal with quantum statistical mechanics, there are sometimes severe difficulties, such as the famous "minus sign problem" encountered when one tries to extend the quantum Monte Carlo methods to fermionic degrees of freedom. If a breakthrough in this area could be found, this numerical approach to statistical mechanics would find widespread application to condensed matter systems at low temperature (e.g. magnetism, superconductors, semiconductors, metal-insulator transitions).

New types of ordering and of phase transition

An area of phase transitions that is still not well understood is the area concerned with the effects of quenched random disorder. While the replica method (Boltzmann medal for S. Edwards 1995) is a useful tool for some aspects, many problems remain. Famous examples are Ising models exposed to random fields, or Ising models with random bonds of competing sign, the so called "spin glasses". Qualitatively new types of ordering and phase transitions have been discovered in such systems in the last three decades. Already the formulation of a mean-field theory, which is trivial for an Ising ferromagnet, is a tour de force for an Ising spin glass, and hence was honoured by a Boltzmann medal (Parisi 1992). However, the location of the "glass transition" in a three-dimensional Ising spin glass, as well as the nature of the low temperature phase of this model, are controversial issues even today. One also does not understand how much this problem has in common with the "ordinary" glass transition, from a supercooled fluid to an amorphous solid. The understanding of this glass transition clearly is one of the "grand challenges" in condensed matter physics in our time. Consequently, it finds much attention now, and will remain a primary theme of research in statistical mechanics in the next decades.

The same statement applies also to surface and interfacial phenomena. While the description of surfaces exposed to a saturated gas as "wet" or "non-wet" in terms of Young's equation for the contact angle of a droplet dates back almost two centuries ago, it was only in 1977 that the concept of a wetting phase transition between these two states was formulated. Meanwhile, the statistical mechanics of wetting phenomena and related issues (multilayer adsorption, interfacial roughening and capillary waves, critical adsorption and surface critical phenomena, faceting transitions of crystals, surface melting and other types of surface-induced order or disorder) are very active fields of research, and are far from being exhaustively exploited.

Soft condensed matter

The last topic of equilibrium statistical mechanics that we emphasise here, "soft condensed matter", is concerned with many materials, notably liquid crystals, polymer solutions and melts, rubber, microemulsions, soap molecules at water-air interfaces and related Langmuir films formed by lipid molecules, biological membranes and supramolecular structures formed by them. While fifty years ago this was considered as a topic of chemistry, and early theories on such problems were honoured by Chemistry Nobel Prizes (Flory 1974), this is now a large area of statistical physics, particularly pioneered by de Gennes (Nobel prize 1991), who showed how useful the tools (scaling, renormalization group) developed for the study of critical phenomena were in this area, solving long-standing and disputed problems like understanding of the end-to-end distance of a long flexible macromolecule in a good solvent.

There are many connections between transitions in soft matter and other problems of statistical physics: for example, the sol-gel transition can be related to the percolation problem where the bonds of a lattice are randomly filled with conducting elements and one asks where macroscopic conductivity appears. Mesophases in microemulsions, in block-copolymer melts, to mention two examples, have surprising analogies to ordered structure, such as in simple solids, but are much more accessible to analytic treatments of statistical mechanics than the latter, because, due to the large length scales involved, "mean-field"-type descriptions are more accurate. This area clearly is one of the fastest growing fields of research in statistical mechanics, and is particularly rewarding because often very interesting connections with other important problems can be made (e.g., there exist links between the problem of "protein folding" and the "glass transition" with its complicated "energy landscape" in phase space). Soft condensed matter is also most usefully studied by methods of non-equilibrium statistical mechanics, since processes are slower and occur on larger length scales and thus are better accessible to experiment. Thus, the process of "spinodal decomposition", the un-mixing of a binary mixture in its unstable region via spontaneous growth of concentration fluctuations, can be studied most completely for polymer mixtures.

Non-equilibrium problems

Non-equilibrium statistical mechanics, of course, is a very important sub-field as well, and a particular area of growing activity. We have already mentioned "non-linear dynamics" in the context of ergodicity, but this field has also given a boost to the study of problems like the onset of turbulence and hydrodynamic pattern formation.

While some problems, like scaling aspects of fully developed turbulence, have been under consideration since the middle of the century, the physics of pattern formation in non-equilibrium condensed matter systems has become a particular focus area only in the last three decades. This includes classical problems of hydrodynamics such as Rayleigh-Benard convection, but also other topics such as dendritic solidification, viscous fingering, eutectic crystallisation, and growing interface fronts on surfaces, all of which obviously have important technological applications, such as for the understanding of metallurgical micro-structures.

Unlike equilibrium problems, which can be formulated in terms of a free energy function that needs to be minimised, no such unifying principle exists for phenomena far from equilibrium, where dynamical equations needs to be solved. For the description of patterns in chemical reactions (such as spiral waves) there are reaction-diffusion equations, for hydrodynamical patterns (e.g. Rayleigh-Benard rolls) there are the Navier Stokes equations of hydrodynamics or simplified versions thereof, like the amplitude equations that resemble the Ginzburg-Landau equations, used for describing the dynamics of critical fluctuations, or for the dynamics of concentration fluctuations in phase-separating systems. For certain systems, like driven granular matter, the derivation of suitable phenomenological equations is still an unsolved problem, and much of our knowledge of patterns in granular media stems again from computer simulation. Of course, all these flow phenomena have important industrial applications.

While some applications of statistical mechanics are fairly obvious — for example developments concerning equations of state in equilibrium, used by engineers dealing with thermodynamic processes — there are also some applications which have developed as unexpected spin-offs. For example research on spin glasses has led to the concept of simulated annealing, which now is one of the established strategies for optimisation problems, and to neural networks, which also have diverse practical applications. At this time, stochastic processes (from random walks to Levy flights) seem to find applications in such diverse areas as biology or analysis of the stock market; whether such analogies are just curiosities or expressions of deep analogies between underlying principles remains to be seen.

Future trends

In summary, it is quite obvious to most researchers in the field of statistical physics that it is an area of great potential, which is far from being fully developed, and finds more and more areas of science to which it may be applied. The area of "soft condensed matter", previously a domain of chemists rather than physicists, is a good example. Often statistical physics also contributes to closing gaps between different fields of physics - e.g. lattice gauge theory as a method of regularising quantum chromodynamics, which established a formal analogy with the path integral formulation of the partition function of statistical mechanics (as in Monte Carlo simulations) has found applications in the theory of elementary particles and astrophysics , notably in theories of the early universe, and of phase transitions of the quark-gluon plasma.

However, we will not attempt here to make specific predictions about the subjects that researchers in statistical mechanics will consider in the next few decades - it is clear that they will be very diverse, ranging from condensed matter physics and physical chemistry to various problems with applications in technology (e.g. simulation of traffic flows), biology and economics. We also expect that the interplay between analytical tools and computer simulation methods is far from being fully exploited; on the contrary it will remain one of the dominating methodological aspects in the future.

Cosmic Ray Physics in the New Millennium

Commission 4
Luke O'C Drury and Thomas K Gaisser

Historical Introduction

The study of Cosmic Rays began at the beginning of the 20th century with attempts to understand the mysterious residual conductivity observed in the electroscopes then commonly used for measurements of radioactivity. As so often in physics, careful investigation of an unexplained background led directly to a startling discovery; in this case that the Earth is continuously being bombarded by energetic particles of extraterrestrial origin, the cosmic rays.

In the early years interest focused as much on what these particles did in the atmosphere as on where they might be coming from. The first of these scientific interests developed into experimental particle physics and high energy physics, but from about the middle of the century this activity moved almost entirely to the new terrestrial accelerators with their precisely controlled beams and well-instrumented targets. Nevertheless, the positron, the muon, the pion and several other mesons as well as the first strange particles were all discovered by cosmic ray experiments before they were produced in accelerators. As recently as 1972 the first evidence for charmed particles was discovered in cosmic ray experiments.

A remarkable feature of the last decades of this century has been a reversal of this trend and a considerable movement of scientists from experimental particle physics back into cosmic ray physics, or astroparticle physics as it is now often called. This has several causes. One was certainly the search for proton decay which stimulated investment in many large underground detectors. While none has recorded a decaying proton, two at least detected the burst of neutrinos from supernova 1987A .

Another factor was the possibility of seeing point sources of very high energy gamma-ray (or other neutral particle) emission. This renewed interest in cosmic rays as an astrophysical phenomenon is developing into what should perhaps now be called particle astronomy. This is not a precisely defined term, but it serves as a useful distinction from the classical astronomies (optical, radio, infra-red, X-ray) which all exploit the wave nature of the photon to focus, refract, reflect or otherwise concentrate the signal on a detector. By contrast, charged particle studies, high-energy gamma ray astronomy and neutrino astronomy all operate with techniques derived from particle physics and typically register simply the arrival direction and energy of the particle. However, the pioneers of X-ray astronomy came from the cosmic ray community, and this field has always retained strong links with cosmic ray physics.

A continuing theme has been the use of the Sun and heliosphere as a laboratory for investigating on a small scale the basic processes of cosmic-ray physics. Space experiments allow direct observation of the interaction between cosmic rays and dynamical structures in the solar wind, in particular the collisionless plasma shocks that form when the solar wind hits an obstacle. This provides the experimental basis for the theory of Fermi acceleration at shocks, a process now thought to operate in a wide range of astrophysical systems and be the major production process of cosmic rays. Similarly, the long-term study of solar modulation provides observational data to constrain theories of cosmic ray transport.

Some recent highlights

Structure and dynamics of the heliosphere

The Ulysses Mission, a satellite sent out of the ecliptic plane and over the solar poles, is obtaining *in situ* observations of the three-dimensional structure of the solar wind plasma and the heliosphere. This is the local environment which cosmic rays of galactic origin have to penetrate if we are to observe them on or near the Earth. The discovery of the so-called anomalous cosmic rays, provides a direct sample of local interstellar material. These cosmic rays are nuclei of neutral atoms swept over by the solar system, ionised in the inner heliosphere, and accelerated at the heliospheric termination shock in the solar wind. Because all stages of this process can be observed in considerable detail they provide a " Rosetta stone '' for understanding similar processes in more distant sources.

Another mission, the Advanced Composition Explorer launched in 1997, has been returning data on composition of the solar wind, solar energetic particles, magnetic fields and the Sun-Earth environment, as well as measuring galactic cosmic ray nuclei. From its vantage point, a million miles upstream from Earth in the solar wind, it is providing real time monitoring of solar activity. Measurements of nickel and cobalt in the galactic cosmic rays show that there has been a rather long time delay (more than 100 thousand years) between nucleosynthesis and acceleration, indicating that cosmic rays are accelerated from relatively old material and not fresh supernova ejecta.

Neutrino mass

Perhaps the most newsworthy physics result of the decade was the discovery of strong evidence for neutrino oscillations by the Super-Kamiokande Collaboration. This experiment, deep in a Japanese zinc mine, uses 50 kilotonnes of pure water viewed by more than 11 thousand huge (50 cm) photomultiplier tubes. It is a descendant of the earlier detectors which observed the neutrino burst from SN1987A. Interactions in these detectors of neutrinos produced by nuclear interactions of cosmic-rays in the atmosphere were first investigated as the background for proton-decay. Because the detected beam covers a large range of neutrino path lengths, from about fifteen kilometres for neutrinos produced directly above the detector to more than ten thousand kilometres for neutrinos that come up through the Earth, it became useful for extending previous searches for neutrino oscillations .

Oscillations of neutrinos (for example between electron-neutrinos and muon-neutrinos, or between muon-neutrinos and tau-neutrinos, or some combination) can occur if neutrinos have an effective mass. The parameters which determine the degree of mixing and the magnitudes of the neutrino masses may be keys to understanding the origin of masses of all fundamental particles; hence the potential importance of these results. Understanding how this evidence for neutrino oscillations fits in with other indications of oscillation (especially the solar neutrino deficit) is currently a major focus of work in the theory of elementary particles.

Opening the TeV astronomy window

Over thirty years ago, J Jelley first detected Cherenkov light flashes at ground level produced by the interaction of particles at energies around a TeV with the upper atmosphere. This meant that TeV gamma-ray astronomy from the ground was possible. However, the enormous background of flashes produced by the charged cosmic rays makes the method essentially unworkable unless some additional discrimination can be used. The last decade has seen a remarkable technological breakthrough with the introduction of sophisticated imaging systems on Cherenkov telescopes, which have so improved the background rejection that a real observational astronomy is now possible in the TeV region - notably with the Whipple telescope.

As usual, when a new observational window is opened something unexpected was found. In this case the Whipple, and subsequently other groups, discovered strong and rapidly varying emission from two nearby Blazars. These are thought to be galaxies with active nuclei (powered by accretion onto a central, super-massive black hole) where we happen to be looking almost straight down the axis of the relativistic jet of material emitted by the nucleus. During outbursts the power emitted in the TeV region by these objects exceeds that at all other wave-lengths! These observations are already placing interesting limits on the intergalactic infrared background and on possible quantum gravity effects on the propagation of high-energy photons.

In addition to the extragalactic sources, several galactic sources have been detected, including the first source announced by the Whipple group with their imaging technique, the Crab nebula. TeV emission has also been detected from the rim of one shell-type supernova remnant (SN1006), consistent with the acceleration of electrons to energies of order 100TeV. In principle, through neutral pion production and subsequent decay, it should also be possible to detect the presence of high energy protons in supernova remnants if, as is generally thought, they are the sources of the bulk of the Galactic cosmic rays.

Particles with too much energy ?

Soon after the discovery in 1965 of the microwave background radiation from the big bang, Greisen in the US and Zatsepin and Kuz'min in Russia independently pointed out that protons of energy more than 10^{20} eV would interact with this microwave background through photo-pion reactions and lose energy on a length scale of order 5 megaparsecs, which is a relatively short distance in cosmological terms. It was confidently expected that the ultra-high energy cosmic ray spectrum would show a cut-off at this energy limit. However it now seems clear that this is not the case. Arrays in the US, and in Japan, have detected a few particles at energies clearly above 10^{20} eV. While "conventional" sources for these extreme particles cannot be completely excluded the difficulty of constructing feasible models has stimulated a great deal of speculation about possible new physics. More data are required, but the fluxes at these energies are only of order one per square kilometre per century !

Prospects for the future

Particle detectors in space

A magnetic spectrometer (AMS) has been tested in a shuttle flight and is scheduled for exposure on the planned Space Station. The emphasis is on search for anti-matter and measurement of antiprotons among the cosmic rays., and follows on from a continuing series of measurements with balloon-borne detectors. Antiprotons produced by higher energy cosmic rays in the interstellar medium are an interesting probe of cosmic-ray propagation. A more exotic component from annihilation of dark matter is also possible.

A major challenge is to study directly the composition of cosmic-ray nuclei at energies above 10^{14} eV, where the conventional acceleration models (based on shock acceleration in supernova remnants) fail. Space missions to achieve this goal are under study.

Quest for the Highest Energy

A very important task is to increase our knowledge of the highest energy cosmic rays and obtain a statistically useful sample above 10^{20} eV with good sky coverage. The Auger project aims to achieve this by constructing two very large detector arrays, one in the northern hemisphere and one in the southern.

A novel idea is to observe air showers by imaging their air fluorescence flashes over a very large volume of the atmosphere from a vantage point in space. Several proposals have been formulated, and with continuing developments in adaptive optics, computing power, pattern recognition and signal processing this is an exciting challenge for the new millennium.

Next generation of gamma-ray astronomy

The success of the imaging technique for TeV gamma-ray astronomy has stimulated a number of proposals for new observational facilities dedicated to this branch of astronomy. Plans to build major new 'telescopes' in both the US and Namibia should lead to observatories covering the northern and the southern skies. In addition, a number of more radical proposals aim to drive this technique to lower energy threshold.

It is important to cover the gap between where conventional space gamma-ray observations fade out at about a GeV and the new TeV window. A Gamma-ray Large Area Space Telescope (GLAST) mission is being developed with this goal, as a co-operative project involving high energy physicists as well as space scientists.

Another exciting possibility would be the discovery of gamma-ray lines of very high energy with these new facilities. Rotation curves of galaxies show that there must be a substantial amount of dark matter in halos of galaxies like our own. One possibility is that this matter is in the form of exotic, massive "neutralinos" (chi) not yet discovered in accelerator experiments (although there are indirect hints from accelerator data for the existence of such particles). Annihilation channels could involve high energy gammas, or jets of particles which would produce excess antiprotons or energetic neutrinos. The latter would give an excess of neutrino events from concentrations of neutralinos captured in the core of the earth or the sun.

A new astronomy

Wherever interactions of high-energy protons occur in astrophysical settings, pions are produced. Each neutral pion decays to a pair of gamma-photons. Charged pions will be produced in the same processes, and their decays produce neutrinos. Any cosmic accelerator with gas nearby is therefore a potential source of both high energy photons and high energy neutrinos. Photons can also be produced in purely electromagnetic processes by electrons (e.g. bremsstrahlung). Therefore neutrino astronomy is complementary to gamma-ray astronomy, having the ability to distinguish hadronic sources from purely electromagnetic sources of photons. Moreover, because of their small cross section, neutrinos can emerge directly from the energetic cores of astrophysical sources.

Overcoming the small interaction probability of neutrinos requires very large detectors. The biggest sensitive volume so far has been achieved by the Antarctic Muon and Neutrino Detector Array (AMANDA) which looks for flashes of Cherenkov light from muons moving upward from their origin in neutrino interactions within and below the sensitive volume of the detector. AMANDA uses a large transparent volume of ice, instrumented with photodetectors, deep in the Antarctic ice sheet. A different approach is being pursued in the deep ocean by several groups in Europe. Both projects aim eventually at sensitive volumes on the scale (a cubic kilometre) required to give a good chance of seeing multi-TeV neutrinos from distant astrophysical sources.

Conclusion

Cosmic ray physics, in both its dual aspects of non-accelerator particle physics and particle astronomy, is making significant contributions to our understanding of the universe. The new facilities which are planned or under construction will certainly continue this trend into the first few decades of the new millennium. In addition to their intended function, history teaches us that well-instrumented sensitive detectors often discover things other than those for which they were built. We may be in for some surprises.

Low Temperature Physics at the Millennium

Commission 5
Marcel Ausloos, George V. Lecomte, John Harrison, and Matti Krusius

Ever lower

The hallmarks of low temperature physics have been the quest for ever lower temperatures, the remarkable discoveries along the way and the many studies of the workings of quantum mechanics at the macroscopic scale. Very roughly, over the past century or more the record low temperature has been reduced by a factor 10 every 10 years; the background temperature of the universe, 3 degrees above absolute zero (3K), was overtaken in 1908. To put this in perspective, particle physicists have achieved similar progress from keV electrons at the turn of the century to TeV protons and electrons at Fermilab and CERN, and over a shorter interval the semiconductor industry has miniaturised from the first mm-sized transistor to single electron devices, again about a factor 10 every 10 years. No other human achievement comes close!

The landmarks in this quest have been: the liquefaction of helium at 4K in 1908 by Heike Kamerlingh-Onnes*; magnetic cooling of solids proposed in 1926, independently, by Peter Debye* and William Giauque*; refrigeration to 0.002K from the dilution of liquid ^{3}He with liquid ^{4}He, suggested by Heinz London, shown to work by P. Das in 1964, and perfected by many others over the following decade; magnetic cooling of nuclei proposed by C.J.Gorter in 1934, realised by Nicholas Kurti in 1956 and most famously by Olli Lounasmaa in 1970; and finally laser cooling of atoms, first proposed by T.Hansch and A. Schawlow in 1975, shown to cool into the µK region by Steven Chu*, even lower by William Philips* when combined with a magnetic trap, and sub-µK with refinements proposed by Claude Cohen-Tannoudji* in 1989.

Discoveries

Superconductivity

Low temperature physicists are proud of the string of fundamental discoveries in the field of condensed matter physics. Some were serendipitous and some resulted from dogged searches in response to a theoretical challenge. The first and still perhaps the greatest was superconductivity in a metal: At a low enough temperature well over half the metals in the periodic table, as well as many alloys and compounds, enter a state where their resistance to current flow disappears. If the superconductor is a wire loop and a current is generated in that loop, then it flows for years with no significant decay. The current flow is not deterred by impurities, atomic vibration or crystalline defects. Discovered by Kamerlingh-Onnes in 1911, a satisfactory understanding was not achieved until the John Bardeen*, Leon Cooper*, Robert Schrieffer* theory of 1957. They showed that the electrons form into pairs and that the motion of these pairs becomes very highly correlated. Together, the electrons can be described by one wave function or order parameter $Y=e^{if}$, of which more later. Rather than closure, the theory was innovative enough to be adopted in many other areas of physics. Implicit in the theory was that there was an upper limit to the superconducting transition temperature of about 25-30K, but to some a limit becomes a challenge. New classes of superconductor were found but the upper limit seemed to be 23K. That was the background for the enormous excitement that accompanied the discovery of a high-temperature superconductor by Georg Bednorz* and Klaus Alex Mueller* in 1986 and the rapid discovery of many others soon after. The upper limit has been pushed up to 150K in these exotic copper-oxide compounds and many theorists are trying to come to a full understanding of the underlying mechanism.

Superfluidity

The discovery that should have come first but eluded experimentalists for 30 years was the superfluidity of liquid ^{4}He below 2K (Piotr Kapitza* and Jack Allen in 1938). The superfluid shows persistent mass flow or zero viscosity and supports quantised vortices. A complete theory of superfluidity has been a much greater challenge but through the work of Lev Landau* and Richard Feynman* in particular we have a very good phenomenological understanding. Once again, we view all of the helium atoms as moving coherently and described by a macroscopic quantum wave function.

For 50 years liquid ^3He, the light isotope of helium, has been acknowledged as an analogue of the electron gas in a metal; the ^3He atom and electrons both act as gases of spin-1/2 particles. There was excitement after the understanding of superconductivity that ^3He atoms might form pairs and condense into a macroscopic quantum state. After several frustrating searches, the quest was abandoned. However, while looking for something else, the transition was discovered by Doug Osheroff*, Dave Lee* and Bob Richardson* in 1972, at 0.003K. This discovery opened a new field and rejuvenated very low temperature physics in a way that was seen later in superconductivity following the Bednorz and Mueller discovery. The ^3He transition was again into a superfluid state but this new superfluid was far more complex with exotic texture and magnetic properties. Perhaps the most remarkable aspect of superfluid ^3He was the way that experiment and theory moved along together with the theory able to explain the exotic properties and point the way to new phenomena with great precision.

The Josephson effect

In 1962, Brian Josephson*, a Cambridge graduate student, presented two equations describing how the electron pairs responsible for superconductivity "tunnel" from one superconductor to another across a very narrow gap. The "tunnelling" current is driven not by a voltage, but instead by the difference in the coherence factors, $f_1 - f_2$, of the electron pairs in the two superconductors. Again, this is quantum mechanics operating at the macroscopic scale. If a voltage difference (V) is applied then the tunnelling current oscillates at a frequency given by (2e/h)V where e is the electron charge and h is Planck's quantum of action. Both equations were soon verified and yet another major field of research was created. Josephson's equations showed that $f_1 - f_2$ is very sensitive to small magnetic fields and so therefore is the tunnelling current. This paved the way for the invention of very sensitive magnetometers. There is no significant radiation from the oscillating current generated by a voltage because of the impedance mismatch between a tunnel junction and free space. However microwave radiation can be mixed in with the tunnel current and so-called Shapiro voltage steps measured, which correspond to $f = (2e/h) V$. One major application has been the present voltage standard defined by this equation and realised with a Josephson junction. Josephson junction circuits have been a test-bed for quantum mechanics and have led to a quantum theory of circuits which will have important implications for the future of electronics.

The quantum Hall effect

Klaus von Klitzing* made a remarkable discovery in 1980 when studying the Hall resistance of a two-dimensional semiconductor at low temperature. The Hall resistance is the ratio of the transverse voltage divided by the longitudinal current when a magnetic field is applied. This resistance should be proportional to the magnetic field and inversely proportional to the number of charge carriers. He found, instead, that as he changed the number of carriers the Hall resistance showed a series of very flat steps and that the resistance plateaux were equal to $(h/2e)/N$, where N is an integer, to better than 10 parts in a million. The precision has since been put at 10 parts in a billion. This is remarkable in a solid with impurities, defects, and atomic vibrations. After several false starts by many theorists, Robert Laughlin found the answer in a topological quantum description of the two dimensional electron gas in a magnetic field. The unit of resistance is now defined in terms of this quantum Hall effect. The precision is such that the resistance of the former standard ohm can be seen to be changing linearly with time, at 50 parts per billion per year. While the quantum Hall effect could be understood in terms of a quantum model, this did not prepare us for what happened next. Horst Stormer* and Dan Tsui* worked with very pure semiconductors, very high magnetic fields and low temperature and found plateaux at *fractional* values of N. The implication was that the elementary charge was not e, but a fraction of e. It was Laughlin* who made sense of this, in terms of a composite quasi-particle arising from correlated interactions between the electrons.

Bose-Einstein condensation

In this short history, the final remarkable discovery resulted from a systematic programme of research highlighted by brilliant experimental techniques.

The goal arose from one of Einstein's predictions from 75 years ago. In 1924 Satyendra Bose sent to Albert Einstein* a paper in which he had created quantum statistical mechanics. Einstein appreciated this, arranged to have it published, and then developed the ideas. He found in the equations that if a gas of integer spin particles (e.g. the hydrogen atom) was cooled sufficiently all the atoms should condense into the same quantum state. While ^{4}He atoms in superfluid helium and the electron pairs in a superconductor bear a resemblance to this Bose-Einstein condensation, the strong interactions prevent them from mimicking Einstein's model system. For many years several groups searched for this holy grail with hydrogen gas and standard low temperature techniques. In fact Dan Kleppner and Tom Greytak did succeed in 1998. Before that though, a group of atomic physicists had taken a different approach. They started with a dilute gas of Rb atoms and slowed the atoms with a set of six lasers. The lasers are tuned to slow atoms that approach them. A set of magnetic field coils were then switched on and trapped the magnetic Rb atoms. Once trapped the outermost atoms are force-evaporated so that the gas becomes colder and smaller in extent. Remarkably, with this elaborate table-top experiment, the final 2000 atoms were cooled to 20nK, with Bose-Einstein condensation setting in at 170nK. This achievement by the Carl Weiman, Eric Cornell group at NIST in Colorado was soon repeated by Wolfgang Ketterle's group at MIT with 5 million atoms and a transition temperature at 2μK. Subsequent experiments have confirmed the quantum coherence of the condensate by allowing two condensates to overlap and observing quantum interference fringes. This is a new field with much interesting physics and the potential for the creation and application of atom lasers.

Applications

Much of our understanding of metals and semiconductors has come, and continues to come, from low temperature research but on the whole their applications are at room temperature in the everyday world. The most significant real application from low temperature physics is the superconducting magnet. This seems such a natural application, to run hundreds or thousands of amps through a resistance-less coil of wire and generate a large field with no Joule heating. However, the first superconductors were returned to normal metals by modest magnetic fields. A second type of superconductor that remained superconducting in large fields entered a mixed state at modest fields, with magnetic flux penetration and dissipation as this magnetic flux interacted with the current. Only in the 1960's did materials scientists learn to "pin" this flux and inhibit the dissipation. Then superconducting magnets did take off and are now a billion-dollar industry with most magnets used for magnetic resonance imaging (MRI) and for particle accelerators.

Josephson junction magnetometers, called SQUIDS for Superconducting Quantum Interferometric Devices, are incredibly sensitive and have found many applications, particularly in scientific research. They are also used routinely in geophysical exploration and the emerging field of biomagnetism. Their sensitivity allows them to detect magnetic fields from electric currents in the heart and brain.

Superconducting electronics, mainly based upon Josephson junctions, has long held great promise. The fundamental switching speed is governed by the Heisenberg uncertainty principle and can exceed terahertz (10^{12} Hz) in high temperature superconductors. This is several factors of 10 faster than reasonable limits for semiconducting devices. Their implementation has been held back by the relative lack of investment, the need for refrigeration and the difficulty of achieving large scale integration with superconducting materials. There is a parallel with alternatives to the gasoline engine: at some point the oil wells will run dry and at some point semiconductors will reach their limit. Recent achievements by Konstantin Likharev and Theodore Van Duzer with rapid single-flux quantum switching devices do look very good.

A possible important niche market for high-temperature superconductors could be the filters used for mobile-phone base stations. The quality and hence resolution of the filters appear to be a factor 10 better than for conventional filters.

At the forefront of electronics are the single electron devices. These depend upon very small thin film islands. When a single electron jumps or tunnels onto an island from an emitter the electrostatic potential increases enough to prevent another electron joining it. Only when the first has tunnelled off onto a collector can another tunnel on.

The island potential can also be altered by a gate voltage, either inhibiting or allowing the tunnelling process. Thus, the single electron transistor. Presently these devices only operate at 1K and below to prevent thermal activation overwhelming quantum tunnelling. The first applications will therefore need refrigeration. In principle though, if the devices can be made smaller (they are already nanostructures), then higher temperature operation is possible.

While not commercial in the usual sense, low temperature devices are being used more and more for detectors in fields far removed from traditional low temperature physics; examples include infra-red detectors for astronomy, x-ray detectors, and calorimeters for neutrino and dark matter searches.

The future

It would be presumptuous to predict future discoveries, particularly given the complete surprise offered by some of the past discoveries. The areas where new phenomena and ideas are expected include the dilute gas Bose condensates, theories for strongly correlated electrons, nanoscale structures and devices, and non-conventional materials. The rapid advances in micro-machining will lead to refrigeration on a chip and perhaps to widespread applications of superconducting electronics. Superconducting magnetometers will follow MRI out of the research laboratory into clinical use, particularly for imaging brain function. What can be said is that the excitement generated by past discoveries and achievements is contagious and it is a pleasure to see so many young scientists at the international conferences and gatherings on low temperature physics and technology. These people will leave their mark!

* Nobel prize-winners

Biological Physics: the Expanding Frontier in the New Millennium

Commission 6
Nobuhiro Go

The relationship between physics and biology

The expansion of physics into chemistry took place after the birth of quantum mechanics. Physics and chemistry are, in a sense, unified. Physics is also expanding rapidly into biology in many aspects, resulting in an increase of the number of contacts between the two fields. So, have physics and biology been unified ? The relationship is not simple. It is now clear that there are no biological phenomena that violate known physical laws. This situation is clearly different from that of a century ago, when the phenomenon of black body radiation was seen as violating the laws of physics known at that time. Study of this phenomenon led ultimately to the establishment of a new view of physical law: quantum mechanics. A similar event, finding a new law of physics which supersedes the currently established ones, is not expected from studies of biological systems, even although biological systems give us impressions very different from those given by objects of conventional physical studies. However, this does not mean that physics is enough to understand biology.

Biology and information of historical origin

Any system of objects of biological study consists of a certain set of atomic nuclei and electrons. But such a description is absurdly far from being enough for any biological system. This absurdity comes from the large volume of information necessary to describe any biological systems, such as how atoms are bonded to each other to form specific molecules and how molecules are assembled in space to assume specific morphological states. This extra amount of information has its origin in the history of the molecular and the biological evolutions. Given such an amount of information, the behaviour of such a system obeys the laws of physics. What biological studies do is twofold:

(a) identification of information necessary to describe the system, and
(b) observation of the system dynamics in accordance with the laws of physics.

To the extent that a history is a process of fixation of random events, biology cannot be contained in physics.

Biology in this century has passed through two important phases. Towards the middle of the present century, biology developed rapidly into the molecular level. Many molecules playing important roles in biological systems were identified. Often an identical or very similar set of molecules is found in different species. This finding gave birth to the concept of the chemical unity of biological systems as opposed to the enormous diversity of biological species. What was achieved during this period was identification of information accumulated during the molecular and the biological evolutions.

The latter half of the present century has witnessed an explosive development of molecular biology based on genetic information stored in nucleic acids. Information acquired by biological systems during the history of the biological evolution has been stored as base sequences of deoxyribonucleic acid (DNA). Elucidation of this fact and subsequent development of technologies of reading and manipulating the sequences led to the explosion of molecular biology. Almost all branches of biology have been affected seriously by this development. The developed technologies are mainly chemical in nature, and the technical role that physics played during this period is relatively modest.

Proteins as functional molecular machinery and the era of structural biology

What are actually stored in base sequences are mainly amino acid sequences of proteins and information necessary to regulate the production of proteins in the cell. Proteins, the products of genetic information, are molecular machineries that are responsible for elementary functions in the cell. There is a one-to-one correspondence between a gene and a protein and an elementary function. Biology is now entering into the era of structural biology, where various biological functions are studied not only at the level of genetic information but also at the level of three-dimensional atomic-resolution structures of molecular machineries. Behind this change of scene is the fact that the experimental determination of the three-dimensional structures of biopolymers is taking place at an accelerated rate due to the development of such technologies as sample preparation using genetic manipulation, X-ray crystallography and nuclear magnetic resonance (NMR). The importance of genetic information has been very persuasively demonstrated by the explosion of molecular biology based on it. However, its success is based on the logic of one-to-one correspondence between a gene and an elementary function, the logic which skips their intermediate, a protein. The era of structural biology means that we are now able to study how biological functions are performed by observing the behaviours of real machineries responsible for them.

In this new era, the relation between physics and biology has become tighter in two ways. Firstly, observation of three-dimensional structures and their dynamic behaviours requires technologies which are basically physical in nature. Here physics is assisting biology by providing important technologies. Secondly, studies of many biological phenomena, after the stage of identifying specific molecules responsible for them, are now raising questions which are physical in nature by performing observations of dynamic behaviour of real molecular machineries. The behaviours observed do not violate the known laws of physics. However, it is becoming clearer that we need new concepts to understand them well. This is natural, because biological systems are very different from the systems studied by conventional physics. The above two aspects will be discussed below.

New physical technologies for biology.

Methods used for structure determination

In the physiological environment, protein molecules assume complex three-dimensional structures that are specific to their amino-acid sequence, and only when they assume their sequence-specific three-dimensional structure are they able to perform their biological functions. Therefore, the starting point of the study of structural biology is the elucidation of the three-dimensional structure at atomic level resolution. This is a much more difficult task than the determination of DNA base sequences. Base sequence information is essentially digital (only four letters A, T, G and C), while analog information is needed to determine three-dimensional structures. Determination of analog information to a high accuracy requires a large amount of information. In practice X-ray crystallography and NMR and, more recently, electron microscopy and neutron scattering, are used for the determination of three-dimensional structures of biopolymers and their complexes. In the field of X-ray crystallography, synchrotron radiation is becoming an increasingly important source of radiation, and is contributing to the opening up of new ways of structure determination. Similarly rapid technological developments are also taking place in NMR, electron microscopy and neutron scattering.

Observation and manipulation of one-molecule systems

The three-dimensional structures determined by the methods described above are averages for a certain state, such as in a crystalline state. In the physiological state they are undergoing conformational fluctuations due to thermal motions. When systems of biopolymers perform their functions, they generally go through a more-or-less specific series of dynamical steps. Identification of such steps is essential for elucidation of the molecular mechanism of biological functions. Usually each of the dynamical steps is a process characterised by a corresponding activated state. Going over an activated state is inevitably a stochastic process. This stochastic nature of the dynamical process presents a difficult problem for the experimental identification of intermediate steps. Usually a physical observation is made on an ensemble of molecules, which then yields an averaged picture. Even when a number of identical molecular systems are set to initiate a certain biological function consisting of a number of elementary molecular steps in a synchronised manner, the modes of action in the constituent systems become very rapidly de-synchronised. A picture obtained by averaging over such a de-synchronised ensemble of systems will be a very poor picture. To escape from this difficulty, it is desirable to carry out a physical observation for a system consisting of as small a number of molecules as possible, ultimately just one molecule. This is just the direction of many studies in biological physics. There are by now many techniques by which observation and manipulation of a single molecular system has been successfully achieved. The physical background behind such single molecule technologies is already quite diverse. This means that a wide variety of experimental methods will be employed in this important field in the near future. They in turn will contribute to the enrichment of the physical understanding of biological phenomena.

New concepts from biological systems

Biological studies at the molecular level usually start from identification of molecular species involved in a specific biological phenomenon. After this stage, observation is made of the system dynamics. The dynamics should follow the laws of physics. Therefore, we want to understand the observation, hopefully in terms of the language of physics. In the new era of structural biology, an increasing number of biological phenomena will be studied from a physical point of view. Will new concepts become necessary or useful in such studies ? The answer appears to be yes. As an example of such a case, the problem of protein folding will be discussed below. As mentioned earlier, protein molecules assume complex three-dimensional structures that are specific to their amino-acid sequence in the physiological environment. A protein molecule is then said to be in the native state. In the case of most small globular proteins (perhaps in the cases of any proteins), the specific three-dimensional structure is determined solely by the amino acid sequence and by the environmental conditions. The history or hysteresis of the system has no influence on the molecule's three-dimensional structure. Thus, after a polypeptide chain with a specific amino acid sequence is synthesised in a cell, no extra information is needed to fold it into the specific three-dimensional structure of the native state. This fact, expressed as Anfinsen's dogma in honour of the person who demonstrated it experimentally, is understood as a consequence of the fact that the native state is realised as an equilibrium state with global minimum free energy. When the environmental condition is changed by more than a certain extent, proteins in the native state are known to undergo transition into so-called denatured state. This is a phenomenon similar to order-disorder transitions such as solid-liquid phase transitions. Therefore the native state should be characterised as a state with a distinctively low energy to cope with the large entropy that can be gained if the structure is unfolded into random states.

Up to this point, basic experimental facts about protein folding are described together with their simple physical interpretations. Even although both facts and interpretations appear to be simple and innocent, they are in fact very peculiar. A protein molecule is a chain heteropolymer with a specific amino acid sequence. Its potential energy surface in a high dimensional conformational space should have a very large number of local minima reflecting the heterogeneity of the sequence of various amino acid side chains. It is highly unlikely that there is a unique state with a distinctively low energy, which, if it were to exist, would become a native state. However, if various energy components comprising the potential energy are mutually consistent in a particular conformational state, such a state would have a distinctively low energy. In the native state of conformations of proteins, this consistency of various constituent energy terms is in fact found to be largely satisfied. This finding is summarised as a consistency principle (also referred to as a principle of minimum frustration) that is satisfied by the native states of proteins. It means that amino acid sequences that satisfy this principle are selected during biological evolution and are used as proteins.

Therefore the consistency principle is a principle pertaining to the history of evolution, but at the same time it is the principle which explains the physico-chemical properties of proteins such as the uniqueness of the native state conformation and the character of folding-unfolding transitions that are similar to order-disorder phase transitions.

This field exemplifies the emergence of a concept that is unique, to a biological system, and important in understanding it. Biological systems are generally enormously complex but yet well organised. This is a characteristic which physicists have not faced very seriously. But, physicists have a tradition of creating new concepts to understand any new objects that they face. In the new era of structural biology when a wide range of biological phenomena will be studied from physical points of view, physicists will create many concepts useful for the understanding of enormously complex biological systems.

Acoustics in the New Millennium

Commission 7
Lawrence A. Crum

Introduction

Acoustics is one of the broadest of all the sub-fields of physics. Acousticians concern themselves with such diverse topics as the physiology of hearing, the complex vibrations of a musical instrument, the noise produced by a jet engine, the development of speech in an infant, the quality of the sound in a concert hall, the propagation of sound over megametre distances in the ocean — indeed, acoustics deals with both the physical and the biological, the pure and the applied, the technical and the social. Acoustics is important to us because it plays an important role in our daily lives; we are constantly surrounded by sounds, some of which are important in our communication, some fill us with pleasure, others annoy us. It would take many volumes to overview such a complex discipline. Below we describe just a few of the "hot topics" that have recently gained public attention.

Sonoluminescence

It might seem rather surprising that sound waves can produce light, but indeed this conversion of mechanical energy to electromagnetic energy has been known for some time. When an acoustic wave of moderate pressure amplitude is propagated through an aqueous liquid, light emissions can be observed. Such an effect was totally unexpected. The power density in a sound wave, even of moderate to high amplitude, is only on the order of microwatts/cm^3; yet, in the phenomenon of sonoluminescence, light energy is emitted with such intensity that it can be easily seen with the naked eye from distances of several meters. This conversion of mechanical energy into electromagnetic energy represents an energy amplification per molecule of over twelve orders of magnitude! Recently, it has been discovered that a single, stable, gas bubble acoustically levitated in a liquid, can emit optical emissions each cycle for an unlimited period of time. Presumably, the oscillations of the bubble cause the gas in the interior to be heated to incandescent temperatures during the compression portion of the cycle.

Furthermore, some recent evidence indicates that the lifetime of the optical pulse can be on the order of or less than 50 picoseconds, and that the temperature in the interior of the bubble can exceed 100,000 K. Since conventional explanations expect the bubble to remained compressed and the temperatures elevated in the interior of the bubble for times on the order of tens of nanoseconds, it is likely that some rather unusual physics is occurring. There have even been some suggestions that sonoluminescence may be due to quantum vacuum radiation. The best guess, however, is that a shock wave is created in the gas which is then elevated to high temperatures by inertial confinement. If shock waves are the mechanism for sonoluminescent emission, then optimisation of the process could lead to extraordinary physics, including nuclear fusion. More realistically, however, single bubble sonoluminescence represents only a very special case of multi-bubble sonoluminescence in which thousands of collapsing gas bubbles are observed to produce light over much of the volume of the high intensity sound field produced within a liquid system. In this case, the presence of light is indicative of the existence of free radical species produced by the high temperatures and pressures within the collapsing gas bubbles. These free radicals have been found to induce a number of unusual chemical reactions — an effect that has given risen to an entirely new discipline: sonochemistry. Perhaps sonoluminescence will be a bridge that links physics and chemistry and leads to many exciting discoveries in the future.

Ocean Acoustic Time-Reversal Mirror:

One of the major problems faced when sound energy is propagated through a real medium (such as human tissue or even the ocean) is the complexities that arise from the individual inhomogeneities that exists within the medium. These inhomogeneities change the local speed of sound and thus a reconstruction of the various sound paths to create an image is influenced by these aberrations, which are generated by the medium itself. One approach to correcting for the complexity of the medium is to propagate a sound wave through the medium and collect not only the intensities of the various sounds that have travelled different paths, but also their phases. Reversing the phases and re-propagating the sound wave over the same path enables one to remove the effect of these inhomogeneities — this process is called phase conjugation and the instrument that accomplishes this effect a time-reversal mirror (TRM). A TRM, also referred to as a phase conjugate array, has been implemented in two experiments conducted in the

Mediterranean Sea in April of 1996 and 1997. The experiments were carried out jointly by the Marine Physical Laboratory of the Scripps Institution of Oceanography and the NATO SACLANT Undersea Research Centre. A TRM focuses acoustics energy to a predetermined spot specified by a probe source, regardless of the time invariant complexity of the medium. Previously, megahertz TRM experiments had been conducted in an ultrasonics laboratory (University of Paris) over ranges of less than one metre. The ocean experiments utilised a vertical source-receiver array (SRA) spanning 77 m of a 125 m water column with 23 sources and receivers and a single source/receiver transponder (SRT) co-located in range with another vertical receiver array (VRA) of 46 elements spanning 90 m of a 145 m water column located from 6.3 km to 30 Km from the SRA. The TRM demonstration consisted of transmitting a 50 ms pulse with centre frequency of 445 Hz from the SRT to the SRA, digitising the received signal and retransmitting the time reversed signals from all the sources of the SRA. The retransmitted signal was then received at the VRA. An assortment of runs were made to examine the structure of the focal point region and the temporal stability of the process. The process was extremely robust and stable out to 30 Km. This research may lead to new concepts in acoustic ocean imaging, sonar and communications, as well as a mean to improve the images in medical diagnostic ultrasound imaging systems.

Recent Developments in Psychological & Physiological Acoustics

High interest continues in otoacoustic emissions (OAEs), which are low-level sounds generated by the inner ear, either spontaneously or from external stimulation. They are measured using sensitive microphones placed in the external ear canal, and appear to reflect normal, non-linear processes in the cochlea. Their potential as a screening tool for quickly and accurately identifying hearing loss is being assessed in a clinical trial with 7,000 new-borns in the U.S. Exciting recent work on gender and hormonal influences on OAEs may reveal more general processes of brain differentiation during development. In behavioural research with human listeners, work with head-related transfer functions (HRTFs) is bringing realistic virtual auditory environments closer to reality. An HRTF is the frequency response (filter characteristic) between a sound source in space and the ear, shaped in large part by the external ear, and thus unique to each individual. Although sound reproduction is improved using average HRTFs, people prefer sounds processed with their own HRTF. The first home audio equipment using this technology recently became available. Other hot topics in psychological acoustics include the inter-related areas of auditory scene analysis, sound-source segregation and auditory selective attention. Considerable progress, including computational models, reflect progress in our understanding of the perplexing question of how listeners parse complex incoming sound fields from multiple sources into relevant and irrelevant auditory signals.

High Intensity Focused Ultrasound

For years acoustic researchers have concentrated on demonstrating that low acoustic intensities used in diagnostic ultrasound produce no or minimal bioeffects, therefore making ultrasound imaging safe. The tide is turning. Therapeutic ultrasound researchers intentionally turn up the intensity to produce *beneficial* bioeffects. It has been shown that High Intensity Focused Ultrasound (HIFU) can stop bleeding from injured solid organs and major blood vessels in about a minute ("acoustic hemostasis"). The therapeutic intensities are about 4 orders of magnitude larger than those of the diagnostic ultrasound, i.e. 10,000 W/cm^2 vs. 0.1 W/cm^2. At these intensities, two major effects are caused by ultrasound.

• The thermal effect raises the temperature to above 60 ^{o}C, causing coagulative necrosis of cells and tissues. While this thermal effect is shared by several other energy modalities including lasers, electrical current, and simple hot irons, ultrasound has the distinct advantage that it can produce the thermal effect deep within a tissue, where hemorrhaging may be occurring in a patient with internal bleeding. This effective mechanism has been responsible for the success of HIFU in "deep volume cauterization" of solid organs, around an injury site.

• The mechanical effect, which is unique to ultrasound, is just beginning to be explored. Bulk streaming due to ultrasound radiation pressure can push blood out of the way, perhaps back into a bleeding vessel, for better visualisation of the operating field as well as enhanced energy deposition in the injury site. Also, tissue emulsification as a result of the large pressure oscillations can provide a seal for solid organ wounds, or a plug for vascular lacerations. Such tissue homogenates contain a large concentration of tissue factors that may accelerate coagulation and hemostasis by orders of magnitude.

HIFU may provide hemostasis methods for both surgical and extra-corporeal applications. The surgical applications may include pre-cauterising volumes of tissues that are planned to be removed by surgery ("bloodless resection"), as well as providing a general tool of hemostasis. The extra-corporeal applications may include arrest of bleeding in trauma patients at the scene of an injury, or during transport to the hospital. Such methods would reduce bleeding and improve the outcome of subsequent trauma surgery, where HIFU methods may come to the rescue again. Acoustic hemostasis may provide an effective, limb- and life-saving method in the near future.

Semiconductor Physics in the New Millennium

Commission 8
Bo Monemar

Achievements in the past.

Semiconductor physics has been alive for about half a century, starting essentially with the invention of the transistor, leading to the award of the Nobel Prize in 1956 to Bardeen, Brattain and Shockley. The bulk properties of silicon were carefully investigated already in the 1950s and 60s, and silicon is indeed the material upon which the giant microelectronics industry is still based, in turn producing the hardware basis of the present Information Technology revolution in our society. The research related to the silicon technology subfield is now not so much semiconductor physics, however. The developments needed for silicon based microelectronics now mainly rely upon cross-disciplinary materials research related to processing steps involving a broad class of materials used in the manufacture of a chip.

Optoelectronics started to grow about three decades ago, with the demonstration of a semiconductor diode laser. This started an upsurge of interest in direct band gap III-V material structures, suitable for optical devices. Tunnelling phenomena in semiconductor structures also became understood, and its importance was recognised with the Nobel Prize to in 1973. Novel growth procedures for growth of thin layers of nanometre thickness were invented — in particular Molecular Beam Epitaxy (MBE) and Metal Organic Chemical Vapour Deposition (MOCVD) — and proved to be indispensable in the development of novel semiconductor structures. Quantum well (QW) structures were found to be advantageous for optical emitters, and the novel physics of low-dimensional (< 3) semiconductor structures has since been extensively studied. About a decade ago there began an enormous growth of interest in the field of one- and zero-dimensional semiconductor nanostructures, which continues to bloom.

The increased perfection of the technology for Si-based (Metal Oxide Semiconductor) MOS transistor structures made possible detailed studies of the properties of a quasi-two dimensional electron gas (2DEG), confined in a few nanometres wide triangular potential at the interface between the Si and SiO_2. Similar structures were soon invented in the direct band gap systems, such as High Electron Mobility Transistor (HEMT) structures, with a 2DEG confined at a heterojunction between two semiconductors. The AlGaAs/GaAs heterojunction became the model structure for a vast number of interesting investigations of the 2DEG. The basic discovery of the Quantum Hall Effect (QHE) occurred in the 1970s, and was recognised by a Nobel Prize to K. von Klitzing in 1985.

A sub-field of great fundamental interest that has developed mainly during the last decade is the behaviour of two-dimensional electrons in semiconductors in a high magnetic field. The idea of composite particles of boson or fermion character, involving fractional charge and attached magnetic flux quanta, provides an explanation of the fractional quantum numbers observed in transport experiments for a 2DEG. This is a fascinating field of basic physics, which now attracts many physicists although the main ideas were presented more than 10 years ago. Experiments are also being refined to demonstrate directly the fractional charge. The classical developments in this field were honoured with the Nobel Prize in Physics to R. Laughlin and H. Stormer in 1998. At very high magnetic fields Wigner condensation of electrons in the 2DEG seems to occur.

Advanced device structures

In the history of semiconductor physics many advanced device structures have been explored. Recently the properties of excitons in a micro-cavity, with strong exciton-photon coupling and photon confinement, define an area that is intensely studied in many materials systems, revealing new physics related both to semiconductors and to optics. There has also been an upsurge in the interest of micro-cavity devices, i. e. devices which combine carrier control with photon control. Vertical micro-cavity lasers have been demonstrated in laboratories, and are expected to reduce the threshold for lasing as well as to increase the speed of such lasers dramatically, which is of considerable applied interest, not least for fast communication applications. For light emitting diode applications the advantage of micro-cavity structures is a much higher external quantum efficiency, due to the facilitated escape of photons from such structures. Such devices are in commercial production in 1999.

An interesting and related recent development in solid state optics has been photonic lattices. So far these have essentially been studied experimentally at longer wavelengths (microwaves) in metallic systems, but recently it has been possible to realise and study two-dimensional photonic lattices in semiconductor systems, with photonic band-gaps in the range of the electronic band-gaps. These systems are potentially very interesting for photon control in future optical semiconductor devices, such as micro-cavity light sources and integrated optoelectronic structures.

Dynamic properties

Another area that has seen rapid development for semiconductors over more than a decade is that of dynamic properties on a very short time scale (femtoseconds and picoseconds). This is particularly important for quantum structures, where the distribution of electron energy states can be tailored at wish. Coherent oscillations related to interference between different electron states can be studied in real time, and infra-red optical THz emission is observed on the femtosecond time scale related to such oscillations. Quantum coherence can now be observed in real time in semiconductor systems. Nonlinear phenomena are very strong in this time domain, promising interesting future device applications. The development of spin dynamics in such systems has also been studied in real time. It has recently been demonstrated that spin transport can be directly monitored, possibly promising development of spin electronics. Other applications include the recent development of photoemission studies on an femtosecond time scale, allowing real time studies of electronic processes on surfaces, including e. g., relaxation phenomena in surface structures of semiconductors. Real time studies of ballistic transport in semiconductor structures have been demonstrated. For instance, very fast hot carrier transport has been monitored directly from optical transients measured in silicon integrated circuits.

Defect studies

No other class of condensed matter is so sensitive to defects as semiconductors. Defects and impurities govern the electronic properties to a large extent, notably conductivity type, carrier recombination, and mobility of carriers. The shallow impurities were understood rather early, but the understanding of defects with electronic states deep in the band-gap turned out to be more difficult. These defects are important, because they govern the carrier recombination in many devices. Experimental methods were developed during the 70s and 80s to measure the most relevant properties of these defects, including their identity. The general picture of the electronic structure and excited states for different classes of defects is now rather well understood, but theoretical calculations of the electronic structure of defects are in general difficult, and accuracies for the position of relevant energy levels in the band-gap are usually not better than 0.5 eV. Calculations of formation energies of defects are probably good within 1 eV, and are very helpful in distinguishing what defects are expected to be dominant in a particular material. Defect vibrational energies can be predicted with a very good accuracy, which is very important for defect identification via comparison with infra-red data for excitation of such local defect modes. The area of electron spin resonance has recently developed strongly towards the use of much higher microwave frequencies, providing very useful tools for identification of defects. The field of defect physics in semicondctors has therefore matured recently, but new materials still raise a challenge for defect studies.

Surface properties

During the last decade the development of surface characterisation techniques has been strong, in particular after the very important inventions of new techniques which allow one to probe the geometrical structure of surface features, and simultaneously the surface potential, with atomic resolution (STM and AFM techniques, Nobel Prize to G. Binnig and H. Rohrer in 1986). These techniques have been applied to assist in the understanding of surface processes, among which epitaxial growth is very important. *In situ* reflectance measurements also allow the monitoring in real time of layer by layer growth with a resolution of one atomic layer. There is presently a strong development of instrumentation for *in situ* moderation and control of growth. Epitaxial growth can now be monitored precisely, and theoretical modelling has advanced to a degree that various growth modes can be simulated.

Nanometre size structures

Nanostructures involving semiconductor materials provide a fascinating area, which, as mentioned above, has now occupied a large fraction of semiconductor physicists for more than a decade. In particular, one dimensional (quantum wires) and zero-dimensions (quantum dot) structures can now be grown with improved techniques. The new techniques invented to produce such materials with nanometre scale features go hand in hand with the development and use of new techniques to characterise the individual features of such a structure with nanometre resolution microscopy and spectroscopy. An example is high resolution Transmission Electron Microscopy (TEM), where the precision in directly measuring the atomic distances in the lattice now approaches 0.01nm. High spatial resolution in optical measurements is achieved with near field spectroscopy.

Part of the development in this field is intimately connected with other areas of condensed matter physics, where nanometre size structures are intensely studied, for example in work on quantum transport in metals. Analogous effects are seen in semiconductors, and single electron transfer processes are detected and studied both electrically and optically (with near field spectroscopy). Recently, the Coulomb blockade processes in semiconductor quantum dots have been studied. An active area is the study of noise in electrical transport data, related to fundamental fluctuations in the charge structure in ultra-small systems. Another interesting topic has been the demonstration of single electron processes at a single defect, both in optical measurements and in electrical transport. Single point defects have also been visualised directly via Scanning Tunnelling Microscopy in a semiconductor surface area. This parallels the studies of single molecule spectroscopy in molecular crystals.

Future outlook.

Although there has been a somewhat decreasing trend in the interest in bulk semiconductor properties over the last decade — this area being rather mature — a clear revival has occurred recently in the sub-field of wide band-gap semiconductors, notably SiC and III-V nitrides. The key to a successful development in these materials systems lies in the important recent advances in crystal growth techniques. Important applications in power devices and high temperature devices are strong driving forces for the current developments of SiC. Production of SiC power devices is foreseen within a decade, probably replacing silicon to a large extent in this application niche.

III-V nitrides and SiC represent an unusual class of direct band-gap semiconductors that are extremely tolerant to a harsh environments and extreme operational conditions. Interesting physical properties occur in strongly strained III-nitride multilayer structures, but most of the physics remains to be explored. These materials are of interest in particular for optical devices covering the entire region between UV and ir. Violet lasers based on InGaN/GaN Quantum Wells are already on the market, and are needed in the expected revolution in home electronics and optical data storage. Digital DVD systems are already on sale, and will lead to a tenfold increase in the storage density in both audio, video and data applications. Other important applications of light emitters are LED based general illumination, potentially replacing the incandescent lamps and the fluorescent tubes used today. The driving force for this development will be the improved reliability of these new light sources (100 year lifetimes), and no adverse environmental impact in their handling or production.

Other interesting applications of these new semiconductors are in the area of high frequency power devices, needed e.g. in future power amplifiers for satellite based communication at frequencies above 10 GHz. It is speculated that the mobile telephone communication, today based on radio frequencies, will to a large extent be satellite based and at much higher frequencies in a decade from now.

For the III-nitrides the already successful realisation of light emitting devices has initiated a strong development of epitaxial techniques to prepare multilayer device structures of low defect density on a foreign substrate, e.g. using lateral epitaxial overgrowth on patterned hetero-substrates. This has proven to be a useful way to produce purple lasers with viable operating lifetimes (> 10000 hours). In a broader long-term perspective, the possible outcome of these efforts is the ability to grow a complicated device structure, using new semiconductor materials with a low defect density, on virtually any desired substrate. This is obviously of very large industrial interest, since the substrate cost is now often prohibitive for device development involving new semiconductor materials. A paramount example is diamond, a material with excellent semiconducting properties, but no viable growth procedure of diamond has yet been developed on a foreign substrate, in spite of extensive work over the last decade. A breakthrough in the general techniques for lateral epitaxial overgrowth may allow the technological use of many new semiconductor materials within the next two decades.

We expect the race towards higher and higher spatial resolution in many measurement techniques to continue in the near future. One example of present directions is the ambition to combine the high spatial resolution of optical and electrical measurements (single atom processes) with magnetic resonance techniques, which sense the spin quanta of single electrons or nuclei. A fascinating class of new sophisticated research tools, measuring different physical parameters of a semiconductor sample with atomic resolution, will probably be available to experimental physicists within a couple of decades. This will be important to many research fields, not least the study of surface reactions on semiconductors, relevant for various sensor applications as well as for the development of processing techniques for semiconductor devices. In general, the interest in the properties of surfaces and interfaces will grow as the physical sample dimension decreases.

As mentioned above, mesoscopic physics and nanostructures nowadays dominate the menu at basic semiconductor physics conferences. Indeed there will be more interesting discoveries to come in this field, as more materials systems are explored, and the perfection and homogeneity of nanostructure samples (such as quantum dot arrays) becomes much improved. We may safely predict that many new fascinating nanosize semiconductor devices will be demonstrated within the coming decade, of particular interest for basic physics. It should be mentioned that many properties of these nanostructures are similar for a wide range of materials (including metals, semiconductors, insulators), leading to a strongly interdisciplinary character of this research field. So far, the possibilities of a large scale use of nanostructured semiconductor materials (with features of a few nanometre size) in devices remain uncertain. It is not clear that the improvements which are predicted for some device properties warrant the advanced processing steps that are necessary to develop in order to move into industrial production. The paramount interest in this area from the basic physics point of view is obvious, however.

Magnetism in the New Millennium

Commission 9
Roger Cowley

Introduction

One hundred years ago the properties of magnetic materials could not be understood and furthermore only a handful of materials had been discovered that were strongly magnetic: iron, cobalt, nickel and a few of their oxides. Although Ampere had shown in the 1800s that circulating electric currents produced magnetic dipole moments, it was realised that the currents needed to produce the observed magnetisation in iron would, if conventional currents, easily melt the iron. This unsatisfactory state of the understanding of magnetism was summarised by the work of van Leeuwen in 1919 who showed that a system of charged particles described by classical mechanics and in thermal equilibrium can have no magnetic properties, in contradiction to the observed properties.

A Quantum Property

Magnetism is an intrinsically quantum property of matter and almost no progress was possible until the development of quantum mechanics. Firstly, quantum mechanics provides an explanation of how there can be atomic or electronic dipolar moments without there simultaneously being dissipative currents. Secondly, the development of the Pauli exclusion principle and the need to have an antisymmetric wave function of electrons led to the understanding of exchange forces through which the magnetic dipole moments interact to produce magnetic structures. This force is dependent upon the magnetic moments of the electrons and is much stronger than the classical magnetic dipolar interaction, which is quite unable to produce the alignment of the microscopic moments in iron.

As a result of these developments there is now a good understanding of the microscopic properties of many magnetic materials. The variety and complexity of the different magnetic structures and properties has expanded enormously so that there are now thousands of known magnetic materials with an enormous variety of properties.

The study of this progress shows many examples of where a better microscopic understanding has led directly to improved materials for applications. Maybe less obviously, the progress has also led to the development of new experimental techniques which are now routinely used far beyond their origins in magnetism and magnetic materials. The study of magnetic materials has also been crucial in the development of an understanding of systems showing co-operative behaviour. Experiments on phase transitions led to scaling theories that are now applied to the early universe, the financial markets and the production of thin films, while work on disordered magnets has led to new models of the brain and artificial thinking machines. It is impossible to review all the important developments in a few pages and so only a few examples will be discussed and these very briefly.

We now understand that whether or not a material is strongly magnetic depends on the competition between different types of interactions. Firstly at the atomic level, atoms with magnetic moments are ones in which the magnetic moments of the individual electrons tend to be parallel. This occurs when the quantum mechanical exchange energy is larger than the atomic kinetic and potential energy difference between the atomic states. In practice this means that the electrons have to be in partially filled atomic levels.

In a solid, the electrons are also needed for chemical bonding. For most magnetic atoms, all the aligned electrons from the last unfilled shell are used for chemical bonding and these bonding states are occupied by pairs of electrons with equal and opposite magnetic moments. The exceptions give rise to strong magnetic properties. These occur when the partially filled atomic shells are hidden within the atoms and there are other electrons outside them which participate in the chemical bonding. This occurs predominantly for the 3d, 4f and 5f shells of the periodic table and most strongly magnetic materials have one or more types of atoms with these shells only partially filled.

Once there are magnetic atoms in a solid, there is a further competition between the exchange interactions coupling the magnetic moments on neighbouring atoms and the so-called crystal field effects. The latter arise because many magnetic atoms are not spherical but have an anisotropic electron cloud. When this is placed in a solid, the electrostatic energy of an atom in the crystal will depend on the relative orientation of the cloud and position of the neighbouring atoms. This reduces the degrees of freedom for the motion of the electron and, since there is a coupling between the shape of the atom and its magnetic moment, the magnetic properties of the atoms in the crystal may be very different from those of the free atom and they may even become nonmagnetic.

New Techniques

Much of this physics was explored in detail for many atoms in different environments by optical spectrometry and in more detail by electron spin resonance (ESR). In an ESR experiment the magnetic ions are placed in a strong magnetic field so that different orientations of the magnetic moments have different energy levels. A microwave electromagnetic field then causes transitions between these levels, producing a resonance. The frequency of the resonance depends in detail on the atom and its neighbourhood, enabling the properties of many different atoms and their environments to be investigated.

Soon after the development of ESR, the technique was applied to study nuclear moments via nuclear magnetic resonance (NMR). This was experimentally easier because the necessary frequencies are in the megahertz region instead of gigahertz, but the main principles and concepts of NMR and ESR are very similar. There have been many developments of these techniques, and especially of NMR, where it is now routinely used in chemistry and biology to determine the environment of particular atoms. With the development of imaging techniques, it is used to image the density of protons or other nuclei in biological tissue. Most hospitals now routinely use MRI (magnetic resonance imaging - the term “nuclear” having been omitted!) to locate tumours and other problems. We can undoubtedly foresee future developments of these techniques to produce better spatial resolution in three dimensions and to enable routine measurements to be made with a wider variety of different atoms.

Magnetic Materials - Old and New

Despite the progress in the understanding of magnetic materials, there are two aspects of materials which are important for their practical application that have not improved over the past century. These are the magnetisation (magnetic moment/unit volume) and the Curie temperature for the onset of spontaneous magnetism. It is disappointing that the alloy $Fe_{65}Co_{35}$ has held the record for magnetisation and Co for the Curie temperature every since the early years of this century. Nevertheless, there has been spectacular progress in the application of magnetic materials by learning to control the anisotropy, magnetostriction, magneto-optics and magnetoresistance. Permanent magnets have been improved by finding compounds of 3d and 4f atoms in which the 4f ions provide the anisotropy and the 3d ions the large exchange interactions. This progress was a direct result of the development of a microscopic understanding of magnetism . It led to Sm-Co magnets in the early 1970s and Nd-Fe-B magnets in the 1980s. As a result, the stored energy product (the figure of merit for the best permanent magnets) has doubled every 12 years throughout the 20th century, making possible many new applications of magnetism in sensors, electric motors and automobiles.

Soft magnetic materials, used for example as transformer cores, have been improved by reducing the crystal field anisotropies so that the electromagnetic losses have been roughly halved every five years. Magnetic recording has also been enormously improved by controlling the grain size and anisotropy of the magnetic media, and by improvements in the designs and magnetic constituents of the read and write heads. As a consequence the recording densities have been doubling every two years since the 1950s.

Future Prospects

It cannot be expected that all these technologies will progress at the same rate. In view of the difficulty in enhancing the maximum magnetisation and exchange interactions, the best possible permanent magnets are already within a factor of three of the maximum theoretical performance. Soft magnetic materials have already improved to such an extent that it is becoming pointless to make further improvements in the materials unless other aspects of their use can be improved.

In contrast, the density of bits stored on magnetic media can in principle be increased by several orders of magnitude before thermodynamic magnetic fluctuations lead to loss of the information. The difficult part of achieving this is in the design of the read heads so as to read the small magnetic fields created by the tiny magnetic particles. The recent discovery of giant magnetoresistance in magnetic superlattices increases the electrical signals available from a given change in the magnetic field and so may help to solve these problems.

On a more fundamental level, the study of the magnetic properties of materials can be expected to lead to new insights and unforeseen effects. One of the challenges of condensed matter is currently to understand the properties of the new transition metal oxides and heavy fermion systems. These are not only high-temperature superconductors, but also magnetic materials which, in some cases, have one or two-dimensional magnetic networks, so called spin ladders, and in other cases show giant magnetoresistance.

All these materials show strong magnetic properties, and it is becoming clear that magnetism is a crucial aspect of them all. The challenge is to determine whether the well known weakly interacting electron model of conventional condensed matter physics can describe their properties, or whether a new condensed matter physics is needed to describe the strongly interacting electrons and their electronic and magnetic properties.

Another development which has already produced important results is the growth of new materials by sputtering, molecular vapour deposition, or molecular beam epitaxy techniques. Magnetic thin films and superlattices can be deposited producing new materials and new effects as highlighted by the discovery of the giant magnetoresistance effect. This field is still in its infancy, and although many 3d and 4f magnetic metals can be grown by these techniques, there are many classes of materials for which superlattices have not yet been grown, so that their properties have not been determined. A related development is the advance of "spin-electronics". In conventional electronics, no use is made of the electron spin. In contrast, with spin-electronics the objective is to control the spin and, for example, to amplify the signal with one spin polarisation differently from that of the other. This opens up the possibility of directly integrating magnetic properties with conventional electronics, thereby making possible new types of sensors, read heads and other devices.

Conclusion

In summary, the past century has seen enormous developments in our understanding of magnetic materials. A combination of quantum mechanics and conventional condensed matter physics now provides an explanation for the properties of many magnetic materials. This understanding has underpinned the dramatic developments in the technology and use of magnetic materials for permanent magnets, soft magnets and magnetic recording, and these are used in many of our most advanced technologies. The study of magnetism has also led to enormous advances in our understanding of co-operative phenomena and competing interactions which have directly influenced our understanding of other fields within and beyond physics. It has led to new technologies for high field magnets and magnetic resonance which are now of crucial importance in biology and medicine.

In the future this progress will continue and probably lead to a new understanding of the physics of condensed matter with strong electron-electron interactions. New artificially grown magnetic materials will lead to progress for magnetic read heads and other devices, thereby improving technology for magnetic media. These materials will open new possibilities for the tailoring of magnetic materials, and possibly to new opportunities created by "spin-electronics".

This review has benefited from a review "Whither Magnet Materials" by Prof J M D Coey presented at the EMMA Meeting in September 1997 and to be published in Journal of Magnetism and Magnetic Materials.

The Structure and Dynamics of Condensed Matter

Commission 10
Rudolf Klein

A source of new ideas

Condensed matter physics is a broad area of physics in which about one half of all physicists work. This is partially reflected by the organisational structure of IUPAP, which has four Commissions representing this part of physics (C5, C8, C9 and C10) and two more which are closely related (C3 and C6). The physics of condensed matter comprises the study of properties of ordered and of amorphous solids, but also of fluids and gases and of complex systems such as polymeric liquids and solids and supramolecular aggregates.

New paradigms originating in condensed matter physics have spread to other areas of physics and to neighbouring disciplines of science. Besides these contributions to basic science, condensed matter physics is of primary relevance to present-day technologies and to the manufacturing of products which influence and form modern societies to a large extent.

The formation of condensed matter by bringing atoms and molecules together gives rise to complex systems which exhibit new phenomena and properties. To understand them it has often been necessary to develop fundamentally new concepts. One example is the study of critical phenomena, which is the behaviour of various physical properties as a critical point is approached. This study has led to the notions of scaling and universality; near the critical point the only relevant length is the correlation length, which serves as a scale for all distances. Moreover, the critical behaviour is the same for systems of a given dimensionality and identical symmetries of the order parameters. Wide variations of the values of the critical temperature or in the kind of microscopic interactions may give rise to identical critical exponents, which characterise the behaviour of physical properties as the critical point is approached. These concepts of scaling and universality are the content of the renormilization group. The notions of broken symmetry and order parameters are not only applicable to condensed matter systems but have also influenced other areas of physics. In similar fashion, the problem of understanding the electronic properties of metals and semiconductors, including high-T_c superconductivity and the quantum Hall effect, has influenced the quantum theory of many-body systems. Yet the fundamental problem of treating the effects of strong Coulomb interaction in many-electron systems is only partially resolved. The relevance of condensed matter physics to the understanding of fundamental problems of basic physics is underscored by the awards of Nobel prizes (for the quantum Hall effect, for tunnelling microscopy, for high-T_c superconductivity and for polymers).

Interaction with neighbouring disciplines

The fertilisation of neighbouring disciplines by methods and results developed in condensed matter physics has a long tradition; there are smooth transitions to chemistry, materials science, electrical engineering, biophysics and chemical engineering. Important advances in the areas between established disciplines are often only possible by close collaborations of scientists from more than one field. The application of methods and concepts developed in physics is often the basis for new understanding in neighbouring sciences. Parts of modern materials science and of electrical engineering are examples of cases where subfields have outgrown condensed matter physics to become independent disciplines. Important new results in biology such as the structure of DNA, of haemoglobin and of the photosynthetic centre became possible only by the use of methods developed for solid state research.

A good example of the importance of theoretical concepts and of the use of modern experimental methods for the description and understanding of systems, which were not at the centre of interest for physicists, is the tremendous advance in the field of polymeric fluids, melts and solids. Concepts originating in the theory of critical phenomena have been of great help for the development of a quantitative description of the structure and dynamics of polymers. Scattering experiments with light and neutrons, which have been perfected for studies of more conventional condensed matter systems during several decades, have confirmed the theoretical models of these complex macromolecular systems. Similar advances for related materials, such as colloids and self-aggregating surfactants in solution, have been made and are still actively pursued. All these materials are of great technological importance and there is realistic hope of improving the understanding of their macroscopic functions on the basis of molecular properties in order to further advance the technology.

Therefore, modern materials science includes polymers and the physics of complex fluids.

The liquid state

The liquid state of matter is a very active field of research. Whereas simple liquids like the rare gases are rather well understood, more complex fluid states exist, such as liquid metals, electrolytes and many kinds of solutions. They are characterised by strong correlations and disorder, and to understand their macroscopic thermodynamic properties on the basis of the interactions between atoms or molecules is often a difficult task. Even the most important of all fluids, water in its liquid state, is only partially understood; the structure of water in the vicinity of a solute may have important effects on the properties of suspended particles. Significant advances in liquid state physics are coming from developments in statistical physics and from computer experiments. The study of liquids was among the first applications after the development of Monte Carlo and molecular dynamics simulation methods. These computational techniques are now rather common in all areas of condensed matter physics. Simulations are often crucial to investigate the validity of theoretical schemes. These numerical methods are now used for systems of increasing complexity, and the future development of faster computers will undoubtedly lead to improved understanding of more complex systems.

Properties of disordered and amorphous materials and of porous media are much more difficult to understand than those of crystals. The nature of the transition from the fluid phase to the glassy state, which is observed for glass forming liquids ranging from low-molecular weight systems to polymers, and the properties of the glassy phase are only partially understood.

Surfaces and interfaces

Properties of bulk materials of perfect crystalline order are largely understood. In the last few decades the emphasis has shifted towards non-crystalline materials and to systems whose properties are strongly determined by their finite size or by surfaces and interfaces. These modern developments are driven not only by a general interest from a basic point of view but also by demands of technology. The increased miniaturisation of components of electronic devices and the use of materials which are structured on a sub-micrometer scale demand the understanding of properties of systems, in which most atoms or molecules are at or not too far from a surface or interface. Adsorbates on smooth or laterally structured surfaces and thin films are important for many technological applications and the growth mechanisms of adsorbates and their structures are challenging problems. A related problem is the microscopic understanding of wetting. New microscopies, such as the scanning tunnelling microscope and related methods, have been developed to investigate surfaces. They can also be used to manipulate atoms and molecules on surfaces, and these methods will soon make it possible to tailor laterally structured surfaces.

Experimental techniques

Although most research in condensed matter physics is "small" science, conducted by small groups of scientists, large scale facilities for scattering experiments with thermal neutrons and synchrotron radiation have been of extreme importance to obtain the atomic and electronic structure and the elementary excitations of solids and liquids. These microscopic properties of materials are necessary for the understanding of the macroscopic behaviour. The present state of knowledge about the structure and dynamics of solids and liquids is largely based on results of neutron and X-ray scattering and it can be expected that these methods will further enhance the understanding of condensed matter in the future. Besides the significance, which these experimental methods have for basic research in physics, there is an increasing demand from neighbouring sciences such as physical chemistry, biology and materials science to use these techniques to solve problems relevant to their fields. Examples are the investigation of the microstructure of technologically relevant materials like the metallic nano-structures and the polymeric solids; also the structures of biologically interesting macromolecules like proteins can be obtained.

Research in the future

Future research in condensed matter physics will deal with much more complex materials than the ideal crystals. Work on semiconducting hetero-structures and on important metallic materials which are structured on the scale of nanometers will continue. Their interesting macroscopic properties are determined by the finite size of crystalline domains. The quantitative understanding of such technologically relevant materials has to be further improved so that their properties can be designed in a systematic fashion.

Closely connected with the efforts to understand the physics of such mesoscopic systems is the question of how many atoms have to be arranged in what kind of conformation in order to have typical properties of solids. This transition area of atomic, molecular and solid state physics is of considerable relevance for many systems of technological importance like the artificially structured semiconductors, metals and magnets, the quantum wells and "artificial atoms" and the thin films on substrates. The common theme of these systems is their lowered dimensionality and effects originating from their finite sizes. Although many physicists are currently working on such problems, research in this area will continue and expand.

There will also be an increasing trend to investigate amorphous, glassy and fluid systems consisting of small molecules as well as of complex macromolecules. Many of their properties are quite different from those of the ideal periodic structures and a detailed understanding of these differences is so far only partially available.

Besides providing results of technological importance, the study of such substances requires basically new methods for their theoretical description, thereby enriching the general knowledge in physics.

Particle Physics for the Millennium

Commission 11
Peter I. P. Kalmus

From simplicity to diversity

The realisation that the great diversity of the world stems from a handful of elementary particles acting under the influence of a few fundamental forces is one of the triumphs of twentieth century physics. In the early 1930s we appeared to have only three elementary building blocks: the protons and the neutrons which were the constituents of nuclei, and the electrons which complete the atoms. The electrons were bound into the atoms by electromagnetism, since they were attracted by the opposite charge of the nuclear protons, but in order that the nuclei do not disintegrate by the mutual repulsion of their constituent protons, a new short range force, the strong interaction, was required.

This simple picture did not last long. Antiparticles which had some properties equal (such as mass) and others opposite (such as charge) to normal particles were predicted and later discovered. The apparent violation of momentum and energy conservation in nuclear beta decay led to the hypothesis that another new particle, named the neutrino, was emitted. The neutrino did not feel either the electromagnetic nor the strong force, and hence escaped undetected in beta decay experiments. It would be created by another new short range force, the weak interaction, which was so feeble that neutrinos on average could penetrate light-years of material such as iron before having a significant chance of interaction, and were therefore thought to be undetectable. However, in the 1950s the huge flux of neutrinos coming from the decay of radioactive decay products in nuclear reactors led to their detection. Since then many experiments have observed neutrinos from various sources: accelerators, reactors, the Sun, supernova SN1987A, and from cosmic ray interactions.

Also in the 1950s and 1960s, experiments using cosmic rays and later the new large accelerators, showed that if particles such as protons hit nuclei with sufficient energy, then additional new particles could be created by converting some of the collision energy into rest-mass, according to the well known equation $E = mc^2$.

These particles were unstable and decayed rapidly into more stable forms, either in around 10^{-23}s by the strong interaction, or more leisurely, say in 10^{-8}s or 10^{-10}s by the weak interaction. By the 1970s the number of so-called "elementary particles" exceeded the number of chemical elements.

Back to simplicity

Fortunately the present situation is again much simpler. There now appear to be only two classes of elementary building blocks, called quarks and leptons. Quarks feel the strong interaction, leptons do not. In our normal surroundings where energies per particle are low, we have only two of each. Electrons and neutrinos are leptons. However, the proton and neutron are no longer elementary, but are made up of two types or "flavours" of quark called up (u) and down (d). Each contains three quarks, the proton has constituents (u u d) and the neutron (u d d). The electric charges are +2/3 for u and -1/3 for d.

At higher energies, this simple pattern of two leptons and two quarks is repeated, but only twice, leading to three generation of quarks and leptons, as shown in Figure 1. Also every quark and lepton has an antiparticle, so we are left with 6 each of quarks, antiquarks, leptons and antileptons.

Figure 1 : Today's Building Blocks

Leptons (do not feel strong force)			**Quarks** (feel strong force)			
electron	e^-	-1	up	**u**	+2	Also
electron-neutrino	ν_e	0	down	**d**	-1	**antiquarks** **antileptons**
muon	μ^-	-1	charm	**c**	+2	**6 leptons** **6 antileptons**
muon-neutrino	ν_μ	0	strange	**s**	-1/	
tau	τ^-	-1	top	**t**	+2/	**6 quarks** **6 antiquarks**
tau-neutrino	ν_τ	0	bottom	**b**	-1/	

The last of the quarks, labeled top, was discovered in 1995, and the first tentative direct evidence for the tau-neutrino was found in 1998, both at Fermilab in the USA. Quarks and leptons all have an intrinsic angular momentum or spin of 1/2 measured in quantum mechanical units. Such particles are called fermions because they obey Fermi-Dirac statistics. In addition to the proton and the neutron, other combinations of quarks form strongly-interacting particles, collectively known as hadrons: these consist of three quarks, or three antiquarks, or one quark and one antiquark. Some hadrons consist of three similar fermions, such as (u u u) or (s s s). Because identical fermions cannot be in the same quantum state, quarks were given an additional attribute dubbed “colour”, which can have three values, say red, green and blue. Of course, these are only names. However all hadrons are “colourless” so there is an analogy between a hadron containing one red, one green and one blue quark, and the white light that can be produced by mixing light of these three colours. Antiquarks have anticolours as well as antiflavours.

Forces

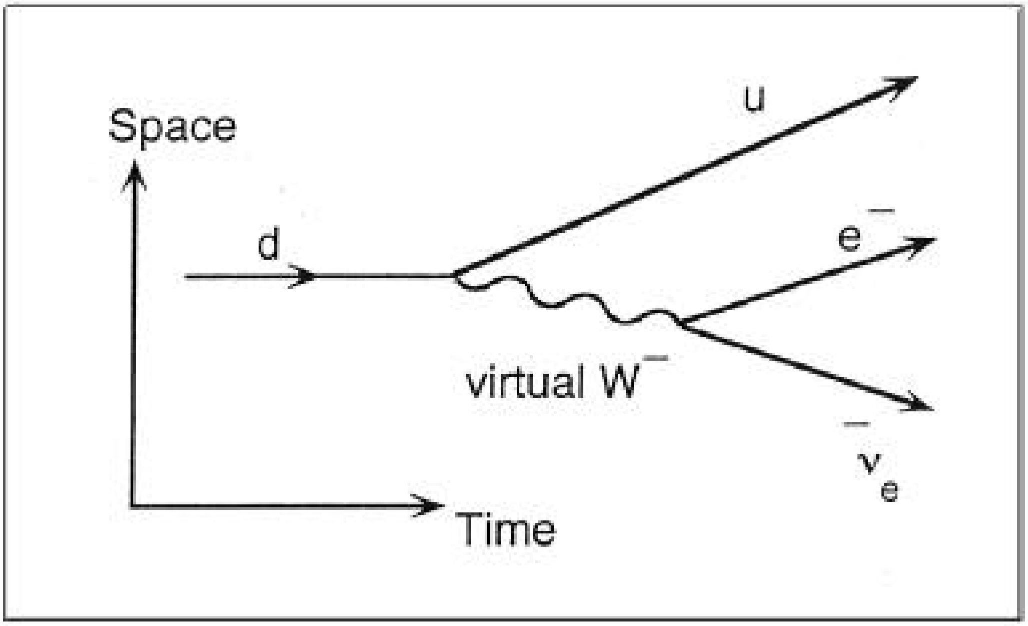
We expect all particles to feel the gravitational force, which however is fantastically weak in comparison with the others. For example, the electromagnetic force between a proton and an electron is 10^{40} times stronger than the gravitational force. All particles feel the weak force. Quarks and charged leptons also feel the electromagnetic force, and quarks feel the strong force.

The forces through which the building block particles interact are transmitted by the exchange of another type of object. The force-carriers are bosons, particles which have integer spin and obey the Bose-Einstein statistics. The carrier of electromagnetism is the spin-1 photon. Gravity is believed to be transmitted by spin-2 gravitons, but these have not yet been detected.

The objects which carry the colour force between quarks and hence glue them to form hadrons are called gluons. Unlike photons, gluons can couple to each other. One result of this is that the strong force increases with distance. Quarks are therefore confined within hadrons, as it is energetically more favourable to produce a quark-antiquark pair than to further separate two quarks. Gluons were first discovered in 1979 at the DESY laboratory in Germany. The theory of strong interactions, known as quantum chromodynamics (QCD), is well developed and consistent with experiments, although it is not easy to test it very precisely. The coupling constant, which is a measure of the strength of an interaction has a value around 0.12 for the strong interaction, compared with 1/137 for the fine structure constant of quantum electrodynamics, and this makes calculations more difficult.

Initially it was thought that a charged carrier, called W for weak, was responsible for the weak force. Feynman diagrams allow one to visualise these interactions. Fig. 2 shows the weak interaction in beta decay where a neutron (free or within a nucleus) changes into a proton, and hence a down quark turns into an up quark by emitting a W^- boson which then decays into an electron and an antineutrino.

FIGURE 2



Feynmann diagram for the weak interatction in beta-decay

In the 1960s, theorists achieved the surprising feat of unifying the apparently disparate phenomena of the electromagnetic and weak forces into a single framework. Electromagnetism has a classical inverse square law and infinite range. In contrast the weak interaction under normal circumstances is very feeble and is confined to sub-nuclear distances. Protons in the solar core collide many times a second, but on average a particular proton will only convert into a neutron after around five billion years of collisions. Hence it can be calculated that the Sun is only half way through its hydrogen burning and has provided both the environment and the time-scale for biological evolution on Earth.

In electroweak theory, there are four mediating bosons. The massless photon transmits the electromagnetic force and the weak force is transmitted by three massive particles : the charged W^+ and W^- particles and the neutral Z^0 particle, which have masses about 100 times that of the proton. The intrinsic strengths of these carriers are identical, but the massive nature of the W and Z particles limits their range to very short distances, a consequence of the uncertainty principle. In collisions at relatively low energies, the particles do not approach each other sufficiently closely for W or Z exchange to occur. However at energies of around 100 GeV close encounters are common, showing electroweak unification. The most spectacular experimental verification of this theory was the discovery of the W and Z particles at CERN in 1983. Electroweak theory has now been tested to high accuracy.

Symmetries

Symmetries play a significant role in particle physics. In mechanics, in electromagnetism, and in strong interaction physics, there is no intrinsic difference between left and right. A process and its mirror image occur at the same rate. This is known as conservation of parity (P). Similarly observable processes would occur with the same probabilities if all particles were changed into their corresponding antiparticles. This is charge conjugation (C). At the microscopic level, the laws for a process and its time reversed process (T) should also be equivalent. For macroscopic systems, time reversal does not hold, but this is a consequence of its statistical improbability rather than of basic laws.

In the 1950s it was found that for weak interactions P and C were not conserved, and in fact they are violated maximally. The strict mirror image of beta decay is not observed unless at the same time particles and antiparticles are interchanged. Later it was found that the product CP was violated in some weak interactions involving neutral K-mesons. This CP violation was small. Its origin is not fully understood, but it is believed to be one of the ingredients required in the very early universe to produce the present tremendous preponderance of matter over antimatter. Two “B factories”, one in Japan and one in California, have started operating in 1999, and are investigating the origin of CP violation, as well as observing oscillations in the B^0 meson system, analogous to K^0 oscillations which have been observed since the 1960s. The first direct evidence for T violation was observed in the neutral K-meson system at CERN and at Fermilab. The product CPT is believed to remain conserved.

Electroweak theory and QCD have been incorporated into what is known as the standard model of particle physics. Although this model works very well it suffers from a number of defects. There are rather a lot of arbitrary numbers which are not intrinsic to the theory but have to be obtained from experiment. The theory predicts nonsensical results at energies slightly higher than now available - equivalent to processes having a probability greater than unity!. In addition, the theory requires that the W and Z particles, like the photon, should be massless. A mechanism which gives mass to the particles by allowing them to interact with a field was first suggested by Peter Higgs. This would have a carrier object — the Higgs boson, which, so far, has not been detected.

In this short summary, very little has been written about the theoretical advances in particle physics. There are schemes which unite the strong interaction with electroweak theory. These are known as grand unified theories, GUTs. Another theory, supersymmetry, unites the building blocks, the quarks and the leptons, with the force carriers. This requires new partner particles for all these objects, none of which have so far been discovered. Superstring theories, and their recent extension, M-theories, which require supersymmetry, are exciting and fashionable. They treat particles as excitations of tiny strings. This avoids objectionable infinities which arise when particles are treated as point objects. Superstring theories do however require more than the usual three space and one time dimension. The unobserved dimensions are assumed to be compactified - curled up so that they are too small to be observable, just as a telegraph wire appears from a distance to be only one dimensional. Superstring theories have the potential to provide a quantum theory of gravity and to unite it with the other forces, and there is much activity in this field.

Future prospects

What will the future hold as seen from mid-1999 ? There are already strong indications, particularly from neutrinos arising in the atmosphere from cosmic ray interactions, that neutrino species can change into each other, for example that ν_μ can turn into ν_τ. These neutrino oscillations can only occur if neutrinos have mass, and such mass could be significant for cosmology, as part of the dark matter problem. Not all experiments are fully compatible with each other, but it seems likely that this will be settled within the next couple of years. The origin of CP violation will be discovered within the next few years. The large hadron collider, LHC, being constructed at CERN in Geneva, will start in around 2005.

It seems highly probable that the Higgs boson will be discovered with that machine, indeed it might be discovered sooner at the CERN large electron positron facility, LEP, which is running at higher energies than previously, or at the Fermilab Tevatron which is being upgraded. If the Higgs is not found then some other new physics is certain to emerge, to avoid the excess of probability that would otherwise come from the standard model.

What else will emerge ? We take for granted that the electron and proton charges are numerically equal, and indeed experimentally they are to better than 1 part in 10^{21}. This may not seem surprising. However, leptons and quarks are quite distinct. The numerical charge equality between 3 quarks and an electron cannot be a coincidence. Perhaps at high energies, such as existed in the early universe, leptons and quarks coupled with each other. At lower energies, this symmetry is broken in an analogous way to electroweak symmetry breaking. In 1997 there was excitement, when some collisions between positrons and protons at the HERA machine at DESY, gave some indication of the existence of such leptoquarks. With more data this interpretation appears wrong, but it still seems likely that in the fairly near future some better understanding will arise of the connection between leptons and quarks. Supersymmetry may be found too. Superstring theory may come up with some predictions which can be tested.

Gravitational radiation is predicted from general relativity, and its existence can be inferred from the careful measurements over many years of the change in period of a binary pulsar. Gravitational waves are likely to be detected directly from some astronomical object within the next few years. So the wave properties of gravity will open a new window in astronomy. However, it seems unlikely that the graviton, the quantum of the gravitational force, will be discovered during the next 20 years.

Nuclear Physics in the New Millennium

Commission 12
Erich Vogt

Introduction

Atomic nuclei are the heart of all matter and comprise more than 99% of the known total mass of the universe. Yet nuclei, lying at the centre of atoms, occupy only about one million-millionth of the volume of normal matter which tells us that they have a density beyond everything we may meet in our daily lives. The field of nuclear physics is therefore of great intrinsic importance in understanding our universe and it has also had a very interesting history.

A discussion of where nuclear physics is heading in the new millennium should be placed within a perspective of the present century of science for much of which nuclear physics was the dominant field of science. The end-of-century complacency about science which characterised the final years of the nineteenth century was rudely shattered by the discovery of radioactivity and, shortly afterwards by the birth of nuclear physics and the emergence of quantum theory to describe the physics of the atom and its nucleus.

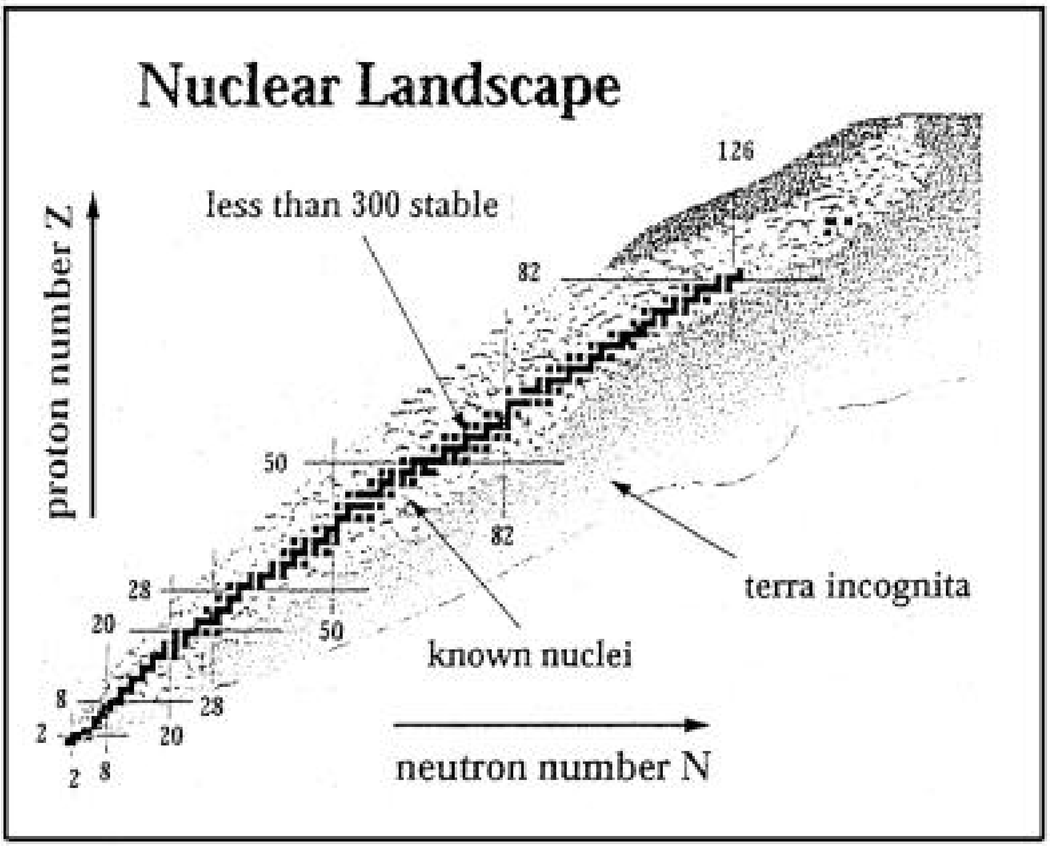
It was Ernest Rutherford who gave us nuclear physics by creating the appealing picture of the atom as a miniature solar system: a tiny, massive nucleus, surrounded by orbiting electrons. The earliest work on radioactivity, to which Rutherford contributed, found that it consisted of three different kinds of radiation: alpha particles (helium nuclei), beta particles (electrons) and gamma rays (photons). In their classic work, ninety years ago, Rutherford and Geiger used the deflections of alpha particles from a gold foil to show that most of the mass of the gold atoms had to reside in a tiny atomic centre (the nucleus) almost a million times smaller the gold atom. Over the next few decades it was found, at the Cavendish Laboratory in Cambridge, which Rutherford headed, that the nucleus itself was made of neutrons and protons. The number of protons in the nucleus determined the element and for each element there were, potentially, many different isotopes differing in the number of neutrons in their nucleus.

Quantum theory, which emerged concurrently with nuclear physics, received its early important tests in describing the physics of the atom. In the first half of this century the atomic nucleus became the most important vehicle for the elaboration of the ideas of quantum mechanics. The binding of the neutrons and protons into stable nuclei — or, alternatively, into unstable radioactive nuclei — required a new short-range force which came to be called the strong interaction.

The nuclear landscape

The nuclear landscape, shown on Fig. 1, is a plot of all of the stable and radioactive nuclei versus their proton and neutron number. The stable nuclei form a diagonal ridge across the figure which terminates beyond lead. The thousands of unstable nuclei have, generally, shorter and shorter lifetimes as we proceed away from this ridge and eventually we reach the driplines at which extra neutrons or protons are no longer bound and therefore simply "drip" off. It is a rich and varied landscape. All of the nuclei, stable and unstable, contribute to the understanding of nuclear systems and are involved in astrophysical processes.

FIGURE 1



Map of bound nuclear systems as a function of proton number Z (vertical axis) and neutron number N (horizontal axis). The black squares show the nuclei that are stable, *that is, non-radioactive or long-lived with half-lives comparable with the age of the earth. There are fewer than 300 such species. Between the stable nuclei and the driplines, discussed in the text, are thousands of radioactive nuclei, some known but most unknown*

Perhaps the most wonderful science story which has emerged in this past century pertains to our new understanding of the history of our universe since the initial Big Bang, billions of years ago. Nuclear physics led to nuclear astrophysics which underlies much of modern cosmology. The very lightest elements were created in the Big Bang and then the remaining elements arose from the processes involved in the birth, life and death of stars. The detailed understanding of the processes remains a modern challenge for nuclear physics because it requires the knowledge of the low energy nuclear reactions of all nuclei.

Access to the strong nuclear binding energy became a very dramatic development just before the second world war. Looking at the nuclear landscape of Fig. 1, it can be appreciated that the stable nuclei terminate, beyond lead, because the electric repulsion of the protons reduces the total binding energy. As a result, fission is possible in which a heavy nucleus splits into two or more lighter nuclei with a great release of energy. When fission was discovered in 1939 it led rapidly to the development of nuclear weapons and nuclear physics became highly political, while at the same time the scientific questions of the field made nuclear physics the queen of the sciences. Fortunately nuclear energy can also be harnessed for the production of electricity: the pursuit of clean energy sources through nuclear reactors is another continuing challenge for the field.

Nuclear physics and particle physics

While quantum mechanics and nuclear physics thrived together a number of other important fields of science were spawned off in mid century — such as particle physics, condensed matter physics, microelectronics, microbiology, etc. — which rapidly joined nuclear physics on the centre stage of science and achieved their own dominance. Though no longer in any sole regal position, the field of nuclear physics remains full of new ideas which promise to carry it into the next century and millennium.

The emergence of particle physics as a separate discipline in the second half of the century has had a strong impact on nuclear physics. It is no longer protons and neutrons and electrons which are the basic building blocks of matter, but, according to the Standard Model the building blocks are quarks and leptons. Further, the strong interaction is not the nuclear force between nucleons but rather Quantum Chromo Dynamics (QCD), the exchange of gluons between quarks. Nuclear physics now pertains to the complex quantal systems (hadrons), including atomic nuclei and collapsed stars, made of strongly interacting quarks. Nuclear physics is then the science of hadronic matter and atomic nuclei, of their properties, their interactions and their constituents. It is now moving in new directions towards a more fundamental understanding of extreme states of this most dense form of matter.

The development of nuclear physics over the past decade has increasingly reaffirmed its strong links to particle physics and nuclear astrophysics. The research is closely related to the description of various phases in the early evolution of our universe. The experiments to detect the quark-gluon-plasma and to study the abundances of the lightest elements, the attempts to model the production of heavier nuclei and to determine the equation of state of nuclear matter, and the search for neutrino masses and dark matter are open problems shared by nuclear physics, particles physics and astrophysics.

The strong binding force (Quantum Chromo Dynamics, or QCD) between the quarks remains largely intractable at nuclear energies and so phenomenological methods are necessary to describe nuclei. At low energies the nuclear properties are described in terms of nucleons and mesons with empirically deduced interactions. Sophisticated tools have been developed to collect information to provide a phenomenological description.

Unstable nuclei : the 'dripline' regions

In the nuclear landscape of Fig. 1 our present knowledge pertains primarily to that small subset of isotopes which are stable or nearly stable. We need to know the properties of isotopes which are very heavy or have very large neutron or proton excesses, that is, they are near the driplines. The isotopes in the extreme regions of the landscape have unusual behaviour and most are involved in the creation of the elements in stars. Sophisticated tools have been developed to collect information for a phenomenological description of nuclei. Recent years have seen remarkable progress in synthesising the heaviest man-made nuclei in the region of superheavy elements, and in probing nuclear systems at the dripline regions where the evidence for nuclear halo states (nuclei with an outer skin of only neutrons) has been found. Our knowledge of nuclei along the proton dripline is beginning to be excellent with the observation of the long awaited Sn(100) nucleus and many other exotic nuclei showing proton radioactivity. The process of two-proton radioactivity still awaits investigation.

A challenge for the beginning of the next millennium is to produce nuclei with extreme neutron excess in intermediate and heavy mass regions so that we may approach or maybe even reach the neutron dripline in the intermediate mass region. Our search for new phenomena in this part of the dripline region is a great challenge and will confront important questions. Are there real neutron skins? Does nuclear structure change when we have large chunks of nucleon matter of very large isospin? The recent very intense development of radioactive beam facilities, worldwide, will certainly play a key role in this progress.

Future trends

The new trend in theoretical nuclear physics will certainly also play an important role in acquiring a deeper understanding of nuclear matter. At high energies and temperatures, the substructure of nucleons and mesons in terms of quarks and gluons becomes important. This substructure leads to a challenge for the next millennium: how to find a more basic understanding of nuclei, that is, how do we proceed from QCD to phenomenological models in terms of nucleons and meson exchange so that we can derive nuclear structure and hadron dynamics at short distances from first principles. We may not be able to find a complete theory but there are many gaps to bridge. New capabilities with energetic and intense electron, photon and proton beams promise to provide comprehensive studies of this very fundamental goal during the ongoing decade.

Most of the studies of nuclear matter, until the present, have explored its properties at or near normal temperatures and pressures. With increasing energy and density, phase transitions are expected and known to occur in nuclear matter and in the early universe. At intermediate energies liquid-gas transitions occur, after which with increasing energy hadronic gas is formed possessing a density as high as two to three times the normal density of nuclear matter. At the high energy limit we expect to see how nuclear and particle physics merge. Future experiments employing collisions between relativistic heavy ions will allow heating and compression of nuclear matter and will create extreme conditions under which such questions can be explored. The quark-gluon plasma, a very important goal, will certainly be readily available within a few years at several laboratories. By getting access to it we expect that our field will contribute to the understanding of the early universe.

Physics for Development

Commission 13
Gallieno Denardo

Introduction

The IUPAP Commission 13 seems rather anomalous compared to most of the other Commissions, because it is not defined by a scientific discipline. Its aim is to strengthen communication and thus co-operation among all countries in all disciplines of physics. For this reason, C.13 needs to keep links with all the other IUPAP Commissions. It is natural that C.13 should devote its attention mainly to the problems of the developing countries where physicists often work in isolation or in modest research conditions.

Motivations

The levels of research, and of training for research, in physics vary remarkably between different countries. From the most advanced countries to the least developed ones, the numbers of PhD's in physics can differ by factors of thousands.

In recent decades, several countries included in the UN list of developing countries, have been able to set up the educational structures needed for the creation of indigenous physics PhD's and for the pursuit of original research activities. Countries such as India, China, the countries of the Confucian rim, Brazil, Argentina, Chile, all have their own groups of physicists and many of them are at an excellent level. By contrast, other developing countries have not only been unable to succeed in following such a process, but have suffered a negative rate of scientific development. The gap is getting bigger for them! In the future these countries will feel dramatically the consequences of scientific regress.

For example, in many African countries, the average age of the faculty members of the physics departments is now more than 50, which implies that in a decade the turnover of university staff will be impossible if no actions are taken immediately. To form the new class of physicists who will supply the required replacement of the retired teachers it is necessary to train young scientists. This will not be achieved through programmes that offer grants to carry out the whole of a PhD course abroad, but rather through "alternate" programmes (sometimes called sandwich fellowships) which are based on the co-operation with "external" universities under the firm condition that the degree is delivered in the country, not abroad. The need of the developing countries for the formation of indigenous PhD's locally is so urgent that it is be considered as a priority by those organisations which aim at stimulating the progress of the Third World.

Memberships

While the majority of the more advanced countries are members of IUPAP and participate in the programme of the Union, a remarkable number of developing countries are not members of IUPAP. This excludes those countries from the benefit of being part of an international forum and enhances their isolation. In its endeavour to stimulate international co-operation in order to involve the developing countries in the international arena of scientific research, C13 does all that it can to encourage and help such countries to become new member states of IUPAP. Following contacts with the highest governmental and university authorities, both Ghana and Senegal became IUPAP members. Now Ethiopia and Cameroon are also under discussion for membership. Many countries, especially in the African continent, are still to be attracted.

Links with all commissions

C.13 offers scientific advice and, through the IUPAP secretariat, some financial support towards the organisation of international conferences. Whilst the conference topics of the other Commissions are specific and specialised, the topics of these conferences can be in any field of physics. The criteria for a positive recommendation from C.13 are not only the scientific excellence, but also the international character. For C.13 a conference should represent an opportunity to strengthen regional co-operation and to foster contacts among scientists — particularly for the benefit of those from the least advanced nations. Physics is one of the means to bring people closer together, and to foster the understanding of different people.

Considering the variety of topics of these conferences, C.13 often seeks for the specialised scientific co-operation and advice of other commissions, or simply makes recommendations to those commissions about an activity that is being considered by C.13. Particularly important is the link with C.14, the Commission for Education. In recent years, the co-operation with the International Commission on Optics (I.C.O.) has developed to a stimulating stage.

Physics for development

Physics is important not only for the development of research and education but also for the advancement of high technology, and therefore of the industrial sector of any country. One of the main concerns of C.13 is the problem of industrialisation in the third world.

In the effort to identify and discuss those problems, the Commission started a series of international conferences with the purpose of debating the ways and means for physicists to contribute to the progress of high technology industrialisation in the developing countries. To this end, successful cases were examined to extract suggestions about the best solutions for other situations. Moreover, those scientific subjects which have relevance to technological development are discussed. Often quoted is the experience of the Japanese development, as well as the progress of other countries, such as India, China, Brazil, Argentina, with confidence that these can offer guidelines for the development of the poorest countries. One result is that in all cases scientific education is the first condition for starting the industrial development process.

In recent times a new element has become important : informatics. The growing speed of diffusion of informatics techniques will from one side allow for a global communication opportunity, but will also leave those who are not part of the new informatics networks at a disastrous disadvantage. Informatization of a country is not only a question of funding; it is even more a question of a scientific culture that is lacking in many countries, like sub-Saharan Africa, South East Asia and the Andean region. This imbalance enhances the educational and technological gap between some developing countries and the industrialised countries. Lack of experts in physics implies also lack of experts in many sectors of high technology and, therefore, the necessity for some governments to rely on foreign experts for their national projects such as new telecommunications and new industrial activities.

C.13 encourages the organisation of conferences on these issues, and is directly involved in the series "Physics and Industrial Development: Bridging the Gap".

The first conference took place in New Delhi (India) in 1994, the second in Belo Horizonte (Brazil) in 1996, and the next is planned for the year 2000 in South Africa. The proceedings of the conferences held in India and Brazil were published and distributed. Of course, each region has its own features: accordingly each of these conferences deal with issues relevant to their region. C.13 devotes special attention to meetings of this type as they exhibit the "resonant" interaction between physics and the educational and industrial development.

Co-operation with other organisations

In accordance with its aims, C.13 maintains contacts with organisations and institutions that run programmes in support of physicists in developing countries, such as the Abdus Salam International Centre for Theoretical Physics of UNESCO-IAEA in Trieste and the IPPS in Uppsala. Whilst this co-operation is achieved in different ways, all collaborations aim at combining the efforts in order to enhance the effects of the actions and contributions. IUPAP, through C.13, shows an extraordinary capacity for serving as a hub of communication. It stimulates co-ordination of different institutions in favour of physics in the Third World. The purposes of C.13 are in part similar to those of the ICTP, in particular of the Office of External Activities, to those of IPPS and to those of a few other Institutions. Those organisations that share the objective of assisting physicists of the developing countries in accelerating the process of integration into the international research community are always welcome to co-ordinate their efforts with the help of C.13.

Physics Education in the New Millennium

Commission 14
Paul J. Black

Physics in the Curriculum

The latter half of the twentieth century has seen a spate of curriculum reform projects, particularly for school physics. There have been two driving forces here, one to produce more physicists to support national competitiveness, the other to bring the physics curriculum up to date. For much of the period, school physics seemed to stop at the end of the nineteenth century. There have been determined efforts to rethink the curriculum to ensure that it reflects current physics - efforts which have called for skills of "didactic transformation" whereby recent research, communicated only in complex professional language, may be conveyed in conceptually and linguistically simpler ways without significant loss of authenticity. Given that the advance of physics seems still to proceed apace, and in directions that attract a good deal of public and media attention, it seems that such work has to be a continuing programme.

At the same time, many countries now see the place of physics, at least for the years of compulsory schooling, as a component of either "science" or "physical science". Thus the subject may not have a strongly separate identity, but rather be presented as combined, or co-ordinated (or, in the hands of some teachers, even integrated) with the other natural sciences. This can often be to the advantage of the subject, because such combined courses are usually taken by all pupils, so that there is no choice to avoid physics, whilst, because its concepts are fundamental to the other sciences, physics usually receives more than its proportionate share of attention in such courses.

A third trend has been emerging more strongly in the 1990s. This has been to question the purposes of an education in physics. The argument has been that if it is to be studied by all pupils, its main aims should focus on the interests and needs of the majority of future citizens, not of the elite minority who will go further with it to become professional scientists or engineers. If it is to serve the broader community, and to contribute to a well-rounded education, then, it is argued, attention ought to be paid to the social and technological implications of the work of physicists, to the philosophy and the history of the subject and to the ways it is embedded in our culture, and to the means of support and the mores of the community of professional physicists. All of this can be done, but only at the expense of reduction in content and/or in the skills specific to science developed in and through physics education.

For higher education, a similar trend of pressures is emerging, for it is becoming more clear that most of those who study university courses in physics are not going on to become research physicists, so that the contribution of such courses to their broader educational development is called into question.

Public and Policy Issues

The issue raised in the preceding paragraph is related to a broader question - who should have the power and authority to decide on the aims, even the definition, for physics education ? Given that national control of the school curriculum, and of programmes of teacher training, long common in many countries, seems to have been spreading to all, it is no longer the case that physicists themselves will be the sole arbiters for the physics curriculum, and may only have a voice if they make intelligent contribution to the public debates about educational priorities and values. In this arena, tensions have arisen recently between those physicists who have specialised in the study and practice of physics education, and others who have used their eminence as research physicists to exert power in educational debates. Such intrusions have often been helpful, but in cases where the research physicists have not studied or respected the insights and experience of full-time teachers and education researchers, some of these 'outside' contributions have been unhelpful.

The most pressing public and policy interests have arisen in respect of two main pieces of evidence. The first has been the frequent signs of decline in the numbers taking up advanced study of the subject, and, partly as effect and partly as cause of such decline, the fall in the numbers of those well qualified to teach the subject. Thus there has been much study of the reasons why the subject is unattractive to pupils: one reason is the lack of connection between the topics in the curriculum and the daily lives of students - lives which often include exciting presentations of contemporary physics research in the media, on topics which are not even mentioned in school. Another possible reason is the perceived difficulty of the subject - a perception which can often be supported by evidence that the average student is less likely to do well in physics than in almost any other school subject. However, many physicists who accept that this is the case nevertheless find it difficult to construct courses which are less demanding.

There is also concern in some countries about a perceived decline in standards of attainment. Whilst this could be general across many subjects, the development in the 80s and 90s of prominent national and international comparative surveys of achievements in mathematics and science have focused particular public and media interest in each country's standing in these areas in relation to the rest of the world. Comparisons between different educational systems are fraught with dangers of misinterpretation and illegitimate interpretations, but this has not inhibited most commentators. What is often ignored is that in many countries there have been huge increases in the numbers of students studying the subject at all levels, particularly in the last years of high schools and in tertiary institutions. It is hard to know how to allow for this factor in comparing trends in test scores, either over the years or across different countries., but experienced researchers generally agree that there is no firm evidence that standards have declined.

Processes of learning

The last twenty-five years of the twentieth century have seen a well-marked change in the contribution of research to physics education. This has arisen partly because of the increase in numbers of those engaged in such work, but more particularly because the research field is no longer one in which psychologists or sociologists use physics teaching as a suitable arena for their more general enquiries, but has become one where researchers with a prime interest and background in science education as such have developed and deployed the instruments and procedures of the social scientists to study the learning of their particular subjects. In particular, detailed studies of the learning of physics concepts has shown that across all levels from primary school to university degree, there are widespread and common misconceptions held by students who have often, nevertheless, achieved quite good results in formal examinations. The more recent shift has been from research which adds to this, by now, voluminous catalogue of misconceptions, to research into processes of conceptual change. Such work has led to some notable achievements, but often with only very broad and non-specific underpinning in theories of learning.

However, the relevant areas of cognitive psychology are very lively at present and there begins to be traffic in both directions, between the empirical advances of subject experts and the theoretical developments of learning researchers. Research into the conditions for effective learning has made clear that to teach and test factual knowledge alone, with the aim that understanding and use will develop later just does not work. It also shows that the teaching on understandings and skills will not equip the student to use these powers in solving real problems unless experience of tackling such problems is provided alongside such teaching. More recent work has emphasised the importance of discussion and argument in the development so leading to renewed interest in the value of grippe work and peer assessment.

Other relevant fields of research have been concerned with motivation for, and choice of the, study of the sciences ; with assessment and testing including effects on learning and the predictive power of tests; on bias, particularly gender bias, in textbooks, classroom practices and testing; and in with practical work.

In debates about practical work in the sciences, much of the expensive investment in teaching laboratories has been called into question because students are often following recipes and routines with little opportunity to exercise choice, creativity, and even thoughtfulness, about the arts of measurement and experimental inquiry. There have been new projects to explore possibilities for students to design, plan and carry out their own inquiries. These present considerable challenge to teachers. There are obvious difficulties in resources and in classroom management that such unpredictable activities raise. However, there are more fundamental educational problems, arising because the selection and guidance of such work demands a very clear conception of the essential nature of science investigation, and of the possibilities that the limited work of students can provide for them authentic experiences of, and insights into, the work of professional physicists. Teachers with no personal experience of research, and whose own training and teaching experience may never have involved such work, have little basis in personal experience on which to make the judgements that are now required.

The other area of new developments has been in the use of information technology. Much hope has been invested in the development of software learning programmes, but even in advanced countries such learning aids have yet to make a significant impact in the majority of classrooms. The models of learning underlying software programmes are perhaps not adequately sophisticated. More common in rich countries has been the use of computers on-line to experimental apparatus for the capture and analysis of data. Nevertheless, training programmes, and particularly those using simulations, as in piloting and driving, have established a firm base in the recruitment selection and training of adults, so that further development at school level may be anticipated. The use of the internet has also begun to open up new possibilities: there have for example been several programmes in which pupils across and even between countries have worked collaboratively in collecting their local data on environmental indicators and then sharing one another's results through a regional or international network.

Looking Ahead

It seems very likely that public interest in education at all levels will intensify. Furthermore, for all of the sciences, not least for physics, this general interest will be sharpened by increasing public concern about the funding for research and about public control over activities of scientists which could threaten their environment or present new ethical problems and unpredictable effects in their daily lives. Given this, control over the curriculum is likely to shift even further from the private interests of scientists to the public interest, and more physicists may have to be prepared to give more energy to engaging in a debate in which they have to respect the public interest whilst ensuring a well-informed understanding of their subject.

New advances can be expected from research into cognition, and it is very likely that this will lead to better models for the learning in specific areas of expertise. Such models could serve to provide a firmer basis for classroom instruction. They would also provide a firm basis for interactive computer programmes; thus, for example, formative assessment which identified the particular learning difficulties of each individual student could help to nip in the bud many obstacles to learning in a way in which even the best of teachers could not possibly manage with a class of (say) 30 or more students.

However, both of these developments, combined also with recent evidence of the ineffectiveness of many of our present efforts in mass education in the sciences, could lead to pressure to study far fewer topics at any level of education, but to study them really well so that the large majority of students achieve some effective understanding, with both interest and enjoyment. The main problem that any such radical programme of change will encounter is recruiting and supporting the imagination and commitment of teachers so that they can face the difficult task of changing their ingrained habits in classroom work.

Somewhere near the middle of the twentieth century, Philip Morrison made the plea that "less would mean more". The next millennium might well see more of us accepting that he was right and re-framing our beliefs about a proper education in physics in order to respond to his challenge.

Atomic, Molecular and Optical Physics in the New Millennium

Commission 15
Gordon W. F. Drake and Indrek Martinson

Introduction

Modern physics of the twentieth century is largely founded on the understandings and insights gained by the study of atoms, molecules, light, and their interactions. In more recent years, remarkable new discoveries continue to provide fresh insights and a driving force for high technology industry. We will trace here some of the most important milestones along the way, and show that the field remains as vibrant and challenging as ever as we enter the twenty-first century.

The Early Period, 1900–1930

The two cornerstones of modern physics, relativity and quantum mechanics, both owe their early origins in this century to the study of atoms and light. The stage had already been well prepared in the late 19th century by the Michelson-Morley experiment, J. J. Thompson's discovery of the electron (the first "elementary" particle), observations of regularities in atomic spectra, and Planck's quantum hypothesis to explain the properties of black-body radiation. Einstein's remarkable three papers of 1905 built on these studies to transform the way we think about the physical world. In addition to the special theory of relativity, he provided a quantum explanation for the photoelectric effect, and an explanation for Brownian motion in terms of random molecular collisions, thereby giving real substance to the ideas of light quanta and the molecular structure of matter.

Shortly after, Rutherford's 1911 work on alpha-particle scattering demonstrated that atoms are like miniature solar systems with planetary electrons orbiting a small dense nucleus containing nearly all the mass. With this model in hand, Bohr and Sommerfeld succeeded in constructing quantization rules based on classical mechanics to explain the structure of simple atomic spectra. However, a truly satisfactory explanation did not come until 1925 when de Broglie's idea of matter waves was transformed into modern quantum mechanics by Schrödinger, Heisenberg, Born and others. This fundamental theory, combined with the existence of the electron spin and Pauli's exclusion principle, could explain the structure and spectra of atoms, molecules and (somewhat later) even solids.

This early period culminated with the work of Dirac in 1928 who unified quantum mechanics with special relativity. The resulting Dirac equation provides the fundamental description of spin-1/2 particles (such as electrons) and their interaction with external electromagnetic fields. As a first test, it provides a (nearly) exact description of the spectrum of atomic hydrogen, but most remarkable was Dirac's association of negative energy states with antimatter—a prediction confirmed four years later by Anderson's 1932 discovery of positrons (anti-electrons) among the decay products produced by cosmic rays.

The Middle Period, 1930–1960

After the initial excitement of the Early Period, atomic and molecular spectroscopy continued to play a very important role in the 1930's; first as a test of the rather crude computational techniques then available to solve the Schrödinger equation for many-electron atoms, and second as a source of data that could be applied to astrophysics, the identification of chemical elements in the solar spectrum, and the determination of elemental abundances throughout the universe. Without these data, our modern theories of stellar evolution and cosmology would not be possible.

In addition, new experimental techniques were coming on the horizon. In the early 1920's, Stern and Gerlach began developing atomic beam methods, and using them to confirm that atoms have magnetic moments associated with electron spin. I. I. Rabi brought atomic beams to Columbia in the 1930's and combined them with magnetic resonance methods, using the newly emerging microwave technology. With this atomic beam magnetic resonance technique, he and his students obtained a wide variety of striking results for the magnetic properties of nuclei (spins and magnetic moments), atoms and molecules. Based on this work, Bloch and Purcell developed the nuclear magnetic resonance (NMR) absorption method, which has yielded a wealth of data on nuclear properties as well as immense applications to other fields of science, such as chemical analysis, biology and medicine (magnetic resonance imaging).

In the late 1940's Kusch experimentally found that the magnetic moment of the electron is slightly larger than that predicted by the relativistic theory of Dirac. At *nearly the same time, Lamb and Retherford observed a tiny energy difference (Lamb shift) between two levels in the hydrogen atom which according the Dirac theory should have been exactly degenerate. These two effects, the anomalous magnetic moment of the electron and the Lamb shift, led Schwinger, Feynman, Tomonaga and others to create a new theory of quantized electromagnetic and electron-positron fields. The new theory, called quantum electrodynamics (QED) has been termed "the most successful theory ever invented." It has been verified to extremely high precision by atomic physics tests of ever-increasing accuracy, continuing to the present day. It also forms the basic model for the construction of other theories of elementary particle interactions involving the nuclear weak and strong interactions, and the electro-weak unification.*

In addition to atomic structure and spectroscopy, there is a second broad area of atomic and molecular physics dealing with cross sections for a vast variety of elastic and inelastic collisions involving atoms, ions, electrons, molecules, molecular ions, and photons. These cross sections are extremely important because they determine the rates of processes and ultimate chemical composition in sources ranging from industrial plasmas to stellar atmospheres, and especially the Earth's atmosphere. The development of atomic beams, together with parallel developments for the control and manipulation of ion and electron beams, allowed measurements of ever increasing variety and sophistication. At the same time, theorists began developing an arsenal of approximation methods ranging from the high-energy Born approximation to the close-coupling method useful at low collision energies. However, without the availability of high-speed computers, the accuracy that could be achieved was rather limited.

The Late Period, 1960–2000

In a famous paper from 1917, Einstein laid the foundations for a field now called "quantum electronics." He found it necessary to introduce the new concept of "stimulated emission" in order to account for the detailed balance of photon emission and absorption processes. Nearly 40 years later this same process of stimulated emission blazed forth in the form of the first masers (Townes, Basov and Prokhorov) and lasers (Maiman, Schawlow, Townes). These sources of high intensity coherent light have not only revolutionised the way that atomic and molecular physics is done, but they have also opened new doors in many other fields *as well, ranging from fibre optics and telecommunications to eye surgery and controlled fusion.*

Lasers and their many varied applications continue to be a major growth industry in both the scientific and commercial senses. Their narrow line-widths, tunability and high intensities make them ideal spectroscopic tools for applications such as combustion studies and remote sensing of the atmosphere. They also make possible entirely new techniques such as two-photon spectroscopy and Lamb dip spectroscopy (optical hole burning) to eliminate the Doppler widths of spectral lines due to the thermal motion of the absorbing atom or molecule. With these techniques, measurements of unprecedented accuracy can be made and new structures resolved in the complex spectra of molecules. New theoretical formulations such as the "dressed atom" picture were developed to describe atoms strongly driven by laser fields, and the wide range of new phenomena they displayed.

More recently, powerful lasers with extremely short pulses (down to the femtosecond range) have come on the scene, opening the way to time-resolved studies of fast chemical processes and laser-induced chemical reactions. The electromagnetic field of the laser light can now be made so strong that electrons are literally ripped out of atoms and accelerated to high energies. The behaviour of matter under these extreme conditions remains an active area of study.

Lasers have also greatly extended the range of scattering phenomena that can be studied by facilitating the preparation of the colliding partners in particular quantum states. This, together with improved techniques for measuring the angular distribution of the scattering products, makes possible what has been termed "perfect" scattering experiments in which all parameters are subject to measurement and control. Such measurements provide stringent tests of theoretical calculations. They also provide much more detailed information on the mechanisms taking place in the more complex rearrangement and reactive scattering processes of interest in atmospheric, space and plasma physics.

The advent of fast electronic computers from the 1960s onwards has had an equally great impact on the theory of both atomic and molecular structure, and scattering phenomena. In atomic structure, Pekeris and his co-workers in the 1960s showed that variational methods for solving the Schrödinger equation could yield results *approaching spectroscopic accuracy for the energies of helium and other two-electron ions. Early results using this method were also obtained for lithium (Larsson), but other methods of lower accuracy must still be used for more complex atoms and molecules. The most important are the configuration interaction method, and many-body perturbation theory (Kelly) borrowed from nuclear physics. More recently, relativistic versions of both of these have been developed and applied with great success to highly ionised atomic systems where relativistic effects assume dominant importance.*

In scattering theory, the close-coupling method, and variations on it, underwent intensive development by Burke and many others to calculate cross sections for electron-atom scattering. Also during the 1960s, Codling first observed compound state (Feshbach) resonances corresponding to doubly-excited states in helium. This stimulated the development of several theoretical methods for the description of these states and their influence on scattering cross sections. Meanwhile, people such as Bates, Dalgarno, Moiseiwitch, and Demkov led the way in developing theories for more complex atom-atom scattering processes such as charge transfer and mutual neutralisation, and applying them to problems in atmospheric physics and astrophysics.

Practically all the information we have about the universe beyond the Earth is brought by photons. The interpretation of photon spectra from astrophysical objects requires a wealth atomic and molecular data, including atomic and molecular energy levels, transition probabilities, cross sections and rate coefficients. An early example is the identification by Edlén (1942) of atomic transitions in highly ionised iron and nickel in the spectrum of the solar corona, thereby proving that the corona has a temperature of 2.10^6 K. More recent examples are the discovery of the molecular ion H_3 in the Jovian aurora, and a detailed explanation for why the planet Mars lost most of its water through photo-dissociation.

The same is true for plasmas, ranging from industrial plasmas for material processing to extremely hot plasmas for magnetic confinement fusion experiments. Atomic and molecular data are vital in determining plasma temperatures, densities, electromagnetic field strengths and identifying plasma impurities. For example, the presence of small amounts of heavy ions in magnetically confirmed fusion plasmas may lead to energy losses and plasma cooling which precludes ignition.

Survey of Recent Developments

The trapping and cooling of atoms and ions by laser beams provides a powerful new method to control and manipulate atoms. Atoms can now be essentially brought to rest in an atomic trap, corresponding to temperatures of less than 1 μK, and specialised velocity-selective techniques can bring the temperature lower still. In 1997, the Nobel Prize in physics was awarded to Steven Chu, Claude Cohen-Tannoudji and William C. Phillips "for their development of methods to cool and trap atoms with laser light".

The trapped atoms open the way to spectroscopic measurements of extremely high precision, resulting in improved determinations of fundamental quantities such as the Rydberg constant, the fine structure constant and the Lamb shift. They provide unique opportunities to study long-range interactions between atoms, and collision processes at very low energies. Improved atomic clocks based on trapped and cooled atoms will ultimately increase the precision of the satellite-based Global Positioning System. One fascinating way to build an atomic clock is based on the "atomic fountain" formed when atoms are gently projected upward from a trap and then fall under the force of gravity through a tuned microwave cavity.

One of the most important results of laser cooling and trapping is the achievement of Bose-Einstein condensation (BEC). At sufficiently low temperatures, atoms with integer values of their total spins can merge into the same common ground state to form a quantum mechanically coherent "condensate". The first realisations of were achieved in 1995, using magnetically trapped, laser-cooled Rb, Na and Li atoms. This has ushered in a new era of intense and strongly expanding research into the properties of this new form of matter and its applications. One important new result concerns the demonstration that the condensate forms a coherent beam when released from the trap, thus forming an "atom laser". Evidence for the gain mechanism has already been obtained. An atom laser would revolutionise atom optics and atom interferometry, as well as other applications such as the micro-lithography of computer chips. The elusive goal of observing BEC in hydrogen was finally achieved in 1998, after many years of effort. The demonstration of BEC is here particularly important because the atomic properties of H can be accurately calculated.

High-precision measurements and calculations continue to play a most important role in contemporary atomic physics. For instance, using advanced laser techniques, the frequency of the 1s - 2s transition in hydrogen has been determined with a precision of only 3 parts in 10^{13}. This sets a new record for the most accurate measurement of any frequency in the visible or ultraviolet region of the spectrum. In addition to providing the most accurate values of the Rydberg constant and 1s Lamb shift in hydrogen, a measurement repeated a year from now would set a new limit on possible cosmological variations of the fine structure constant with time. Similar advances in both theory and experiment have been made in spectroscopic studies of helium and other three-body systems. On the theoretical side, the non-relativistic part of the problem is now solved for all practical purposes, and interest is shifting to the first high-precision tests of quantum electrodynamic effects in systems more complicated than hydrogen. In scattering theory, techniques such as the "converged close coupling method" are now capable of providing essentially exact cross sections for fundamental problems such as electron-hydrogen scattering.

For well over 20 years much atomic physics work has been directed toward tests of the Weinberg-Salam Standard Model. Many laser-based experiments have thus been undertaken to detect the very minute parity non-conservation (PNC) effects, usually in heavy atoms. By combining the PNC data with results of sophisticated atomic structure calculations, the so-called weak charge can be determined. In 1997 an atomic-beam-laser experiment for Cs determined the PNC with a precision of 0.035%. Besides confirming the Standard Model, the experiment provided evidence for the existence of the nuclear anapole moment. The latter is caused the interaction of an electron with the parity-violating components of the nuclear wave function.

About 50 years ago, H. Casimir predicted the existence of an attractive force between two parallel, uncharged metal plates, separated by vacuum. While many calculations and experiments have provided support to the existence of the Casimir effect (a consequence of QED), a direct observation was first reported in 1997.

Storage and cooler rings for ions have made a wealth of new precision measurements in atomic and molecular physics possible. The currently operating five storage rings for atomic and molecular physics experiments provide unique opportunities for new measurements through their combination of the properties of ion accelerators and ion traps. Recent results include accurate determinations of Lamb shifts for hydrogen-like and helium-like ions of uranium, U^{91+} and U^{90+}, respectively.

(Such ions have also been produced in electron-beam ion traps, EBIT). The results are in agreement with QED calculations, thereby providing important confirmation of QED effects in the presence of strong Coulomb fields. In the field of molecular physics, cross sections for a wide range of processes which occur in the atmospheres of the Earth and other planets, or in interstellar space, are now amenable to direct laboratory measurement.

The corresponding electron storage rings predate the ionic ones by many years, and the synchrotron radiation they produce has long been a primary research tool in chemistry and biology, as well as physics. Recently, a number of powerful new synchrotron radiation facilities have been constructed in various countries around the world, opening the way to a range of interesting atomic and molecular physics experiments. For example, the triple ionisation of atomic Li by a single photon has recently been demonstrated. These facilities will play an increasingly important role as a standard research tool for applications such as chemical analysis, and structural determinations of biological molecules.

Highly charged ions can carry a large amount of potential energy, which greatly exceeds the kinetic energy of the ions (which emerge from powerful ion sources or ion traps) and make slow collisions with solid surfaces. This leads to "hollow atoms" (neutral atoms with all or nearly all electrons in outer shells, while inner shells remain empty). A number of fundamental atomic processes can be probed with hollow atoms, and they can also be used to create nanoscale structures on surfaces.

Projections for the Future

Despite the past century of development, the study of atoms, molecules and light will remain a rich treasure trove for the coming decades. The relentless advance in the power and versatility of lasers will continue to open new opportunities in areas such as:

(1) high precision measurement as tests of theory and the determination of fundamental constants,
(2) time-resolved studies of fast molecular processes and reaction dynamics, and the use of laser frequency and phase coherence to control and direct molecular processes,

(3) high intensity lasers and studies of the interactions of atoms with strong electromagnetic fields, leading to the development of new x-ray sources and table-top particle accelerators,
(4) extension of lasers themselves into the x-ray region, and the creation of x-ray holograms of biological structures,
(5) applications to improved methods for atomic trapping and cooling, and their use in studying interactions between atoms and molecules under carefully controlled conditions,
(6) studies of the properties of Bose-Einstein condensates, and the development of an atom laser.

The last topic of atom lasers is clearly in its infancy, much as ordinary optical lasers were when they were first developed 40 years ago, and their possibilities for future development may be equally limitless. The most immediate applications would be to the micro-lithography of computer chips, but the coherent control of atoms opens longer term possibilities for the fabrication of micro-machines and molecular computers. This would greatly extend the range of possibilities for the nanostructures lying at the interface between molecular physics and condensed matter physics.

The continuing rapid advances in computer technology will make possible essentially exact calculations for the electronic structure and scattering processes involving ever more complex atoms and molecules. This in turn will open a vast new source of data for the modelling of atmospheric and plasma processes, and ultimately for a detailed quantum understanding of chemical and biological systems.

More broadly speaking, atomic, molecular and optical physics deals with phenomena on the energy scale of the everyday world around us. That is why the links with high technology industry are so close, and why it plays such an important role in our quest to gain ever more sophisticated control over the environment in which we live.

Plasma Physics in the New Millennium

Commission 16
Frans W. Sluijter

Introduction

Langmuir first coined the name Plasma Physics in the late twenties to describe the state of matter in which the atoms of a gas are largely ionised into free ions and electrons. The field in fact existed earlier as it gradually developed from the study of gas discharges, but it remained somewhat obscure and limited to a small number of participants until 1958. In that year, the Geneva Conference on the Peaceful Uses of Atomic Energy gave the field an enormous boost.

Several key theoretical studies of the basic physics of plasmas had already been carried out in the period leading up to the Geneva Conference. In 1946 Lew Landau published his monumental paper on the kinetic theory of dispersion of waves in plasmas in which he corrected an earlier treatment by Vlasov. The correction was the discovery of the phenomenon of what we now call Landau damping, or instability—a phenomenon due to the interaction of particles resonant with a particular plasma wave. Landau damping is then controlled by the distribution function of charged particles relative to those having a velocity equal to the phase velocity of the wave. If there are more particles travelling slightly slower than slightly faster, then there is a net transfer of energy from the wave to the plasma.

The phenomenon of Landau damping first surfaced in plasma physics, but it has since acquired a much more general significance in other areas of physics. After the rather abstract treatment by Landau based on function theory, Van Kampen gave an elegant treatment derived from a sophisticated normal mode analysis. Finally Dawson gave a treatment based on the physical nature of the phenomenon, and a careful analysis of the interaction of the resonant particles with the wave.

Fusion Research

The onset of thermonuclear research gave Plasma Physics an enormous boost. The aim is to build a reactor in which the hydrogen isotopes deuterium and tritium are sufficiently heated in a plasma that they undergo fusion to form helium. Just as in the sun, the process releases large quantities of energy, which can then be used to generate electricity. At the time of the Geneva conference, it was realised that the quest for controlled nuclear fusion was too big an endeavour to be possible for one nation. This type of research was soon declassifiied and international exchanges began. Results from the Russian and American programs became available in the open literature, and new programs were started in Europe and in Japan. In Europe the Euratom nuclear fusion program was organised with associations between Euratom and national organisations.

The goal—a working nuclear fusion reactor—turned out to be a much harder nut to crack than physicists at first thought. The difficulty is to obtain a sufficiently high plasma temperature and density for a sufficiently long time. A variety of plasma instabilities makes it difficult to achieve all three conditions simultaneously. An apparent early "success" of the so-called Zeta experiment in Britain was in fact based on a misinterpretation.

A big step forward was the invention by Sakharov and Tamm of the tokamak—a toroidally (donut) shaped magnetic confinement machine analogous to a big transformer in which the current in the secondary coil is carried by the charged particles in the plasma. The plasma itself is confined to a toroidal shape by a magnetic field. The machine represented a large leap forward toward the confinement of denser plasmas at higher temperatures. It was Artsimovich in Russia who was the main force behind the successful ascent of the tokamak. A British fusion team that went to Moscow with their advanced laser temperature measurement apparatus confirmed his experimental claims. Artsimovich further convinced the Americans to abandon their so-called stellarator approach. Eventually this led to the construction of the highly successful TFTR (Tokamak Fusion Test Reactor) in Princeton and, under the auspices of Euratom, of the construction of JET (Joint European Torus) in Culham, England.

Research on the stellerator, a machine that was also based on the magnetic confinement concept, was never fully abandoned. The concept is now being followed in Germany with the building of a new big stellerator in Greifswald.

The main hindrance to progress up to now has been the lack of understanding of transport in highly heated, high density plasmas far from thermodynamic equilibrium.

So much of the success depended on the effectiveness of semi-empirical scaling using dimensional analysis. Research with these techniques has indeed led to controlled nuclear fusion, but still somewhat short of the real goal: a self-sustained fusion reactor. Recently, some light is being shed on these problems by, amongst others, the work of Schüller and Lopes Cardoso who oberved that at high resolution, plasmas contain filament-like structures. They have developed a new transport theory based on the existence of such filaments.

At this moment, the question is whether a further large magnetic confinement fusion machine should be built. A fairly detailed design has been prepared for a machine that should demonstrate a sustained thermonuclear reaction at the so-called "break-even point," where the delivered energy available at least equals the necessary energy required to heat the plasma. It is now up to the politicians to decide about the funding.

More recently, the concept of "inertial confinement" has come to the fore. In this approach, pulses from several high power lasers very rapidly heat a deuterium-tritium fuel pellet. Fusion then occurs in the hot high-density plasma in the brief period of time before it disperses. Most of this research is still classified. There have been a great many theoretical and computer "experiments", but a full experimental evaluation of the concept is still in a preliminary stage.

Plasmas in the Ionosphere

Alongside the development of plasma physics oriented toward controlled fusion devices, other areas of plasma physics have also seen dramatic advances during the past century. At the opposite extreme from hot high-density plasmas are the cold plasmas found, for example, in the ionosphere of the earth. The theory of plasma waves was very much stimulated by the need to understand the propagation of radio waves in the ionosphere. Hence a lot of understanding came from the field of radio science. One of the earliest contributions was due to Olivier Heaviside who postulated the so-called Heaviside layer in the ionosphere. A rather sophisticated theory of propagation of waves in cold magnetised plasmas is due to Appleton and Hartree. Their theory was cast into a final form in the so-called Clemmow-Mullaly-Allis diagrams, which give a parameter space with plasma density and magnetic field as coordinates. The space is then subdivided into regions with certain

propagation properties of the different waves depending on the direction of propagation with respect to the magnetic field.

Very soon it was discovered that many non-linear wave effects are present in plasmas. One of the first phenomena of this kind to attract attention was the so-called

Luxembourg effect—a cross modulation discovered in the thirties. Radio Luxembuorg had a transmitter so powerful that it heated the ionosphere just above the transmitter. If another station happened to use this heated region of the ionosphere for the reflection of its wave, the signal became modulated by the signal from Radio Luxembourg. The result was that the listener got the program of radio Luxembourg intermingled with the intended program.

The further development of these early theories is now the basis of many diagnostic methods in use in many domains of laboratory plasma physics. In particular, insight into wave propagation in inhomogeneous plasmas has been very much stimulated by the demands of diagnostic tools to measure the temperature, density, and other properties of plasmas.

Applications

Other developments in plasma physics have come more or less directly from the study of gas discharges in low temperature high-pressure plasmas for applications to the lighting industry. The interaction of radiation and plasmas and a detailed knowledge of the collision mechanisms within the plasmas are the essential tools for the construction of efficient light sources. Other applications in the microelectronics industry, notably for the plasma processing of surfaces in the form of coatings or for the etching of surfaces, have become major areas of growth. Even the possibility of using plasmas for the fabrication of large-area solar cells seems to be within reach. Such devices would be particularly attractive because they would make possible a large reduction in the cost of power generation from solar energy.

It seemed in the recent past as if plasma physics were developing into two completely separate domains—the fusion research and the low temperature plasma research. However, now that the prospects of building a real plasma fusion reactor becomes more and more realistic, the fusion people are becoming increasingly interested in the plasma processes taking place at the outer edges of the confined reacting plasma. In this region, complex processes and potential loss mechanisms resulting from interactions with the wall become of prime interest, as well as "divertor" techniques to remove neutral atoms and impurities. But that comes very close to the domain of the industrial plasmas, and so the two are meeting and needing each other again.

A new and exciting branch of plasma physics to emerge in the last decennium is the physics of dusty plasmas. Small particles, consisting of clumps of many molecules with a wide range of different charge states, exhibit all kinds of familiar and new plasma features. A brand new dynamical variable in the problem is the charging and discharging of the particles. As these dusty plasmas occur in many experimental situations where small but unavoidable dust particles are present, their study is amply justified. A whole theory of phase transitions, and even crystallisation, has developed. Thomas, Morfill and others have conducted beautiful experiments to demonstrate these novel effects.

Plasmas and Space Science

The largest working fusion reactor in our neighbourhood is the sun. Since Gamow, Bethe and von Weizäcker cleared up the source of energy as being a fusion reaction, the sun has given rise to an enormous corpus of plasma research; including such examples as the self-generation of magnetic fields or the theory of sunspots. Of particular relevance here is the branch of plasma physics known as magneto-hydrodynamics. Astrophysics, however, is more than the physics of the sun. The interstellar matter is also in a highly ionised state. Hence plasma physics also rules there. One of the most surprising recent outcomes is the relevance of dusty plasma theory to atmospheric and space science. Topics of investigation nowadays are, for example, the role of charged dust in star formation, and the study of dust in the Jovian magnetosphere.

Reference Sources

The development of plasma physics in all its broadness can be followed very well from the invited review papers delivered in the successive sessions of conferences as the International Conference of Phenomena in Ionised Gases, and the International Conference on Plasma Physics. Also the annual meetings of the Plasma Physics Division of the EPS are important sources. The history of fusion research is well documented in a number of monographs (Bromley, Heppe, Heinen, and Herman), while Post wrote a short history of plasma physics in Twentieth Century Physics Vol. III (Brown, Pais and Pippard, editors).

Quantum Electronics in the New Millennium

Commission 17
Hans-A. Bachor

Introduction

The laser opened a new area of physics and technology in the early 1960's. It gave access to new optical phenomena, all based on the process of stimulated emission. Initially a curiosity, the laser has rapidly led to many new applications ranging from precision measurements to communications, and from welding to surgery. Their many varied applications have become an integral part of our daily lives.

The laser itself developed rapidly. The early systems were mainly based on gas laser technology, especially the widespread He-Ne, Argon and Krypton lasers for scientific and medical work, and the CO_2 laser for engineering applications. These lasers are reliable but very inefficient and costly in their operation. The last 10 years have seen a complete change in the technology based on all solid state technology. The semiconductor diode laser appeared initially as an alternative for low power (milliwatt) operation in the red and near infrared regime. This compact laser combines simplicity, small size and low cost. It has become the essential component of all optical storage technologies, in particular the CD for music and the CD ROM for data storage. The requirements are a good beam quality, single mode characteristic and reliability.

Photonics and optical communications

The same laser is also now widely used in communication systems. Just as electrical signals are controlled and manipulated by electronic devices, so also it is now possible to control and manipulate light signals with optical devices, giving rise to the new field of photonics. The technology of photonics forms the backbone of the extensive optical communications networks spreading around the globe. Its success initially derived from the development low-loss single mode optical fibres that can transmit optical signals over large distances without amplification. The modulated laser signal is then transmitted through the optical fibre and manipulated by optically active signal splitters, combiners and amplifiers. A major recent breakthrough is the development of erbium-

doped fibre lasers for use as repeater stations. These allow higher speed operation and higher bit transfer rates over long distances. In the near future, simultaneous operation at several wavelengths (multiplexing) will further increase the capacity of these systems. The clever use of the nonlinear properties of fibres through specially shaped pulses, called optical solitons, can increase the speed even further.

High power lasers

The same semiconductor lasers have been developed for high power continuous wave operation. The available power per laser increases every year. Now diode lasers with powers of hundreds of watts are available. These lasers are ideally suited as optical pump sources for solid state laser systems such as the Nd:YAG laser. This laser operates at 1000 nm. It has an excellent beam quality, very high efficiency and small size. Its high power of more than 100 watts makes it perfectly suited for precision machining. Presently these lasers are replacing the old CO_2 technology in many engineering applications. They are superior in their precision and versatility and more efficient.

The interaction of laser light with nonlinear optical materials leads to a wide variety of new phenomena. The interaction is nonlinear in that the material emits light at a frequency different from the incident signal. For example, frequency doublers emit light at twice the input frequency, and optical parametric oscillators emit light with a frequency equal to the sum or difference of two input signals. This effect can be used to amplify a very weak signal by mixing it with a strong signal. The quality and utility of nonlinear materials have improved dramatically in the last few years, greatly expanding the available wavelength range of solid state lasers. For example, the frequency-doubled, Nd:YAG laser at 500 nm is a now low cost alternative for the Ar ion laser. Combined with optical parametric oscillators, they provide continuously variable wavelengths both below and above 1000 nm. New materials, such a periodically poled lithium niobate (PPLN), have increased the efficiencies of these wavelength conversions and promise simple and easily tuneable systems.

Fast pulses

Enormous progress has been made in shortening the length of laser pulses. While in the 1980s pulses shorter than a nanosecond were rare, it is now possible routinely to reach the absolute limit of a few femtoseconds. This corresponds to only a few optical cycles. In order to achieve this limit, new laser media had to be developed that have an extremely broad gain spectrum. In particular the material Ti sapphire brought a breakthrough. In addition, nonlinear pulse compression techniques, such as nonlinear Kerr mirrors, were invented to further shorten the pulses. Femtosecond pulses are now readily available, allowing the probing of extremely fast biological and chemical processes. Reactions can be observed with an unprecedented time resolution. A parallel development will be the use of the pico- and femto-second pulses for the shaping and drilling of materials. Since the material has no time to melt, the fast pulses create perfect edges and holes. In this way ultra-short pulses will find their way into practical engineering.

Quantum optical processes

Even the simplest laser is based on quantum optical processes. It was known right from the beginning that this leads to quantum fluctuations and thus limitations in the precision of the frequency of laser light. The quantum mechanical intensity fluctuations (shot noise) and the intrinsic laser linewidth are consequences of quantum optics and the uncertainty principle. Since the mid 1980s it has been possible to generate alternative types of light (called squeezed light) that allow an improvement of the measurement of one property, or quadrature, of a laser beam, while sacrificing a precise knowledge of the complementary property. Such squeezed light is now available routinely and, apart from fundamental tests of quantum optical principles, can be used to improve the sensitivity of optical sensors beyond the standard quantum limit. Related are ideas for quantum non-demolition measurements, such as counting the number of photons in a cavity without destroying them by absorption in a detector. The use of nonlinear processes can achieve optical measurements without the quantum mechanical disruption of the system, provided that information is lost about the complementary property of the system (in this case, the phase of the light waves).

Laser interferometers are presently being built for the detection of the gravitational waves resulting from cosmological events such as supernovas or the collapse of stars. To obtain the necessary sensitivity, these kilometre-sized instruments will have to monitor the position of mirrors with the precision of optical wavelengths, and in addition measure displacements as small as 10^{-17} meters. The above techniques of quantum optics will give a sensitivity that will ultimately be limited only by the quantum noise of the light.

Of similar interest are the quantum properties of individual photons. Since photons have spin 1, they are bosons obeying Bose-Einstein statistics. Because of the quantum correlations this introduces amongst the photons, the detection of one photon affects the properties of the remaining light. As a consequence, the effect of a device to split a photon beam into two branches is considerably different from that of a junction in a wire that carries fermionic electrons. This can be exploited by encoding information directly onto the properties of the photons, for example by modifying their state of polarisation. Any loss of photons from the signal then has a measurable effect on the remaining light. It therefore becomes impossible, at least in principle, for an intruder to tap information without leaving a trace. This idea for secure quantum cryptography has recently found a very rapid development from theoretical concepts to practical systems. Other applications will include proposals to transmit data complete with all their quantum information (optical teleportation), and to use light as the transmitting medium in computers based on quantum states.

It is possible to generate more complicated states of correlated photon beams using the optical parametric oscillator. Separate beams emerge, but the timing of the photons in the beams is perfectly linked. Because of quantum correlations between photons, measurements of photons in one beam allow conclusions to be drawn about photons in the other beam. These beams have been used to test some of the fundamental assumptions of quantum mechanics. For example, it may be that the indeterminacy of quantum mechanics is removed by a more fundamental underlying theory containing local “hidden variables” which determine uniquely the outcome of experiments. Based on an experiment originally proposed by Einstein, Podolski and Rosen, Bell derived a set of inequalities which must be satisfied if local hidden variables exist. However, measurements with photon beams show that Bell’s inequalities are violated, thereby ruling out local hidden variable theories. These optical experiments are now the best tests of quantum mechanics.

Laser - atom interactions

Lasers allow the selective interaction with atoms in specific excited states since they can be tuned to a specific transition of a particular atom or molecule. This ability has led to many spectroscopic applications in chemistry. These include extremely sensitive analytical and diagnostic techniques, and the ability to monitor chemical concentrations. A great advantage is that the monitoring can be done remotely by analysing the light scattered back from a laser beam. This so-called LIDAR, in analogy to RADAR, is increasingly used as a tool for the detection of pollution in the atmosphere and for environmental monitoring. Tuned laser light can also be used to influence or control chemical reactions. This will undoubtedly have significant applications to the industrial processing of chemicals. Already the use of many-photon ionisation for isotope separation is a well established technique in the current technology for the enrichment of nuclear fuel.

The use of coherent light has led to more complex interactions where the atom is coherently driven. This allows the use of special pulses to completely invert the atom system and to observe coherent phenomena such as photon echoes and optical nutation. The analogy to NMR is very strong and it is possible to built systems that show a variety of coherent effects.

In addition, the interaction with light also changes the momentum of the atoms. Suitably detuned laser beams can be used to decelerate and even stop atoms. This is equivalent to cooling the atoms, and temperatures as low as micro Kelvin have been achieved. In combination with magnetic fields, it is possible to trap large number of cold atoms. These slow atoms exhibit clearly the wave-like nature associated with large deBroglie wavelengths. Many forms of atom diffraction by both material structures and periodic light fields have been demonstrated. Atom interferometry, which uses a coherent superposition of de Broglie waves, is now a mature technique that can be used for detailed measurements of atomic properties. A potential application is the precision measurement of variations in gravity from point to point on the earth. These gravity gradients are of great interest to geologists in locating mineral deposits and mapping other geological features of the earth.

Since 1995 it has been possible to cool atoms even further and to observe the influence of the bosonic nature of atoms. In particular, the atoms can form a Bose-Einstein condensate in which all the atoms enter the same coherent quantum state. The system is then represented by one macroscopic wave function for many atoms. The properties of these condensates are intriguing because they exhibit the quantum nature of matter on a macroscopic level. They have the properties of a superfluid, but with a density low enough that the interactions between the atoms are still weak. For this reason, it is possible to study theoretically the quantised vortices and quantised excitations of these novel systems. One of the most exciting recent advances is the possibility of extracting a coherent beam of atoms from the Bose-Einstein condensate to form what amounts to an atom laser—the atomic analogue of an optical laser. This field is still in its infancy, but the potential applications to microelectronics, micro-machining and atomic holography may turn out to be as great as for the optical laser itself.

Looking ahead

This overview shows that laser physics and optical technology have made great progress in many parallel directions. All properties of laser light have been dramatically improved. and so far there is no end in sight. At the same time lasers have become simpler, cheaper and more reliable. Today's applications affect every aspect of our lives and span many areas of technology. Now optical techniques complement and sometimes replace conventional electronics. The techniques of fibre optics and photonics have started to transform the communications industry. In addition, lasers will play an increasing role in engineering and the chemical industry. At the same time, the intrinsic and unique quantum properties of light will lead to new fundamental tests of physics and to further investigations of the macroscopic manifestations of quantum mechanics. The potential applications of just one very recent development, the atom laser, are as difficult to predict as they were for the optical laser when it was first invented, but it is certain to have an important impact in the future.

Mathematical Physics in the New Millennium

Commission 18
David J. Rowe

Introduction

Mathematical physics spans every sub-field of physics. Its aim is to apply the most powerful mathematical techniques available to the formulation and solution of physical problems. Mathematics is the language of theoretical physics and, like other languages, it provides a means of organising thought and expressing ideas in a precise consistent manner. Physicists who are articulate in the language of mathematics have made the greatest contributions to the modern formulations of physics. The list is long and includes such names as Newton, Maxwell, Einstein, Schrödinger, Heisenberg, Weyl, Wigner and Dirac.

Mathematical physics is both interdisciplinary and in the mainstream of physics. Whereas experimental physicists make use of engineering and electronics techniques in their investigations, theoretical physicists make extensive use of mathematics. What is special about mathematical physicists is that they communicate and interact with both physicists and mathematicians. Some address mathematical problems that arise in physics. Others are primarily theoretical physicists who invoke mathematical methodology in the interpretation of physical phenomena, e.g., by the development and solution of physical models. What they have in common is an interest in understanding the exciting systems and mathematical challenges that physics uncovers. The results advance physics as a whole and make contributions to mathematics and new technology. Physics is not an isolated activity. It both feeds on and enriches many related areas.

The value of strong interactions between scientists and mathematicians is underscored by the fact that many scientific revolutions have been linked to corresponding developments in mathematics. In this short essay, it is possible to mention only a few examples selected from the suggestions and paragraphs received from many contributors.

General relativity : the theory of gravity

In his general theory of relativity, Einstein introduced the revolutionary idea that gravity could be understood as a warping of space-time. This science fiction-like idea emerged as a logical consequence of a simple principle: the principle of equivalence.

For centuries, the study of geometry was restricted to flat spaces. Then, as a result of investigating the consequences of discarding Euclid's axiom about parallel lines never meeting, new curved-space geometries were discovered. These provided a natural, and even simple, language for the conceptually difficult task of describing the curvature of four-dimensional space-time.

General relativity was a theory ahead of its time due to a paucity of experimental contacts. Even by mid-century, it remained unclear if the gravitational waves implied by the linear approximation to general relativity were real and the notion of what we now call a black hole was dismissed as an absurdity.

Then, under the stimulus of advances in astronomy and cosmology, general relativity entered a golden age. Penrose and Hawking applied global techniques to the causal structure of space-time and were able to prove very generally that singularities are inevitable at the endpoint of gravitational collapse and the big bang. Within a few years, understanding of gravitational collapse and black holes progressed from its inchoate beginnings to a sophisticated discipline comparable in elegance, rigour and generality to thermodynamics, a subject that it turned out unexpectedly to resemble.

Insight into the origin of this resemblance came in 1974 with Hawking's discovery that, at the quantum level, black holes are thermodynamical black bodies with characteristic temperatures. Many see this result as a clue to some future synthesis of general relativity, quantum theory and thermodynamics. Its exact nature remains, at century's end, a mystery.

A new discipline, numerical relativity, has mushroomed in the last decade thanks to advances in digital technology and refinements in the numerical integration of hyperbolic differential equations. Within the next decade it should become possible to compute the pattern of gravitational waves emitted from a pair of inspiralling black *holes (the "binary black hole grand challenge") and to link these predictions with observational results from several gravitational-wave detectors now going on line.*

By geometrising the gravitational field, general relativity introduced a new viewpoint: the aim of describing all the basic forces and elementary particles in terms of some structure more general than Riemannian geometry. Non-commutative geometry, twistors and loop variables all represent gropings in this direction. The most actively pursued program is superstring (or M-) theory. It has been said that string theory is a part of twenty-first century physics that fell by chance into the twentieth century, before the appropriate mathematics had been developed. M-theory calls on the full arsenal of modern mathematics—topology, homotopy, Calabi-Yau spaces, Riemann surfaces, moduli spaces, Kac-Moody algebras, and so on, a symbiosis, which can only get closer as the field develops.

Quantum mechanics

Quantum mechanics has long been a subject of intense investigation in both physics and mathematics. The first steps towards a quantum theory came from the pioneering work of physicists such as Planck, Einstein, and Bohr. The formulation of quantum mechanics, by Heisenberg, Schrödinger, Born, Dirac and others as the fundamental theory of non-relativistic matter, invoked abstract mathematics: linear algebra, infinite-dimensional complex (Hilbert) spaces, non-commmutative algebra, and group theory. Quantum mechanics became a sub-field of mathematics in 1949 with its rigorous formulation by von Neumann.

Object like atoms are characterised in quantum mechanics by sets of wave functions and energies, which satisfy a differential equation, called the Schrödinger equation. However, following initial success in deriving the energy levels of the hydrogen atom, it soon became clear that exact solutions of the Schrödinger equation are possible only for systems with few particles or for models with special symmetries. Approximate solutions are obtained by separating the problem into two parts such that one part has simple properties and its Schrödinger equation is exactly solvable. It is then assumed that the wave functions for the complete problem can be expanded in terms of the known solutions for the simpler problem. Moreover, by ordering the solutions of the simple equation by increasing energy, one can obtain a sequence of approximations to the full problem which, if they converge, give accurate results as found, for example, in numerous applications to atomic physics.

In considering the validity of such an approach, mathematical physicists investigate the properties of differential equations and the completeness of solutions to the Schrödinger equation. A set of wave functions is said to be complete if an arbitrary wave function can be expanded in terms of them. However, completeness is hard to prove for general many-particle systems for which some of the particles may be unbound to the others. It has recently been proved under special conditions.

Fortunately for physics, the physical world has a hierarchical structure which enables condensed matter to be explained in terms of atoms and molecules which, in turn, are explained in terms of nuclei and electrons, etc. This stratification suggests the construction of sequences of models in which the building blocks of one model are the objects of study of a more microscopic model. Furthermore, models of complex systems can be constructed, with restricted degrees of freedom, to explain particular phenomena. Useful models are ones with clear mathematical structures, which enable the properties of a model to be inferred from basic assumptions (axioms). Enormous progress has made during the past twenty years using dynamical symmetry (group theory) for such purposes.

Group theory; dynamical systems

In physics, group theory provides a mathematical formalism to classify and study the symmetry properties of a system. The fundamental books of Weyl and Wigner on the theory of groups and quantum mechanics established group theory as an essential tool of quantum mechanics. Between 1928 and 1938, Wigner (sometimes with students) introduced time reversal invariance and made applications to: atomic and molecular spectra, properties of crystals and their energy bands, nuclear structure and spectroscopy. In 1929, Bethe introduced the use of finite crystal point groups to the analysis of degeneracies of quantum states in crystals; this led to crystal field theory which in turn played a fundamental role in the design of lasers and fibre-optic communication systems. Of particular significance for later developments was Wigner's 1930 paper on vibrational spectra of molecules. This paper introduced to physics the "Frobenius method", later called "the method of induced representations". In 1938, Wigner used this method to construct all irreducible unitary representations of the Poincaré group for positive mass particles in what is recognised to be a landmark of twentieth century physics. In the forties, Racah laid the foundations for calculating the properties of many-particle quantum systems such as occur in atoms, nuclei and subatomic particles.

The method of induced representations is now a widely used tool in both mathematics and physics, with applications, for example, to the theory of crystal space groups and rotations of molecules and nuclei. Fundamental applications to the theory of Fermi surfaces and the related band structures that underlie the theory of conductors (and semiconductors) have been made in recent years. The theory of induced representations has also been applied extensively in nuclear and other areas of mathematical physics within the framework of coherent-state theory.

An example of a subject investigated initially for purely mathematical reasons is that of Penrose tiling. The problem was to tile a plane aperiodically with tiles of at most two shapes. Solutions to this problem were later invoked to explain the so-called "quasi-crystals" observed in 1984. Such crystals are now known to be quasi-periodic and described by functions with a number of periods greater than the dimension of space.

The last twenty-five years has seen an explosion of uses of dynamical groups and spectrum generating algebras for the construction and solution of models. Advances have followed the recognition that solvable models can usually be expressed in algebraic terms so that the powerful methods of group representation theory can be exploited in their solution. The idea goes back (at least) to a famous 1946 paper of Tomonaga. Modern developments followed the SU(3) model of nuclear rotations and the quark model of baryons and mesons.

That the theory of Lie groups should apply to quantum mechanical problems is natural, considering the fact that Sophus Lie founded his theory for the purpose of solving differential equations like the Schrödinger equation. However, in contrast to the Schrödinger equation, most of the other basic equations of physics are non-linear (e.g., Einstein equations, Yang-Mills equations, Navier-Stokes equations). This has inspired many developments during the last 30 years on the solution of non-linear differential equations. Technical tools have been provided by advances in computer science, i.e. algebraic computing.

A crucial development was the discovery of "solitons", i.e., waves that are stable with respect to mutual collisions. Solitons were found in numerical simulations and, *subsequently, for a large class of non-linear equations, now called non-linear integrable partial differential equations. They are widespread in nature. In oceans they are destructive and can interfere with oil drilling. In optical fibres they are used to carry undistorted information.*

Another important discovery in non-linear mathematical physics is that of "deterministic chaos". It was shown that systems governed by simple non-linear differential equations, that should be entirely deterministic, actually behave in an unpredictable way over large time periods. The reason for this "non-integrable" behaviour is a very sensitive (exponential in time) dependence of the solutions on the initial data. An example of such a chaotic system is given by the Lorenz equations from meteorology. Deterministic chaos is observed in virtually all complex non-linear systems. Integrable (soliton) systems typically have infinitely many symmetries and a very simple singularity structure. Chaotic ones have little symmetry and exceedingly complicated singularity structures.

Many-body theory; statistical physics

Many-body theory and statistical physics are attempts to describe the properties of extended matter, which might comprise as many as 10^{24} atoms per cubic centimetre and for which a detailed microscopic description is inconceivable. A central idea of many-body theory is to make expansions which become exact as the inverse of the particle number approaches zero. In statistical physics the behaviour of particles is described by probability theory. In equilibrium statistical mechanics the assumption is that all states of the particles in some fixed volume with a fixed number of particles and fixed energy are equally likely.

A fascinating challenge is to understand and predict properties of phase transitions, such as melting and boiling. A classic discovery of Onsager was that it is possible to find an exact solution for a two-dimensional (Ising) model of a phase transition. Recent discoveries have placed this discovery in a much larger context, relating it to conformal symmetry of two-dimensional systems. Another development is the renormalisation group, whose applications to statistical mechanics were promoted by such pioneers as Ken Wilson. This is an attempt to explain certain universal properties of phase transitions. In particular, it is helping explain the extraordinary similarities (critical exponents) of phase transitions in very different systems.

Many-body theory and statistical mechanics take on new features when combined with quantum mechanics. In particular, the notion of equally-likely state has to be revised for systems of identical particles. There are two kinds of elementary particle: bosons and fermions. Quantum mechanical wave functions are symmetric under exchange of coordinates of a pair of bosons and antisymmetric under exchange of fermions. A consequence of this is that two fermions are precluded from occupying the same state; this is the exclusion principle.

One of the early predictions for bosons was Bose-Einstein condensation (BEC), a phenomenon that has recently been observed. BEC raises many interesting questions; e.g. does it depend on the symmetry under exchange of bosons or on an absence of the exclusion principle? The observation of BEC for a system of hydrogen atoms would appear to favour the former. This is because a hydrogen atom is not quite a boson; it is a pair of fermions (a proton and an electron). Thus, while hydrogen atoms are symmetric under exchange, they also obey an exclusion principle. The evidence is that correlated pairs of fermions behave in suitable limits as bosons. A dramatic example of this is superconductivity in which electrons combine to form Cooper pairs. Thus, whereas systems of bosons form superfluids at low temperatures, electrons in metals form superconductors. These phenomena are among the few manifestations of quantum mechanics at a macroscopic level. They have many fascinating properties and commercial applications; they are also of intense mathematical interest. For example, much is learned from them about the nature of phase transitions. Some insights into the nature of superconductivity and the approach to a phase transition in a finite many-body system comes from nuclear physics. The suppression of superconductivity in rotating nuclei with increasing angular momentum is particularly relevant because of the mathematical similarity between Coriolis forces and magnetic fields. The problem of explaining superconductivity at a high critical temperature is a current challenge.

Often matter is not in equilibrium. There is a flow of particles or of energy, and often the flow itself is changing in time. This requires a non-equilibrium statistical mechanics. Currently non-equilibrium statistical mechanics is beginning to provide an understanding of the limits of cruder theories of nature, such as macroscopic theories of fluids or plasmas.

Symplectic geometry; symplectic groups

Loosely speaking, symplectic geometry is the mathematics of phase spaces. These are the basic spaces of classical mechanics in terms of the positions and momenta of particles. They also provide the appropriate framework for the quantisation of classical systems. Because of its practical applications, symplectic geometry is an area where the interaction between mathematics and physics is especially close.

An example is the study of the stability of the solar system. This is a system for which all the relevant laws of physics are known to great precision. However, working out the consequences of those laws is nontrivial. One can integrate the equations of motion step by step to obtain accurate predictions of planetary orbits over time periods of billions of years. Yet it remains an open question as to whether the solar system is bound or not; i.e. if a planet might not some day in the future acquire enough energy to leave the system. Recent developments have shown how the motion of an ideal fluid can be described. This has led to important applications in geophysical fluid dynamics as well as in fluid mechanics.

A fundamental concept of symplectic geometry is the so-called "symplectic form". This is a concept that expresses the pairing of position and momenta as "canonical variables". The fundamental relationship between pairs of canonical variables gives rise to the famous conservation law, known as Liouville's theorem, for the volume of phase space occupied by a system of particles. The content of the theorem is illustrated by the observation that, without removing energy from a system of particles, it is impossible to squeeze them into in a small space by application of a force field without giving them large momenta. A related implication for quantum mechanics is the uncertainty principle; one cannot simultaneously measure the values of a pair of canonical variables, like position and momentum, to better than prescribed limits of accuracy.

Closely linked to symplectic geometry and equally important is the group theory of linear canonical (i.e., symplectic) transformations. These groups have been widely used, for example, for the description of electromagnetic and particle beam optics. An optical lens or a magnetic focusing device corresponds to an element of a group of symplectic transformations. Thus, the effect of a sequence of lenses or focusing devices can be inferred by the standard mathematical rules for composition of group elements. By such means, the aberration effects of optical and particle-beam transport *systems can be computed and corrections made to a high level of accuracy. The development of symplectic techniques has revolutionised the design of such systems.*

During the past thirty years, the links between classical and quantum mechanics and the routes from one to the other have been explored in great depth using the methods of "geometric quantisation". Geometrical quantisation is a series of methods which associate unitary group representations ("quantum mechanics") to certain Hamiltonian group actions ("classical mechanics"). The approach takes advantage of insights gained in physics to advance the mathematical study of group representations. It has also been used effectively to study the quantisation of collective models, notably in nuclear physics.

Coherent states; optics

Coherent states are used in many areas of physics and mathematics. They were first defined by Schrödinger in 1926 as minimal uncertainty wave packets and used to exhibit the classical behaviour of a harmonic oscillator within the framework of quantum mechanics. Because of this special "classical behaviour" of quantum harmonic oscillators, coherent states have been used widely, following an influential 1963 paper of Glauber, for describing the coherence properties of electromagnetic radiation; e.g., the light emitted by a laser.

Analysis of optical systems in terms of coherent states is appropriate because, while much of optics can be described by classical theory, some problems require a quantum treatment. Coherent state theory lets one have it both ways. This is particularly important for the theory of quantum interferometers. An interferometer superposes optical beams and the resultant interference effects can be used to infer information about the beams, such as their wavelengths, or about the interferometer, such as the relative phase shift between paths of the interferometer. The minimal wave-packet character of coherent states makes them useful for considering the quantum limits to phase measurements in interferometry. Quantum effects become important for light beams of finite photon number. Interferometers can also be constructed for matter waves, including neutrons and neutral atoms.

Coherent states were generalised and given group theoretical definitions around 1972. Since that time, the mathematical analysis, generalisation, and ever widening set of *applications for coherent states has become a field of study in its own right. For example, it has become possible to apply the powerful methods of group representation theory to the analysis of multi-path interferometers. Coherent states associated with a vast number of transformation groups have been constructed; they have been generalised further to quantum groups and even to no groups at all.*

Coherent state methods have proved invaluable for constructing representations of Lie groups in the forms needed for applications in many-body quantum mechanics. This use has developed substantially during the past 25 years, including generalisations to vector-valued coherent states.

Spaces of coherent states have interesting geometries and feature in the theory of geometric quantisation. They have been used in path integral constructions, inequalities in statistical physics, and descriptions of classically chaotic systems; they have been applied, for example, to the quantum Hall effect, atomic and molecular physics, nuclear physics, and particle physics. Future applications may include quantum communications, quantum cryptography, and quantum computation.

A practical development to emerge from coherent state theory is the use of "wavelets" as alternatives to traditional Fourier analysis. The idea was introduced by Morlet in 1983 for analysing seismic waves. It has since been set on a rigorous mathematical footing and has become a powerful tool in electrical engineering for signal processing, and in computer science for data compression.

Quantum field theory

Field theory evolved from quantum electrodynamics (QED). It became a theory of particles and fields when it was understood that a relativistic quantum theory of a fixed number of particles is an impossibility.

A problem in QED before mid-century was its prediction of infinite values for a number of physical quantities. It turned out that the infinities were artefacts of expressing the theory in terms of parameters, like the electron mass and charge, which, if computed, would themselves diverge. With the right parameters and techniques for avoiding summations of divergent series, QED achieved extraordinary precision, e.g., in predicting Lamb shifts and the anomalous magnetic moment of the *electron. Many names were associated with these adjustments of QED, known as "renormalisation"; the list includes French, Weisskopf, Schwinger, Wheeler, Feynman, Dyson, and Tomonaga. QED now ranks as a major achievement of twentieth century physics. It has had many practical applications in areas as diverse as superconductivity, lasers, transistors and microchips.*

The latter half of the century has seen many attempts to generalise QED to other force fields of nature. The most successful is the 1954 non-Abelian gauge theory of Yang and Mills. This theory, which uses sophisticated concepts of differential geometry (e.g., connections on fibre bundles), has had a profound impact on mathematical physics. It interfaces with such diverse topics as spontaneous symmetry breaking, non-integrable phases, integrable systems, solitons, knots, and Kac-Moody algebras. The quantised version of YM theory has been spectacularly successful. It underlies the 1967-68 unified theory of electromagnetic and weak interactions of Glashow, Weinberg, and Salam. Likewise it provides the framework for quantum chromodynamics, a self-consistent theory of the strong interactions that evolved from the 1961-65 quark models of Gell-Man and Ne'eman. These developments show that all the fundamental interactions, including gravity, share a common geometric structure.

A separate remarkable development has been supersymmetric field theory, a theory that unites bosonic and fermionic fields within a common algebraic structure. It is hoped such a field theory will hold the key to the major outstanding problem of the theory of fundamental interactions which is to quantise gravity and provide the sought-after unification of all the fundamental interactions. String theory, which characterises particles as strings rather than points, presents a promising approach to this difficult problem. But it will be some time in the next century before its success or failure is known.

Acknowledgements

The author is pleased to acknowledge many suggestions and the provision of numerous paragraphs, most of which have been incorporated into the article in one way or another, from the following contributors: Stephen Cook, Rashmi Desai, William Faris, Gordon Drake, Werner Israel, John Klauder, Michael Luke, Louis Michel, Lochlainn O'Raifertaigh, George Rosensteel, Mary Beth Ruskai, Barry Sanders, Ted Shepherd, Shlomo Sternberg, Scott Tremaine, Pavel Winternitz, Djoko Wirosoetisno, and Brian Wybourne.

Astrophysics in the New Millennium

Commission 19
Humitaka Sato

Introduction

For many centuries, astronomy was concerned only with the motion of astronomical objects in the sky and did not consider the objects themselves. It was only in the later decades of the last century that physicists started to study the problems of the constitution and energy-source of the stars. The study of atomic spectroscopy and photometry in the physics laboratory had brought a new technique to astronomical observation. The rapid growth of atomic physics as well as of the theory of radiations in the early part of this century soon contributed to physical study of astronomical objects themselves.

Following the discoveries of nuclear physics, combined with progress of new technology in detectors, semiconductors and space research, there appeared many discoveries in the 1960s, notably of quasars, the cosmic microwave background(CMB), pulsars and black holes.

In the coming century, enlarged optical telescopes and space telescopes are expected to play a crucial role, in combination with the observation in other wave bands. With the physics of these which emerged in 1930s, together with studies of the energy source of star-light, the origin of chemical elements was explained almost completely up to about the early 1960s. Then it also became possible to describe the whole life of stars, not only in their normal visible 'shining' stage but also in their final stages, including the supernova explosion, white dwarf star, neutron star and black hole stages. All of these were originally theoretical predictions which had to await the discovery-decade of astrophysics in the 1960s.

In the first half of this century , research with the large telescopes recognised galaxies, discovered the expanding universe and produced extensive information about stellar evolution. In the latter half, our observations of the universe have expanded in their wave-bands, from optical light into all bands of radiation, from radio, microwave, infra-red, through visible to ultra-violet, X-rays and gamma-rays.

Theoretical predictions

In the last quarter of this century, particle physics and general relativity have played an important role in the exploration of the origin of our universe. These fields of physics have created a comprehensive story about how space-time, matter and astronomical structure have emerged in the expanding universe.

The early stage of the big bang universe was in an extremely high energy state, with energy much higher than the energies attainable by current accelerators. Then those studying particle physics came to regard the early universe as the sole place to obtain observational data at energies beyond those of terrestrial accelerators. The phase transition of the vacuum predicted from the unified theory of fundamental forces should be marked by the existence of various' relics', which would be observable in the current universe. Thus the search for such relics through observations of the universe can be envisaged as a sort of High-Energy archaeology.

According to this scenario, the seed of gravitational inhomogeneity which has evolved into the present large-scale structure in the distribution of the galaxies should have originated from the vacuum fluctuation of the quantum fields; the reason why anti-baryons cannot be found amongst the 'remains' would be related to the proton decay and CP-violation observed in the weak interaction. The weakly interacting particles, such as are expected in the supersymmetric theory, would not pair-annihilate in large degree and they might be dominant in the gravitational mass in the universe; these are called Dark Matter. The topological defects generated at the phase transition of the vacuum might have produced another present-day 'relic' — the ultra-high cosmic rays. Many other theoretical expectations have been laid down and await observational check in the new century.

In the following sections, some of the urgent problems at the turn of the century are described.

Neutrino Oscillation or Cold Interior ? Neutrino Astronomy

Nuclear physics together with particle physics has explained the energy source of the stars, how they were formed and how they will die, and how most of the atomic elements have been formed through stellar evolution. The discovery of the supernova neutrino burst in SN1987A was a dramatic proof of the theory of the stellar interior.

Water Cherenkov counters which detected the neutrino burst have since been expanded to a larger scale. Thus, there is now a better chance of catching similar neutrino bursts in the near future.

The solar interior can be explored through the detection of solar neutrinos, and current theory predicts two components, at low and high energies respectively. Currently, only the high energy component has been observed and this has exposed a puzzle about the standard model of the sun. On the other hand, particle physicists are trying to explain this discrepancy by an amusing feature of the particle called 'neutrino oscillation' but this approach is also not conclusive. Detection of the low energy component would help to resolve the puzzling situation.

Pair electron plasma or electron plasma? Radiation from Pulsars.

The radiation mechanism of pulsars is not yet well understood. There are two possibilities about what state of matter will actually radiate; it could be either an electron-proton plasma or an electron-positron plasma. The enormous strength of the magnetic fields on any rotating neutron star should cause the production of electron-positron pairs. The physics of these processes seems to be relevant to the study of plasmas generated by a strong laser beam in laboratory.

Star first or Galaxy first? Structure Formation in the Expanding Universe

Deep surveys of the universe by space and large diameter telescopes have revealed a surprisingly early formation of the stars and the metallic elements. This has challenged us to explain how to form stars from a primordial gas without metallic elements. Here we can propose a question: which is formed first, the stars or the galaxies ? In the 'star first' scenario, smaller clouds of a mixture of stars and gas have merged into a galaxy, whilst in the 'galaxy first' scenario, stars have been formed in a contracting gaseous cloud with the size of a galaxy. In the former scenario, we could expect stars (or groups of stars with globular cluster size) outside galaxies.

The early star formation would be impossible according to the gravitational growth of the primordial density perturbation which has been constrained by the Cosmic Background Explorer (COBE) observation and by a natural extension of the perturbation spectrum towards the smaller sizes. Therefore, the non-gravitational cause must be carefully investigated for the stage shortly after the recombination of hydrogen, involving such processes as the inhomogeneous degree of ionisation and other plasma-radiation coupled dynamic process. Gravitational contraction of the mixture of stars and gas will result in various states depending on the recipe of this mixture; the variety of galactic figures may reflect such recipes.

Would everything be as expected? Detection of Gravitational Waves

Gravitational waves are the last waves yet to be detected among the four waves corresponding to the four fundamental forces. Gravitational wave detectors under construction, such as LIGO, will detect any burst of gravitational waves. Most people have no doubt that this result will be obtained. So there would be great debates if LIGO does not detect the bursts as expected. There might be two ways to explain such a result, looking either for an astronomical source or to gravitational theory. Most specialists would doubt an astronomically based explanation, e.g. invoking the coalescence process of a binary stellar system or the rate of such coalescence, and would look rather to correct general relativity theory.

What is dark matter, dark stars or dark particles?

Stellar luminosity is amplified by any foreground star through the action of its gravitational lens. Dark stars in the halo of our Galaxy are a source of this micro-lensing and they are called as Massive Compact Halo Objects(MACHO). For galaxies and clusters of galaxies, the mass estimated from dynamical features is always greater than the mass estimated from luminosity and this non-luminous deficit is identified to be dark matter. But we do not know what fraction of it in the halo of our Galaxy is MACHO.

On the other hand, the big bang cosmology together with particle physics predicts the existence of numerous relics of weakly interacting massive particles. The dark matter in astronomical systems could be these dark particles. The dark stars and the dark particles are quite different in their nature but they behave in a similar way in large astronomical systems.

The so-called Dark Matter problem has arisen partly because of many discrepancies in the precision of measurements. In the current astronomy, a refinement of many astronomical quantities is being pursued through advanced technology and the Dark Matter problem might melt away in future.

Bottom-up or Top-down? The Origin of High Energy Cosmic Rays

The spectrum of cosmic-ray flux with energy can be described by a single power-law over 12 decades and we are tempted to ask where this spectrum ends. The composition of the lower half of the 12 decades seems not so different from the solar abundance but we have little information about the upper half, which will be an extra-galactic component. The spectrum seems to show a tiny change in the transition from the galactic to the extra-galactic components but it is still very smooth without a big gap. We are now checking the high energy end of the spectrum. According to the big bang cosmology, the cosmic microwave background should have been distributed uniformly throughout space and its photon density is more than 400 per cc. During the travel of cosmic-ray particles in this dense photon cloud, they should interact in an inelastic manner if the mutual energy is large enough to create mesons. Then the sources would be limited to the neighbourhood around us and the flux will drop.

How to get such high energy? One is to accelerate charged particles by electromagnetic processes which is called the bottom-up approach, and another is to seek for an exotic process of particle physics beyond the standard theory, such as cosmic strings and so on, which is called the top-down approach. If the mechanism for extra-galactic cosmic rays is a top-down one, the spectrum might extend toward much higher energy. Detection of the high energy neutrinos will contribute to resolving this problem.

Reform or Selection? The Origin of the Expanding Space-time.

Einstein's general relativity describes nicely the current expanding space-time. If we trace back to the beginning according to this theory, the space-time terminates its existence. The Einstein theory is a non-quantum dynamical theory of space-time and the problem of the beginning is included in a realm of the quantum dynamics of space-time. Thus the observed expanding universe is posing a challenging new problem to next century physics. It is true that this target is identical with that set by the unified theory for the four forces but the motivation is quite different.

Our universe seems very uniform if regarded in an astronomical setting and that would suggest the uniformity of the space-time and of all physical laws. Some people ask why it is so uniform and other people will just think that only a uniform universe deserves to be the universe. Currently in the inflationary scenario we try to explain how to make uniform whatever is created. On the other hand, people can express doubt about "whatever", because some quantum theories predicts the highest symmetry as the most probable. The uniformity might be due to selection rather than through the process of inflation.

Computational Physics in the New Millennium

Commission 20
William J. Camp and Jaroslav Nadrchal

A new area in physics

Computational Physics is a relatively young part of physics because it is fundamentally beholden to automatic computation means that did not exist before World War II. Modern computers have developed in a tight symbiosis with computations in physics, and their development proceeded through mutual interaction. Computational Physics has been rapidly maturing as the third leg of the scientific enterprise alongside Experiment and Theory. Traditionally, computational physicists have been self-trained, there having been no formal curricula aimed at educating computationalists. Indeed there really has been little formal discussion of what computational physics is. However, in the past few years, many schools have begun undergraduate and graduate-level programs in computational science and engineering. Computational physics plays a vital role in these programs. This development will help ensure a growing cadre of trained computational physicists.

Computational methods and tools continue to evolve at explosive rates. Today, $5000 personal workstations have computing speeds as fast as those provided by a $5,000,000 supercomputer in 1990 - and available memories are actually much larger. This democratisation of supercomputing is opening up computational physics to scientists in every country. We may thus expect far greater use of simulation as a basic tool of physics enquiry as we go forward into the next century.

New possibilities for simulations

In the past few years, researchers have increasingly been able to investigate fundamental questions in physics computationally with unprecedented fidelity and level of detail. For example, fluid dynamics simulations aimed at understanding turbulence have recently been carried out with over 200 billion computational degrees of freedom in three dimensions. This allows the examination of fluctuations over a three-order-of-magnitude span in length scales. Using Monte Carlo methods, researchers can now carry out statistical mechanical simulations with stunning fidelity and detail. For example, with current algorithms on the largest machines they could now carry out simulations of the Ising model with 10^{12} spins in three dimensions. Doing so would allow them to faithfully simulate the behaviour of the Ising model over six orders of magnitude in reduced temperature near the critical point.

Similarly, quantum chromodynamic simulations based on lattice gauge theory are already beginning to provide quantitative estimates of important baryon masses. Electronic structure studies of the ground states of metals, semiconductors and molecules are becoming a fundamental tool in material science. Today, *ab initio* molecular dynamics studies of systems with tens of thousands of electrons and thousands of ion cores can be carried out and accurate material and molecular structures can be predicted using density functional approaches. As recently as a decade ago, simulations with more than 100 electrons were not practicable. Currently the most accurate method for the study of many-electron problems is the Quantum Monte Carlo method. With today's faster computers and algorithmic improvements for handling the fermion sign problem, QMC simulations are becoming feasible at large enough scale as to make QMC a viable alternative to Hartree-Fock or density-functional approximations when accuracy is paramount.

Puzzling phenomena such as sono-luminescence are yielding to understanding through a combination of molecular-dynamic and continuum shock-physics simulations. Four-dimensional, highly-detailed simulations combining resistive magneto-hydrodynamics with radiation transport are becoming possible. These tools are aiding in understanding the life cycle of stars and are being used to design inertial-confinement fusion experiments aimed at net energy gain from fusion in the laboratory.

In biophysics, there is a revolutionary progress in simulating the folding of complex proteins. Simulations are helping to unravel the physical processes involved in the informational role of primary DNA structures (the genetic sequence) as well as delving into the role of secondary structures (e.g., detachments and loops) in DNA. Researchers are also modelling with increasing detail the physics of enzymatic catalysis. Recently key progress is being made in the use of classical density functional theory to model ion channels in cells.

Handling experimental data

Finally, computational physics involves more than using simulation to provide insight and interpretation. It involves the acquisition and management and understanding of seas of experimental data. Two areas stand out. In high-energy physics, the ability to acquire, store and interpret terabyte data sets is becoming a key part of progress in accelerator experiments. Similarly, in geophysical modelling of global climates, satellite data provide critical information on the overall status of global climate as well as key global parameters needed to improve models and to validate theoretical methods. The acquisition and management of these data sets poses grand challenges in real-time data acquisition, in large-scale data management, and in data visualisation.

Prospects for the future

Looking forward, within the next few years we may expect lattice gauge simulations in QCD sufficiently accurate to confirm or eliminate current theoretical models and approximations. In biophysics, we should see great progress in *ab initio* and classical molecular mechanical simulation of many of the dynamic processes involved in the microscopic evolution of cellular building blocks. In material physics, we should see a revolution in mesoscopic physics enabled by microscopic computer experiments on solids and melts with realistically modelled defects.

In the area of the physics of computing, progress continues in attempts to develop fundamentally new approaches to computation based on quantum computers. The problems to be overcome are extremely formidable. Nevertheless great progress has been made — essentially all of it in the past five years — and we may expect a rich exploratory development phase to unfold in this area over the next five years. On a more practical level, the availability of inexpensive, commodity simulation engines with capabilities in the many gigaflops / gigabyte range along with new educational and research initiatives will continue to attract more physicists into the computational arena. In sum, the past five years have been the brightest in the history of computational physics and progress in the next five will eclipse even the accomplishments of the past five.

Optics in the New Millennium

Affiliated Commission 1
Pierre Chavel

Introduction

Lessons from the past may be helpful when thinking about the future. In 1948, the founders of International Commission on Optics selected for their discussions such topics as the accommodation of the human eye and its resolving power, the combination of aberrations and diffraction, the design of microscope objectives, interferometers for testing camera lens aberrations, elements of thin film design, diffraction gratings, and new mineral and polymer glasses. When comparing this list with the scope and state of the art of optics today, two major facts appear quite conspicuously. First, it is indeed true that there has been progress in all of these fields, in the following ways : —

- The human retina is being investigated by adaptive optical systems, where a deformable mirror compensates the aberration of ophthalmic media to focus and scan a diffraction limited spot on the retinal cells. Will adaptive optics ever be fitted to our spectacles and provide diffracted limited imaging to everyone?

- The most complex optical systems ever built provide f : 0.5 diffraction limited imaging at ultraviolet wavelengths over several square centimetres for the replication of computer chip masks. Thin films can be designed and fabricated in stacks of nearly one hundred layers to match virtually every conceivable spectral reflectance profile. How far into the x-ray range will they affect future lithography tools for micro- and nano-technologies?

- Interferometers are available in all sizes from submicron Fabry Perot cavities to sensors with kilometre long arms. Diffraction optics has evolved from gratings into holography and lens achromatisation. Will miniaturisation techniques allow one to fit an optical system in the volume of a microcomputer chip?

- Optical materials include non-linear crystals, rewritable holographic materials such as photo-refractive crystals, liquid crystals and polymer light emitting diodes.

Will white LEDs invade our daily life for better energy yield and longer lifetime of our lamps?

• Ten meter mirror telescopes, all fitted with adaptive optics facilities to compensate for atmospheric turbulence, combine their images coherently over distances larger than 100 m. What shall we learn from them about planets outside the solar system?

Yet, the second obvious fact is that optics now encompasses much more than the great unforeseeable progress on these subjects that were already of interest fifty years ago. In 1948, nobody predicted the advent of the laser just twelve years later, or about the key role of optics in modern information systems. By emphasising these two domains in the following two sections, we shall undoubtedly fall short of many forthcoming revolutionary changes. But we may be able to point to some major aspects of 1999 optics and their development in the first years of the new millennium. In the United States, the National Research Council (NRC) has devoted a significant effort to identifying the growth points in optics. A detailed account of the findings of the NRC appointed Committee on Optical Science and Engineering can be found in their report. It presents a much broader overview of optics than these few pages can do.

Lasers

The diversity of lasers is an indication of their wide variety of uses, ranging from basic science to many branches of engineering. We shall examine just a few.

Cold atom experiments and the rise of atom optics, a new field of physics which was recognised by the 1997 Nobel Prize in physics being awarded to S. Chu, C. Cohen-Tannoudji and W. Phillips, rely in part on the mature state of laser instrumentation. Atomic beams, usually of noble gases or alkali metals, are first slowed down by a large number of successive collisions with laser photons. When the atoms have been brought essentially to rest, they are trapped and further cooled by a combination of additional laser beams and magnetic fields. The result is a so-called atomic molasses with typically billions of atoms grouped in a cubic millimetre or so and with a residual temperature below one microkelvin, i.e. speeds in the range of millimetres per second. When the trap is opened, the falling molasses becomes the source for atom optics—the first kind of optics so far that applies to massive neutral particles.

Optical analogues of lenses, mirrors, beam splitters, and interferometers for atoms are being developed. Other possibilities with atomic molasses include diffraction by holes in a membrane. Extremely cold and compact molasses have been driven to the coherent state of Bose Einstein condensates, where all atomic wave functions widely overlap and all atoms are in the same quantum state. The possibility of individually driving the atoms may open the way to the ultimate tool for lithography.

Large lasers such those as the National Ignition Facility under development in the United States are the record holders in terms of energy per pulse. The challenge of inertial confinement fusion, for both military and energy applications, is being pursued by irradiating millimetre-sized deuterium-tritium targets with megajoules of 350 nm light produced by tens or hundreds of frequency-tripled, amplified doped glass laser beams. The near term perspective here is more scientific in nature, with a better understanding of dense plasma. The long-range goal of a cheap energy supply from fusion is at this stage considered unrealistic by most specialists.

Other large lasers are being developed for the optical detection of gravitational waves using the largest interferometers ever designed. Continuous, frequency stabilised laser beams will feed Michelson interferometers with arm lengths in the range of several kilometres, with the arms themselves being Fabry Perot cavities to increase the effective length of interaction with gravitational waves. A relative path length sensitivity of better than one part in 10^{21} will be needed to observe the expected events. Several projects in Europe, the United States and Japan are in various stages of development. Their combined operation will essentially form a world observatory for gravitational events. An important target will be to produce, from detection of gravity waves, evidence of the density of black holes in the universe.

These examples may give the impression that lasers are huge, complex and costly systems. While lasers always belong to high technology, the largest market for lasers lies in the million piece sales of compact disk readers, based on 780 nm compound semiconductor lasers with unit costs down to less than one US dollar. Yet, laser miniaturisation is still going on with the so-called “vertical cavity” lasers. For about two decades, laser diodes used to be constructed from flat semiconductor chips that emitted light through their edges. A radically new concept imagined in the nineteen-eighties, that took several years to turn into a real device, was to stack a bottom mirror, a sub micrometre-thick gain medium and a top mirror all atop a semiconductor substrate to emit light “vertically”, i.e.

perpendicular to the substrate. The total laser volume is reduced to a few cubic micrometers and arrays of thousand lasers have been built on one chip – with the only difficulty that it is impractical to connect them to thousands of independent electrodes. At present, 760 nm and 980 nm wavelength VCSELs (Vertical Cavity, Surface Emitting Lasers) are being manufactured in arrays of a few tens for their first commercial applications, and development is in progress for the extension of the principle to the optical telecommunication wavelength range near 1.5 µm (see below).

Yet another class of lasers are the so-called solid state microlasers consisting of doped dielectric crystals that show high gain at specific wavelengths. It is difficult to obtain high powers from laser diodes in the form of high quality optical beams. The identification of materials for highly efficient conversion of pump diode laser light into high optical quality laser beams over a wide range of wavelengths is in progress. Some compact, centimetre size designs include the pump laser, the solid state laser and a frequency doubler. More complex, experimental systems even include all-solid-state wavelength tuneable non-linear crystals, the so-called optical parametric amplifiers and oscillators. The goal here, indeed, is to offer easy to use, compact laser sources for the broadest possible wavelength range, from the blue to the mid infrared. Applications will dictate which systems can be manufactured in large quantities and therefore at a low cost.

An overview of the field of lasers cannot be given in just one or two pages. We shall therefore only mention in passing such important aspects as laser cutting and welding, laser ablation, lasers in metrology standards and atomic clocks, lidars (laser radars) that monitor air quality by measuring the back scattered light from aerosols above polluted areas, ultrafast lasers and their developing application to non-invasive biomedical imaging, and laser “tweezers” that manipulate micrometer sized samples. There are also applications to fundamental physics such as the use of lasers to explore the dynamics of non-linear physical effects involving chaos, multi-stability, spatial solitons, light bullets and other pattern forming effects in space and time. While lasers are almost ubiquitous in modern optics, progress in optics cannot be reduced to lasers and we should now turn to some other aspects of the field.

Information optics

For many years, the prospect of optical computers competing with electronic computers was a favourite topic in science journals. It is now apparent that this was a naïve expectation if light is merely used to mimic electronic computers. What people failed to realise was that the performance of computers is measured by the number of operations per second, not a speed, and that electronic signals (as opposed to the electrons themselves) already propagate through wires and semiconductors at essentially the speed of light. However, optical signals can be used to improve the performance of computers in other ways. The correct arguments are:

1) Operations in computers get faster when capacitors to be loaded during circuit operation get smaller. This is possible if some of the longer wires are replaced by the propagation of electromagnetic waves through free space or in dielectrics.
2) Light in the hundreds of terahertz range has a very broad signal bandwidth, which is still far from being completely exploited today.
3) Light beams can cross each other without cross-talk or interference, allowing more components to be packed into a smaller volume.

The development of optical telecommunication depends on the first two arguments above. Improvement in the absorption and dispersion of optical fibres led to the first optical communication links around 1980. The replacement of multimode fibres by monomode fibres allowed reduced dispersion and better signal quality. The advent of fibre amplifiers around 1990 provided an efficient way to increase the optical telecommunication bandwidth, since amplifying and regenerating optical signals optically turned out to be better than detecting and re-emitting them using opto-electronic repeaters. Further progress is now arising from the simultaneous transmission of several signals coded on different wavelength channels in one fibre. Current commercial capacities are increasing from 10 to 40 gigabits per second, even in the more demanding undersea networks, and 1 terrabit per second has been demonstrated in the laboratory. For the past twenty years, the time required for the performance of optical communications systems to double has been even shorter than for electronic computers (the so-called Moore’s Law). One may wonder which new ideas will be needed to continue this exponential rate of progress. Perhaps sub-Poisson statistics will allow lower energy per bit, with quantum optics directly impacting large scale markets. Optical computing as such will quite probably emerge again in the form of all-optical operations in switching and signal routing, as well as amplification. Everyday life will quite likely be dramatically affected by inexpensive fibre optical connections to the home, making possible high speed internet links.

The third argument mentioned above will likely lead to optical interconnections between the various levels of computer architectures where high density becomes a problem. More compact, faster and most likely parallel access optical memories are likely to emerge, such as those based on quadratic non-linear effects in crystals, and on rewritable holographic memories in photo-refractive materials. Perhaps computer evolution will end up following nature and combining photo-sensors and neurons into smart retinae.

Conclusion

There is a unity in the broad and diverse field of optics. Other aspects of optics could have been highlighted in this survey, such as the impact of optical imaging and sensors in the life sciences and humanities, and the importance of materials development for optics. The interrelations between optics and micro- and nano-technologies may some day combine with micro-electronics to produce smart opto-electronic detector arrays for full electronic imaging in video and still pictures. Pasteur once said, “there are applications of science, there is no applied science”. Optics is progressing as a branch of science, with its roots deeply in physics; applications of optics are progressing and extend their impact well outside physics. Optics has served as the foundation for many of the advances in physics and engineering that have enriched the field of science at the end of the twentieth century. Optics has also been a direct contributor to the improvement of human life world-wide. The impact and recognition of Optics has been increasing steadily in the last decades and the trend will continue well into the next century.

Gravitational Physics at the Millennium
Progress, Problems and Prospects

Affiliated Commission 2
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General Relativity and Gravity

General relativity, the reigning theory of the gravitational force and the geometrodynamics of space-time, was the brainchild of the most famous scientist of the twentieth century, Albert Einstein. But unlike quantum theory - the other conceptual revolution in which he played a seminal role - Einstein's theory of gravitation languished on the sidelines for nearly half a century after the initial flurry of 1919, because relativistic deviations from Newtonian predictions were almost unmeasurably small under all astrophysical conditions then conceivable. Only after 1960 was it recalled to centre stage, when the discovery of X-ray sources, active galactic nuclei, quasars, pulsars and the cosmic microwave radiation revealed the presence in our universe of strong-gravity regimes and spectacular relativistic effects.

Today the theory is central to our understanding of some of the most exotic realms of science, from black holes to the evolution of the cosmos fractions of a second after the big bang. However, it is not yet the ultimate theory of gravitation. Attempts to reconcile it with quantum principles and to subsume it within a Grand Unified Theory of all the basic forces have encountered obstacles, signalling that general relativity must give way to something more fundamental when space-time curvature becomes so huge that the radius of curvature approaches the Planck length, about 10^{-33}cm. Curvatures of this order are expected only in the deep interior of black holes and at the moment of creation itself. There is increasing consensus that general relativity should give an accurate description of all aspects of gravity that will ever be directly observable.

Experimental confirmation of the theory has progressed enormously since 1915. A milestone was the discovery, by Russell Hulse and Joseph Taylor in 1974, of the binary pulsar, a pulsar in an 8-hour non-circular orbit about another neutron star. General-relativistic effects on the orbit are much larger than in the solar system (the total perihelion precession is 4°/yr!), and all have been confirmed to better than 1%.

Most significantly, the orbital period is decreasing at a rate that squares with the loss of energy by gravitational radiation as calculated from Einstein's quadrupole formula. This indirect but compelling evidence for the reality of gravitational waves lends encouragement to international efforts currently under way to detect and analyse such waves directly.

Gravitational waves

Several detectors nearing completion will measure the distortion of spatial geometry due to passage of a gravitational wave by monitoring the separations of three suspended mirrors using laser interferometry. The nearest concentration of stars that is large enough to yield wave-bursts inappreciable numbers (at least a few per year) is the Virgo supercluster, about 60 million light-years from us. To detect such bursts, the interferometers must be sensitive to fractional changes in arm length as small as 10^{-21}.

At least two systems will be operating with this sensitvity in 2002, with improvement by a factor of perhaps 10 about five years later. LIGO, the Laser Interferometer Gravitational-wave Observatory, will have two identical interferometers with arms 4 m long, located in Hanford, Washington and Livingston, Louisiana. VIRGO is a 3 m interferometer under construction in Pisa, Italy. Smaller instruments are being built or are under consideration in Japan, Germany and Australia.

Sources with well-defined wave-forms are the most promising for early detection. It is anticipated that the initial observations will be of the last minutes (inspiral and merging) in the lives of compact binary systems, (a fate that awaits the binary pulsar 100,000 years from now).These immediately pending observations pose a major challenge for theorists — to develop numerical simulations of the wave patterns which can then be used as templates to filter the data. This requires use of supercomputers and advances in numerical techniques which now involve the co-ordinated effort of workers at many centres.

The merging of two compact objects (e.g., a neutron star and a black hole) is also a plausible model for the origin of the mysterious gamma-ray bursts. The gravity-wave observations will therefore be awaited with interest by gamma-ray astronomers.
However, coincidences are unlikely to be found immediately, as most gamma-ray bursts are at cosmological distances, far beyond the range of the first generation of interferometers.

For frequencies below 1 Hz, the gravity-wave signal is drowned out by earth-noise (e.g. traffic and weather), and it is necessary to go into space. The Laser Interferometric Spacecraft (LISA), which it is hoped will fly about 2008 as a joint project of ESA and NASA, will consist of 6 spacecraft in solar orbit, arranged in the form of two equilateral triangles with a baseline of 5 million km. It will routinely see gravitational radiation from binary stars in our galaxy. It will be able to study mergers of supermassive black holes in galactic nuclei out to cosmological distances and in such detail as to map the ultra-strong field regime near the horizon. The bad new is that it is unlikely there will be more than a few such events per decade.

A satellite scheduled for launch in 2000 will carry the Stanford Gyroscope Experiment, which will measure "inertial-frame dragging," i.e., the way in which a massive spinning body drags the space around it into a swirling motion like a tornado. In the case of the spinning earth, this effect is very small, a precession of just 40"/yr. in the orbital plane of the satellite. The cryogenically cooled gyroscopes of the Stanford Experiment, monitored with SQUIDs, will be able to measure this precession to an accuracy better than 1%.

It is possible that frame-dragging has already been observed in the space near a rapidly spinning supermassive black hole by the Japanese X-ray satellite ASCA (Advanced Satellite for Cosmology and Astrophysics). Four days of observation of an iron fluorescence line with a highly variable profile in the X-ray spectrum of one active (Seyfert) galaxy suggest that this line originates from the innermost stable orbits of an accretion disk, very close to an event horizon. If confirmed by further measurements and similar examples, this would mean that X-ray observations are probing the very heart of a galactic nucleus (extending over light-minutes), virtually exposing the surface of the central black hole itself.

Active galactic nuclei, quasars and black holes

Active galactic nuclei and quasars have been suspected since the 1960s of harbouring supermassive black holes, but it is only in the last five years that strong confirmatory evidence has come to hand. In 1994 the Hubble Space Telescope measured the Doppler shift of spectral lines of gas orbiting 60 light-years from the centre of the giant galaxy M87 in the Virgo cluster. The orbital speed (550 km/s) and Kepler's law lead to the inference that a mass equal to 2 billion solar masses is hidden within this radius!

Since gas is easy to push around, this evidence alone is insufficient to convince a hardened sceptic. Much more compelling — because based upon the motions of stars — is the case for a massive black hole at the centre of our own galaxy. In 1996, astronomers at ESO's New Technology Telescope in Chile announced the results of measurements(extending over three years) of transverse stellar velocities in the central 0.3 light years. (Ordinary light from these stars is obscured by dust in the galactic plane, so the measurements are performed in the near-infrared.) Together with the line-of-sight velocities obtained from spectroscopy, this yields three-dimensional information about the motions. The orbits are Keplerian and imply a central mass of 2.5 million solar masses.

The clincher is the peculiar spiral galaxy NGC4258 (distance 20 million light-years). This has in its core a molecular gas disk (average radius about half a light-year) the motion of which can be accurately mapped with VLBI (Very Long Baseline Interferometry, which has angular resolution 100 times better than the Hubble Telescope) via the 1.3 cm (microwave) maser emission line of H_2O. The mass within the disk, inferred from the(precisely Keplerian) velocity distribution, is 36 million solar masses. If this is not a black hole, it must be something even more exotic: a star cluster as dense as this could not be stable and would rather quickly collapse to a black hole.

If as little as 1% of supernovae form black holes, there should be 10 million stellar-mass black holes in our galaxy. Very few, however, would now be in the accreting environment which would make them candidates for detection as X-ray sources, i.e., in a tight orbit with a normal star. In fact, less than a dozen have so far been found, beginning in 1972 with Cygnus X-1, the first black hole ever discovered.

Theoretical Progress

There is space only for brief allusion to some of the highlights on the theoretical front:

• The recognition, around 30 years ago, that black holes are stereotyped objects, completely specified by their mass, angular momentum and charge. (The last has no astrophysical significance: a charged black hole would be rapidly neutralised by currents from the interstellar plasma.) This so-called "no-hair" property enormously simplifies the task of model builders, and it has formed the basis of all work on black holes by theoretical physicists, astrophysicists and gravity-wave theorists.

• Sophisticated numerical simulations of gravitational collapse in the last few years have revealed an unexpected and intriguing feature, still poorly understood analytically. The process of black hole formation, near its critical point (mass zero), shares many of the properties of a phase transition.

• The celebrated discovery by Hawking in 1974 that black holes are "hot" and evaporate thermally by a quantum tunnelling process. (For astrophysical masses, the temperature is insignificant and the evaporation time practically infinite.) Efforts continue to understand at a deeper level the cabalistic Bekenstein-Hawking formula, which effectively equates the entropy of a black hole to its area. It has been hailed as one of the triumphs of superstring theory that recently it has proved possible to reproduce this formula, as well as other (scattering) properties of black holes, from the study of strings in a flat space.

• The idea that cold stars appreciably heavier than the sun are gravitationally unstable and should collapse to form neutron stars or black holes was advanced more than 60 years ago by Chandrasekhar, Zwicky andOppenheimer. For many years it was ignored or ridiculed. Its development since then is one of the success stories of twentieth science.

Dark Matter

Another theoretical prediction from the 1930's, once scoffed at as unobservable but now accepted as commonplace, is gravitational lensing — the bending of light from a distant galaxy or quasar by foreground masses to produce multiple images or luminous arcs. It was first seen in 1979, and dozens of examples are now known. Weak lensing, in which the galaxy image is merely distorted, has in the last few years been honed into a powerful tool for mapping and weighing dark matter at moderate cosmological distances (red shift z = 0.2 to 0.5). This material will produce systematic distortion in the images of background galaxies (about a million per square degree!) which can be measured using large mosaics of CCDs (charge-coupled devices) and analysed statistically.

Since no form of mass can dissociate itself from gravity, gravitational techniques such as orbital dynamics and lensing are the most direct and currently the best means we have for estimating the invisible-mass content of the universe.

Invisible matter dominates the universe. At the century's end, its nature remains a puzzle. Moreover, matter may not be the only invisible component cosmologists have to reckon with. Recent observations of Type Ia supernovae (which are employed as standard candles in cosmology) out to moderate cosmological distances ($z \sim 0.4$ to 0.9) point to an unforeseen conclusion: it appears that the Hubble expansion is speeding up! If these 1998 reports are confirmed, it would indicate that a sizeable fraction of the universe is in the form of "false vacuum" energy, characterised by negative pressure and repulsive gravity. One of the alternatives cosmologists would then have to consider is the revival of an old, discarded idea: the cosmological constant. Einstein had introduced it in 1917 (before it was known that the universe is expanding) in order to save a presumedly static universe from collapse - a step he later came to regret as the "biggest blunder" of his life. (Really it was not; there were one or two others which vie for that distinction.)

Cosmological Models

These new developments have thrown our preconceptions about the basic ingredients of the universe into turmoil for the present. Nevertheless, there is every prospect that within ten years we shall have a firm handle on all the basic cosmological parameters (to few percent). In particular, there is a fair chance that we shall finally have the answer to the old question: is there enough mass to close the universe and to eventually reverse the expansion? Much of this information will come from two satellite-borne instruments, NASA's MAP(launch date 2000) and ESA's Planck Surveyor (2007), which will map the cosmic microwave background (CMB) in unprecedented detail.

The progress made by cosmology since the discovery of the CMB in 1965 has been extraordinary. Calculations of light-element formation in the first three minutes of the expansion are in excellent agreement with observed abundances for the four lightest elements, lending strong support to the claim that the big bang model is an accurate description from the first millisecond or so onwards. Miraculously (and fortunately) the overall gravitational dynamics is adequately described by the first and simplest of all dynamical models of the universe — the homogeneous, isotropic Friedmann model. (A brief episode of "inflationary" expansion very near the beginning, at around 10^{-32} s, provides an attractive, though highly speculative, explanation for the "miracle".)

Today's cosmologists can fairly claim that they have penetrated to within a second of the big bang, and moreover that they have quantitative observational support for this claim. A number of theoreticians are bolder: they speak with an air of equal sobriety about events 10^{-32} s after the big bang or even the creation itself. Whether this is real progress or just a case of inflated cosmological chutzpah is a question on which opinion is strong and divided. Such speculations transcend any direct link with observation and could fairly be classed as meta cosmology. Nevertheless, they represent a rational attempt to extrapolate known laws in the time-honoured tradition of physical science since the days of Galileo.

The ultimate barrier is the big bang itself. Here, general relativity predicts a singularity, which is to say the theory has broken down and must defer to a still non-existent quantum theory of gravity.

There is a growing consensus that the most promising candidates for such a theory are supergravity, an 11-dimensional version of general relativity which unifies gravity with the other forces; and a10-dimensional theory of superstrings (the extra dimensions are supposed to be curled up and unobservably small). It has recently emerged that both are merely different aspects (vacuum states) of a still-mysterious, all-encompassing master theory, call M-theory. M-theory gives the impression of being gradually unveiled rather than fabricated, the hallmark of all great theories of the past.

Conclusion

Gravitational physics and cosmology are experiencing an exciting phase, when the "big picture" is coming into focus for the first time. We can expect a crescendo of discoveries in the new millennium, both in theory and observation, clarifying how our universe began and how it will end, the mystery of what lurks inside black holes, the nature of the foamy substratum that underlies the space-time continuum of our experience, and the composition of the invisible mass that dominates our universe. We have many new insights and revelations to look forward to!

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