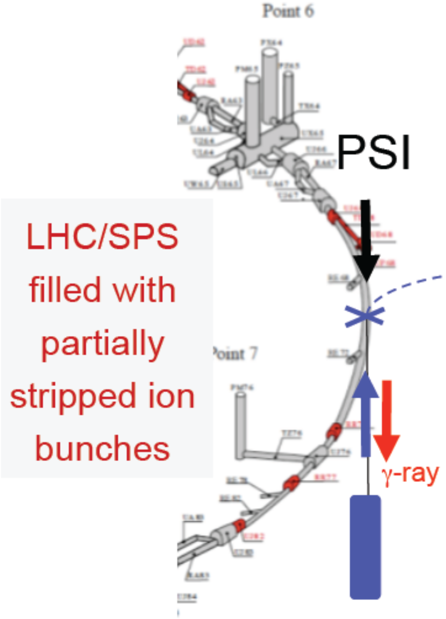
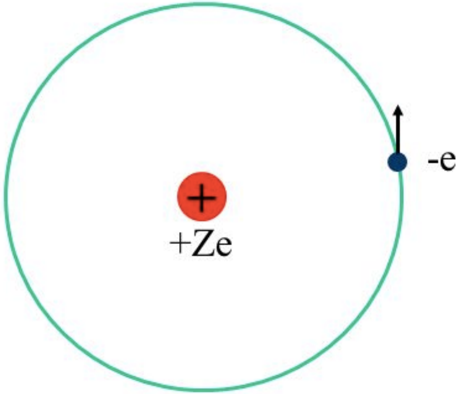
Gamma Factory @ CERN

Novel opportunities for Atomic, Nuclear, and Applied Physics



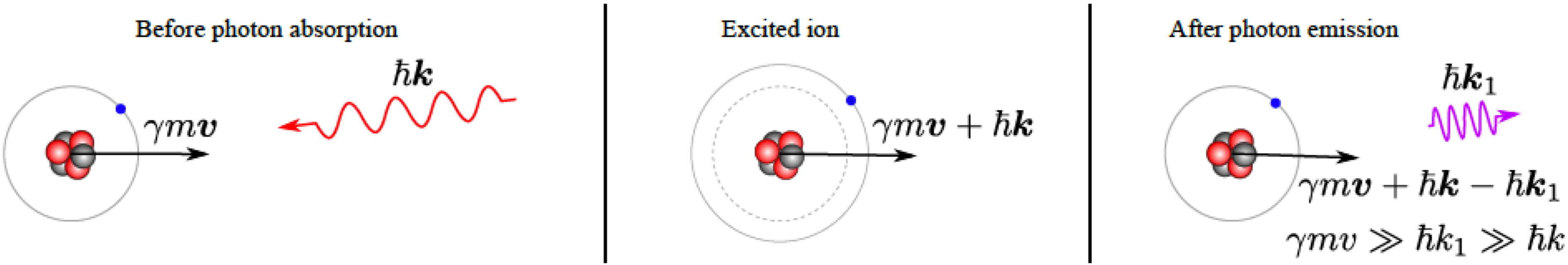


Quantum Science Seminar, December 17, 2020

Dmitry Budker
Helmholtz Institute Mainz, JGU Excellence Cluster PRISMA+, and UC Berkeley

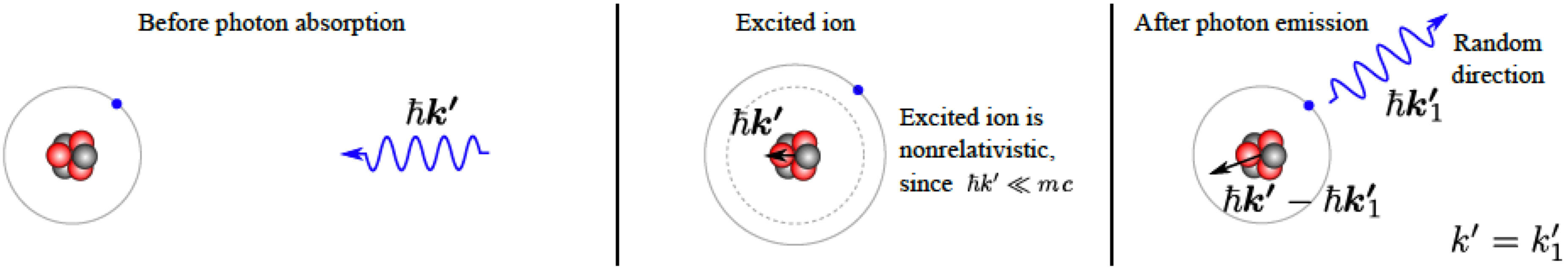
Photon scattering on **relativistic** ions

In the laboratory reference frame:



Photon-energy boost: $2\gamma_L \times 2\gamma_L$
backward emission angle: $1/\gamma_L$

In the initial ion reference frame:



Photon-energy boost: $2\gamma_L$

Gamma Factory @ CERN

Partially Stripped Ion beam as a light frequency converter

$$\nu^{max} \longrightarrow (4\,\gamma_L^2)\;\nu_i$$

Tuning of the beam energy, the choice of the ion type, the number of left electrons and of the laser type allows to tune the γ-ray energy, at CERN, in the energy domain of 100 keV – 400 MeV.

Example (maximal energy):

LHC, Pb^{80+} *ion*, $\gamma_L = 2887$, n=1→2, λ = 104.4 nm, E_γ(max) = 396 MeV

Witek Krasny

Gamma Factory @ CERN

The gamma ray source for Gamma Factory

*The idea: replace an electron beam by a beam of highly ionised atoms (Partially Stripped Ions - **PSI**)*

K.A. ISPIRIAN, A.T. MARGARIAN, N.G. BASOV, A.N. ORAEVSKI, B.N. CHICHKOV E.G. BESSONOV, K-J. KIIM, M.W. KRASNY...

The expected magnitude of the γ-source intensity leap

Electrons:	Partially Stripped Ions:
$\sigma_e = 8\pi/3 \times r_e^2$	$\sigma_{res} = \lambda_{res}^2/2\pi$
r_e - classical electron radius	λ_{res} - photon wavelength in the ion rest frame

Electrons:	Partially Stripped Ions:
$\sigma_e = 6.6 \times 10^{-25}\ cm^2$	$\sigma_{res} = 5.9 \times 10^{-16}\ cm^2$

Numerical example: λ_{laser} = 1540 nm

~ ***9 orders of magnitude difference in the cross-section***

~ ***7 orders of magnitude increase of gamma fluxes***

Witek Krasny

PSI @ LHC

Is this possible?

A major news from CERN! (July 2018)

During a special one-day run, LHC operators injected lead "atoms" containing a single electron into the machine (Image: Maximilien Brice/Julien Ordan/CERN)

Protons might be the Large Hadron Collider's bread and butter, but that doesn't mean it can't crave more exotic tastes from time to time. On Wednesday, 25 July, for the very first time, operators injected not just atomic nuclei but lead "atoms" containing a single electron into the LHC. This was one of the first proof-of-principle tests for a new idea called the Gamma Factory, part of CERN's Physics Beyond Colliders project.

Gamma Factory PBC study group

90 scientists
35 institutes
>10 countries

A. Abramov[1], S.E. Alden[1], R. Alemany Fernandez[2], P.S. Antsiferov[3], A. Apyan[4], H. Bartosik[2], E.G. Bessonov[5], N. Biancacci[2], J. Bieroń[6], A. Bogacz[7], A. Bosco[1], R. Bruce[2], D. Budker[8], K. Cassou[9], F. Castelli[10], I. Chaikovska[9], C. Curatolo[11], P. Czodrowski[2], A. Derevianko[12], K. Dupraz[9], Y. Dutheil[2], K. Dzierżęga[6], V. Fedosseev[2], N. Fuster Martinez[2], S. M. Gibson[1], B. Goddard[2], A. Gorzawski[13,2], S. Hirlander[2], J.M. Jowett[2], R. Kersevan[2], M. Kowalska[2], M.W. Krasny[14,2], F. Kroeger[15], D. Kuchler[2], M. Lamont[2], T. Lefevre[2], D. Manglunki[2], B. Marsh[2], A. Martens[9], J. Molson[2], D. Nutarelli[9], L. J. Nevay[1], A. Petrenko[2], V. Petrillo[10], W. Płaczek[6], S. Redaelli[2], S. Pustelny[6], S. Rochester[8], M. Sapinski[16], M. Schaumann[2], M. Scrivens[2], L. Serafini[10], V.P. Shevelko[5], T. Stoehlker[15], A. Surzhikov[17] I. Tolstikhina[5], F. Velotti[2], G. Weber[15], Y.K. Wu[18], C. Yin-Vallgren[2], M. Zanetti[19,11], F. Zimmermann[2], M.S. Zolotorev[20] and F. Zomer[9]

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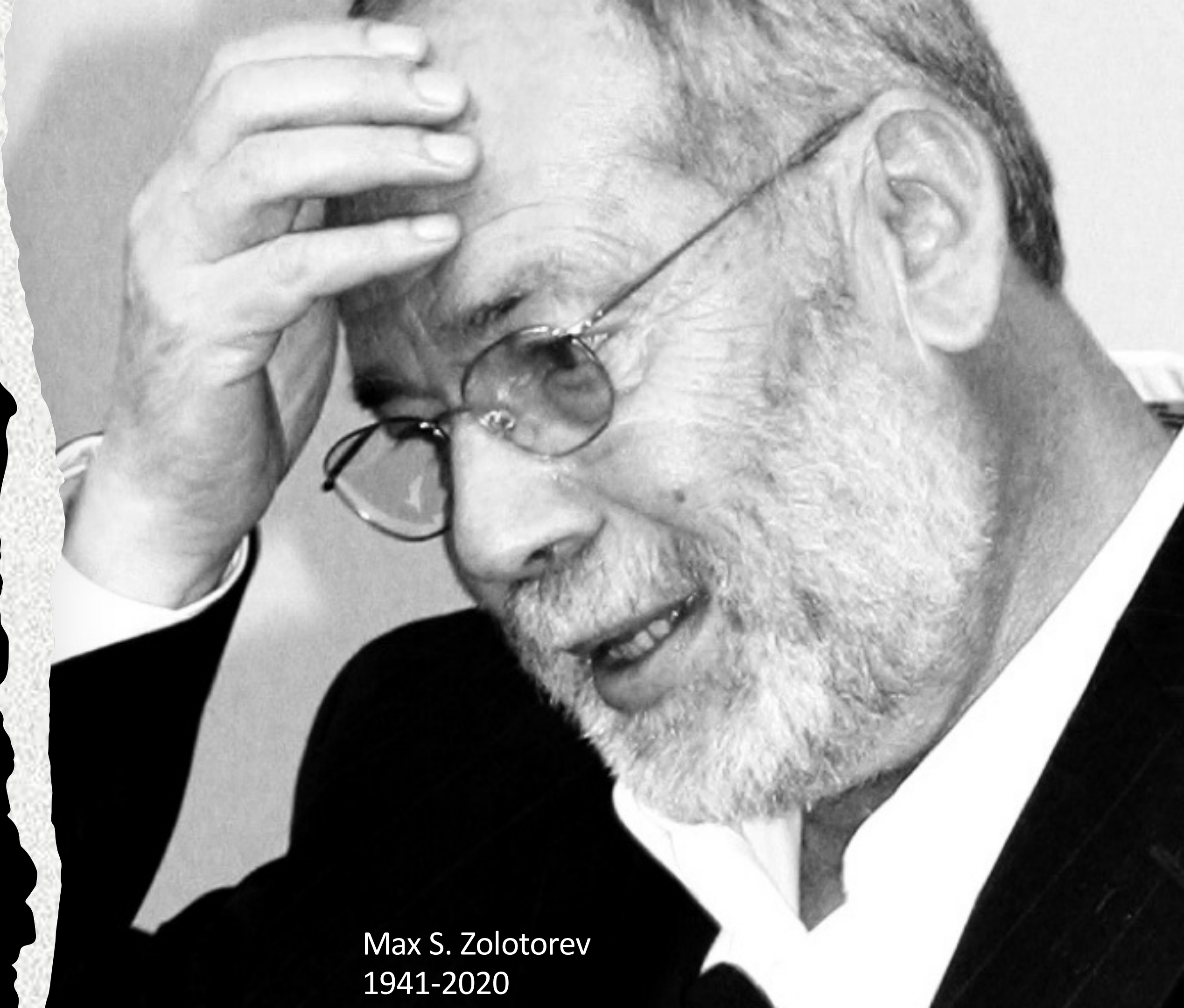
CERN Physics Beyond Colliders

Prof. Dr.
Witold Krasny

GF group is open to everyone willing to contribute to this initiative!

- Parity violation in relativistic ions
- Laser cooling @ RHIC, SPS, & LHC
- Optical stochastic cooling
- Atomic physics @ GF



Max S. Zolotorev
1941-2020

FEATURE ARTICLE

Ann. Phys. (Berlin) 2020, 2000204

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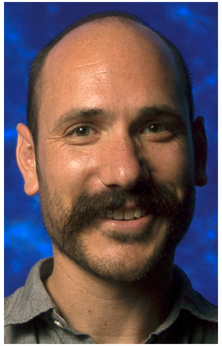
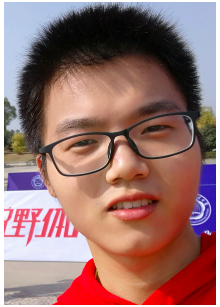
Atomic Physics Studies at the Gamma Factory at CERN

Dmitry Budker, José R. Crespo López-Urrutia, Andrei Derevianko, Victor V. Flambaum, Mieczyslaw Witold Krasny, Alexey Petrenko, Szymon Pustelny, Andrey Surzhykov, Vladimir A. Yerokhin, and Max Zolotorev*

duality

Light Source ↔ Giant Ion Trap



Expanding Nuclear Physics Horizons with Gamma Factory

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(Dated: December 5, 2020)

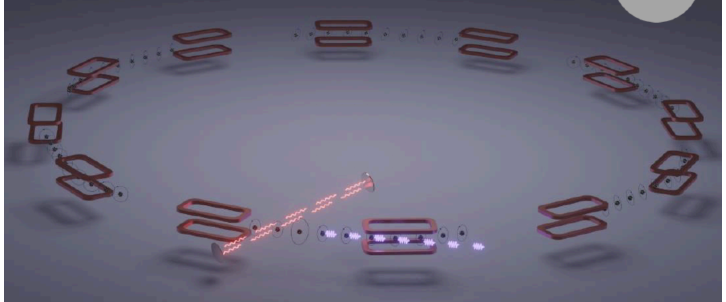




Virtual MITP Workshop

Physics Opportunities with the Gamma Factory

30 November – 4 December 2020



- Accelerator developments
- Atomic and fundamental physics
- Search for Dark Matter
- Nuclear and particle physics
- Rare isotopes and isomers
- Nuclear-physics applications
- Studies with primary, secondary and tertiary beams
- Gamma Factory in a global landscape

Contacts

Web: https://indico.mitp.uni-mainz.de/event/214/overview

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Adriana Palffy
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Workshop is sponsored by the Mainz Institute for Theoretical Physics

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Special Issue
Physics Opportunities with the Gamma Factory

Submisson deadline: April 1st, 2021

Scope:

- Accelerator developments
- Atomic and fundamental physics
- Search for Dark Matter
- Nuclear and particle physics
- Rare isotopes and isomers
- Nuclear-physics applications
- Studies with primary, secondary and tertiary beams
- Gamma Factory in a global landscape

Guest Editors

Dmitry Budker
Mikhail Gorshteyn
Witold Krasny
Adriana Palffy
Andrey Surzhykov

About the journal:

Annalen der Physik (IF 3.317) is one of the world's renowned physics journals with an over 225 years' tradition of excellence. It comprises all areas of physics, from fundamental research to forefront applications including interdisciplinary fields.

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Outline of the talk

- *What is **Gamma Factory** (GF)*
- *Opportunities with primary, secondary, and tertiary beams*
- *Atomic physics at the GF*
- *Nuclear photophysics with fixed targets*
- *Applied physics examples*
- *Conclusions*

Spectroscopy of PSI

PSI=HCI=Highly Charged Ions

Hydrogen-like Ions

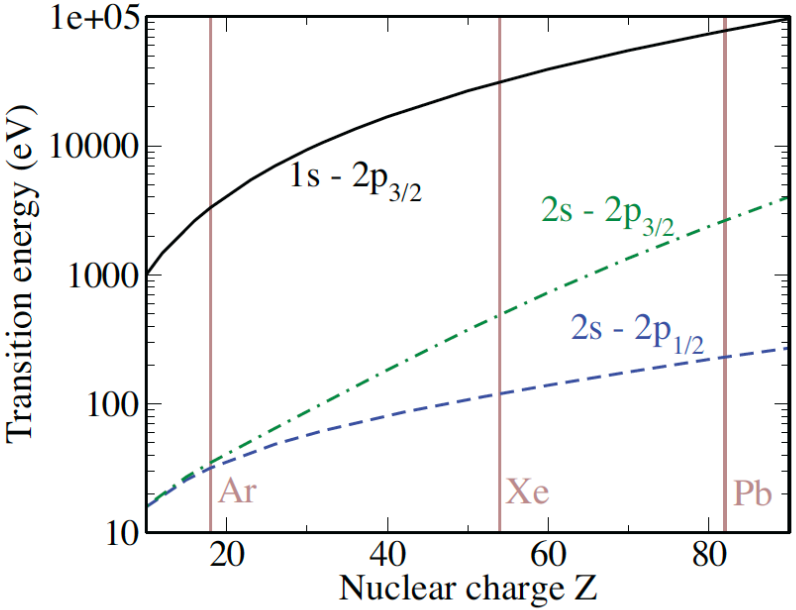
Transition energy $\Delta E_{nn'}$	$\propto (Z\alpha)^2$
Fine–structure splitting	$\propto (Z\alpha)^4$
Hyperfine–structure splitting	$\propto \alpha(Z\alpha)^3 m_e/m_p$
Lamb shift	$\propto \alpha(Z\alpha)^4$

Strong E-fields!

Pb^{81+} : 10^{16} V/cm

Schwinger critical field

$$E_s = m^2c^3/(e\hbar) \approx 1.3 \times 10^{16} \text{ V/cm}$$



H-like

Li-like

: direct excitation of heavy PSI with primary photons

Li-like ions

Ion	Transition energy	Reference
Pb^{79+}	230.823 (47)(4)	theory, [5]
	230.76(4)	theory, [6]
Bi^{80+}	235.809(53)(9)	theory, [5]
	235.72(5)	theory, [6]
U^{89+}	280.645(15)	experiment, [7]
	280.775(97)(28)	theory, [5]

TABLE III. Energies (eV) of the $1s^2\,2s\ ^2S_{1/2} - 1s^2\,2p\ ^2P_{1/2}$ transition in heavy lithium–like ions.

PoP experiment

Parameter	**Value**
crossing angle	2.6°
Ion magnetic rigidity	787 T m
Ion γ factor	96.3
Ion beam horizontal RMS size at IP	1.3 mm
Ion beam vertical RMS size at IP	0.8 mm
Ion revolution frequency	43.4 kHz
Laser photon energy	1.2 eV
Laser frequency	40 MHz
Laser pulse energy	5 mJ
Ion $2s_{1/2} \rightarrow 2p_{1/2}$ transition energy	230.8 eV
Maximum energy of back scattered photon	44.5 keV

Projected 10^{-4} uncertainty in the PoP experiment: better than current theory state-of-the-art

⬇️

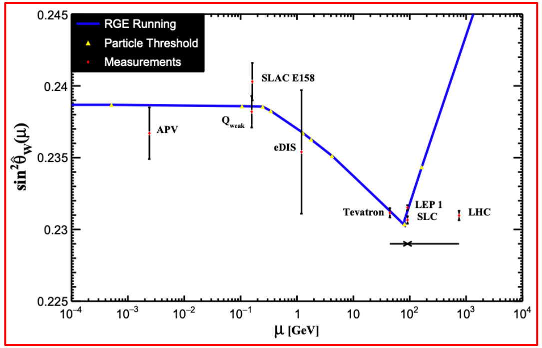
□Atomic Physics already in PoP!□

Fundamental symmetry tests at the

VOLUME 78, NUMBER 25 PHYSICAL REVIEW LETTERS 23 JUNE 1997

Parity Nonconservation in Relativistic Hydrogenic Ions

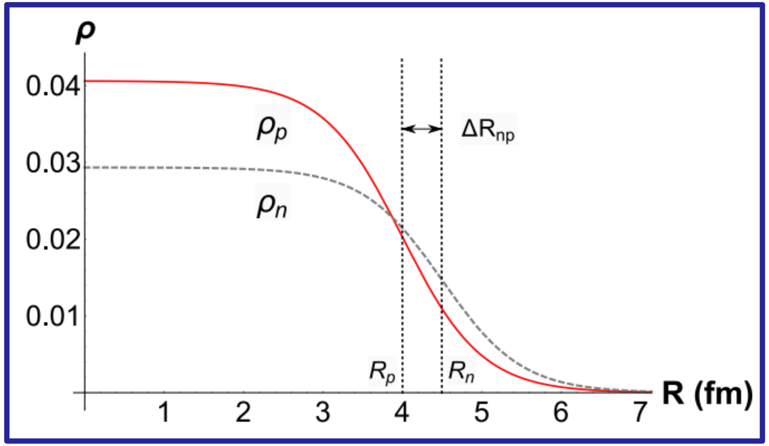
M. Zolotorev and D. Budker

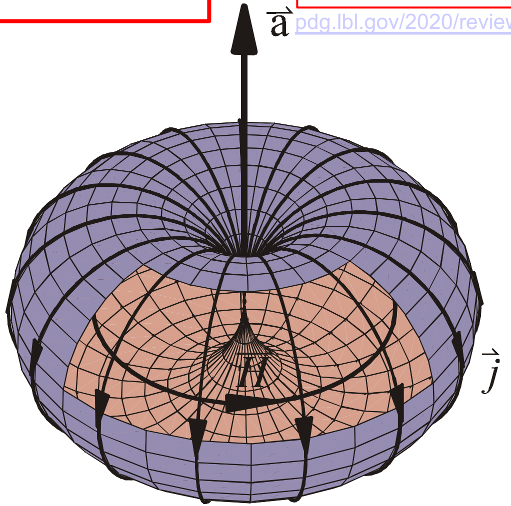


pdg.lbl.gov/2020/reviews/rpp2020-rev-standard-model.pdf

Why ?

- New physics (e.g. *Z'* bosons)
- Neutron skins
- Nuclear anapoles





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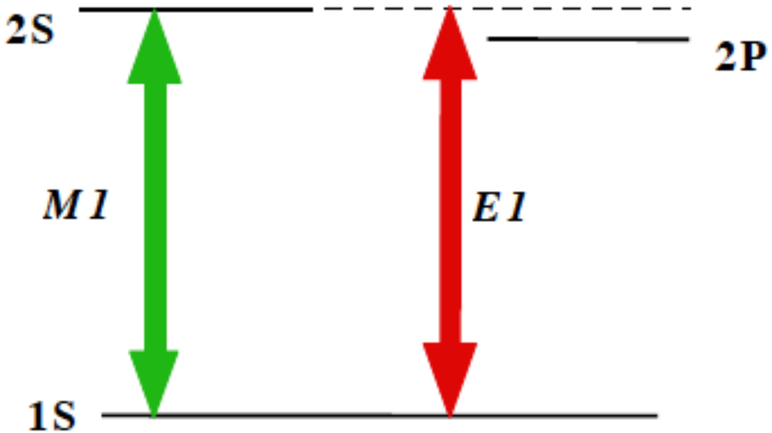


Fig. 1. The 1S→2S transition in a hydrogenic system.

level-mixing

$$|2S\rangle \Rightarrow |2S\rangle + i\eta|2P\rangle, \qquad i\eta = \frac{\langle 2P|\hat{H}_w|2S\rangle}{E_{2S} - E_{2P}}$$

☞ circular dichroism

Table 2. Parameters of relativistic ion storage rings.

Parameter	RHIC	SPS	LHC
γ_{max} for protons[a]	250	450	7000
Number of ions/ring[b]	$\sim 5 \cdot 10^{11}$	$\sim 2 \cdot 10^{11}$	$\sim 5 \cdot 10^{10}$
Number of bunches/ring	57	128	500-800
R.m.s bunch length	84 cm	13 cm	7.5 cm
Circumference	3.8 km	6.9 km	26.7 km
Energy spread w/o laser cooling	$2 \cdot 10^{-4}$	$4.5 \cdot 10^{-4}$	$2 \cdot 10^{-4}$
Normalized Emittance (N.E.)	$\approx 4\ \pi \cdot \mu m \cdot rad$	$\approx 4\ \pi \cdot \mu m \cdot rad$	$\approx 4\ \pi \cdot \mu m \cdot rad$
Dipole field	3.5 T	1.5 T	8.4 T
Vacuum, cold	$<10^{-11}$ Torr (H_2, He)	-	$<10^{-11}$ Torr (H_2, He)

[a] For hydrogenic ions, $\gamma_{max}^{ions} = \gamma_{max}^{p} \cdot Z-1/A$

[b] Estimated from proton and heavy ion data.

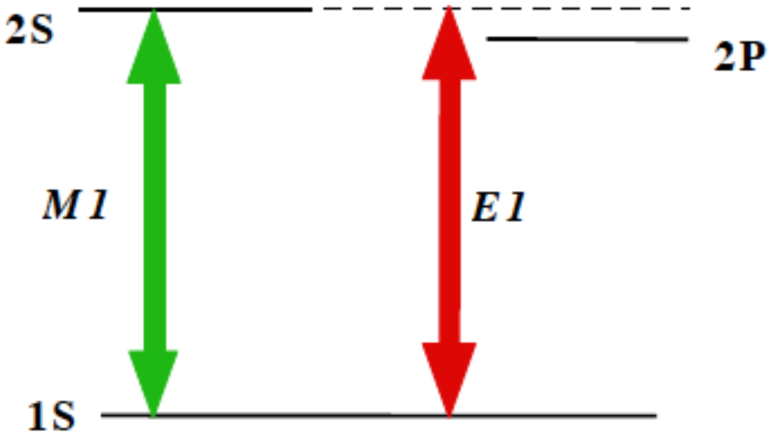


Fig. 1. The 1S→2S transition in a hydrogenic system.

Table 1: *Z*-dependence of atomic characteristics for hydrogenic ions. In the given expressions, α is the fine structure constant, $\hbar=c=1$, m_e is the electron mass, G_F is the Fermi constant, θ_w is the Weinberg angle, and *A* is the ion mass number.

Parameter	Symbol	Approximate Expression
Transition Energy	$\Delta E_{n-n'}$	$\frac{1}{2}\left(\frac{1}{n^2}-\frac{1}{n'^2}\right)\alpha^2 m_e \cdot Z^2$
Lamb Shift	ΔE_{2S-2P}	$\frac{1}{6\pi}\alpha^5 m_e \cdot Z^4 \cdot F(Z)^a$
Weak Interaction Hamiltonian	$\hat{H}_w$	$i\sqrt{\frac{3}{2}}\cdot\frac{G_F m_e^3 \alpha^4}{64\pi}\cdot\left\{(1-4\sin^2\theta_w)-\frac{(A-Z)}{Z}\right\}\cdot Z^5$
Electric Dipole Amplitude (2S→2P$_{1/2}$)	$E1_{2S\to 2P}$	$\sqrt{\frac{3}{\alpha}}\cdot m_e^{-1}\cdot Z^{-1}$
Electric Dipole Amplitude (1S→2P$_{1/2}$)	$E1$	$\frac{2^7}{3^5}\sqrt{\frac{2}{3\alpha}}\cdot m_e^{-1}\cdot Z^{-1}$
Forbidden Magn. Dipole Ampl. (1S→2S)	$M1$	$\frac{2^{5/2}\alpha^{5/2}}{3^4}\cdot m_e^{-1}\cdot Z^2$
Radiative Width	Γ_{2P}	$\left(\frac{2}{3}\right)^8 \alpha^5 m_e \cdot Z^4$

[a] The function *F(Z)* is tabulated in Ref. 12. Some representative values are: *F*(1)=7.7; *F*(5)=4.8, *F*(10)=3.8; *F*(40)=1.5 .

Unique to

measure in isonuclear chains

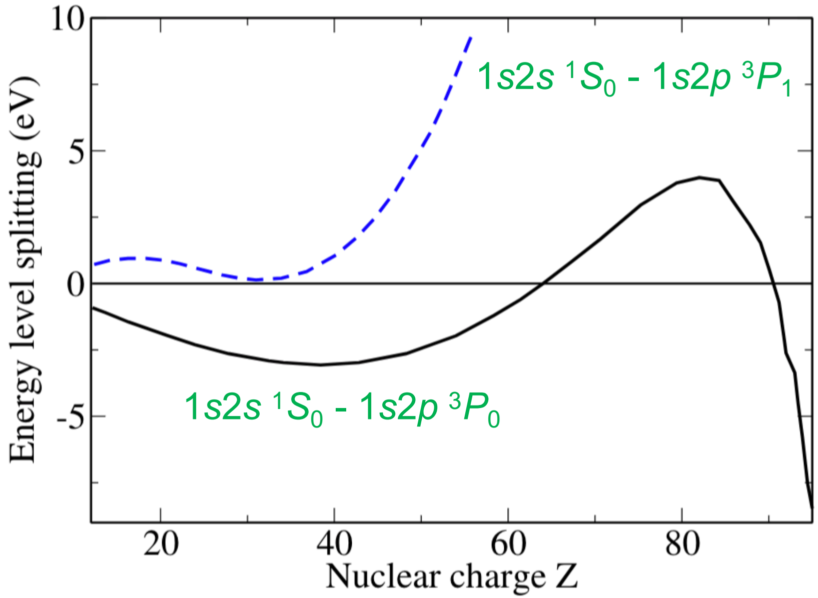
(+isotopic chains)

control of systematics

for neutron-skins

Not only hydrogenic ions are interesting for parity violation!

Level-crossing in He-like ions



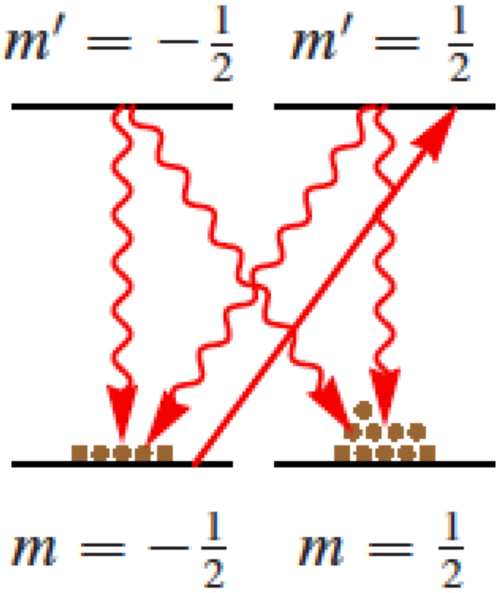
Parity-violating mixing

$$\eta = \frac{\left\langle \Psi_s \middle| \hat{H}_w \middle| \Psi_p \right\rangle}{E_p - E_s - i\Gamma/2}$$

$\propto Z^5$

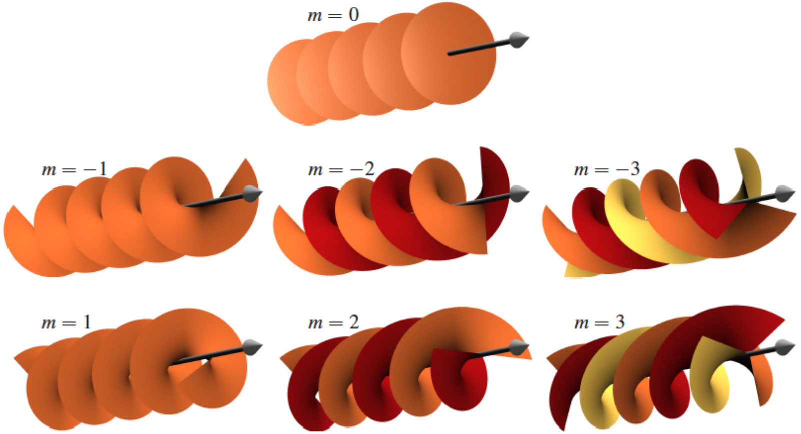
Enhancement near level crossings

Optical Pumping of PSI



- Single-path polarization via optical pumping
- Both electronic and nuclear polarization
- Will polarization survive a round trip?
- If yes ☞ measure static and oscillating **EDM**
- Regardless ☞ nuclear-spin dependent parity violation

More atomic physics at the γgf



- Laser cooling of PSI in the ring: enabling technology!
- Twisted light (gamma)
- PSI in strong external fields (also for parity violation)
- Tests of special relativity
- Scattering of gamma rays on ions (Thompson, Delbrück, …)
- …

Nuclear physics at the

- Physics opportunities with primary, secondary and tertiary beams
  with previously unattainable parameters
- Direct measurements of astrophysical S-factors at relevant energies
- Spectroscopy of nuclear gamma transitions
  on par with laser spectroscopy of atoms
- Gamma polarimetry at the 10^{-5} to 10^{-6} rad level
- Precision measurement of parity violation in hadronic and nuclear system
  at previously inaccessible asymmetry
- Production of high-intensity, monoenergetic and small-emittance
  tertiary beams: neutrons, muons, neutrinos, etc.
- …

Nuclear physics at the γGF: examples

- Direct nuclear-transition spectroscopy of stored nuclei (or PSI)
- Interplay of atomic and nuclear d.o.f.
- (γ,π) reactions to probe halo nuclei
- Photoproduction of pionic(kaonic) atoms,

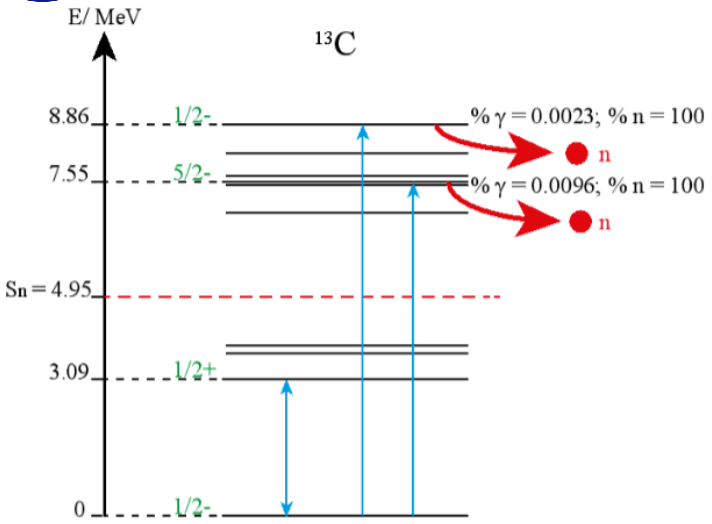
  e.g., $\gamma + {}^3\mathrm{H} \rightarrow ({}^3\mathrm{He} + \pi^-)_{ns}$

  V.V.Flambaum, Junlan Jin, D.B., arXiv:2010.06912 (2020)

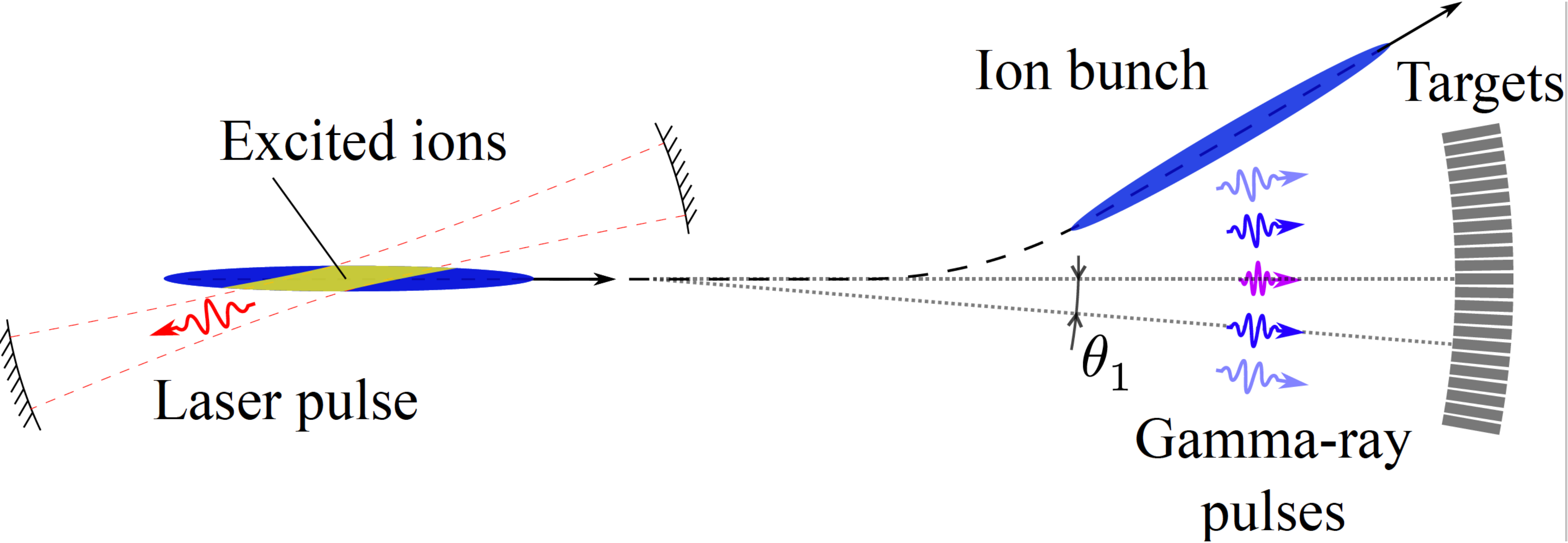
Isotope	I_g^P	Transition energy	I_e^P	Excitation lifetime
^{129}Xe	1/2+	39.578 keV	3/2+	12.8 ns
^{229}Th	5/2+	29.19 keV	(5/2+)	30 ns
^{161}Dy	5/2+	25.651 keV	5/2-	95.7 ns
^{119}Sn	1/2+	23.871 keV	3/2+	109 ns
^{151}Eu	5/2+	21.541 keV	7/2+	275 ns
^{57}Fe	1/2-	14.412 keV	3/2-	940 ns
^{73}Ge	9/2+	13.3 keV	5/2+	3.3 msec
^{45}Sc	7/2-	12.4 keV	3/2+	201 sec
^{205}Pb	5/2-	2.3 keV	1/2-	3 hours
^{235}U	7/2-	76.7 eV	1/2+	10^{17} years
^{229}Th	5/2+	8.28 eV	(3/2+)	$\sim$ 10 min

Nuclear physics at the GF: examples

- High-resolution spectroscopy of γ-resonances
- Fano effect in γ-resonances
- Giant resonances, pigmy resonances
- (γ,α) reactions: astrophysical S-factors
- Nuclear E1 polarizabilities, e.g., $^{208}\mathrm{Pb}(\gamma,\gamma')$
- Parity-violating photophysics
- Lepton-pair photoproduction (e^+,e^- and μ^+, μ^-)

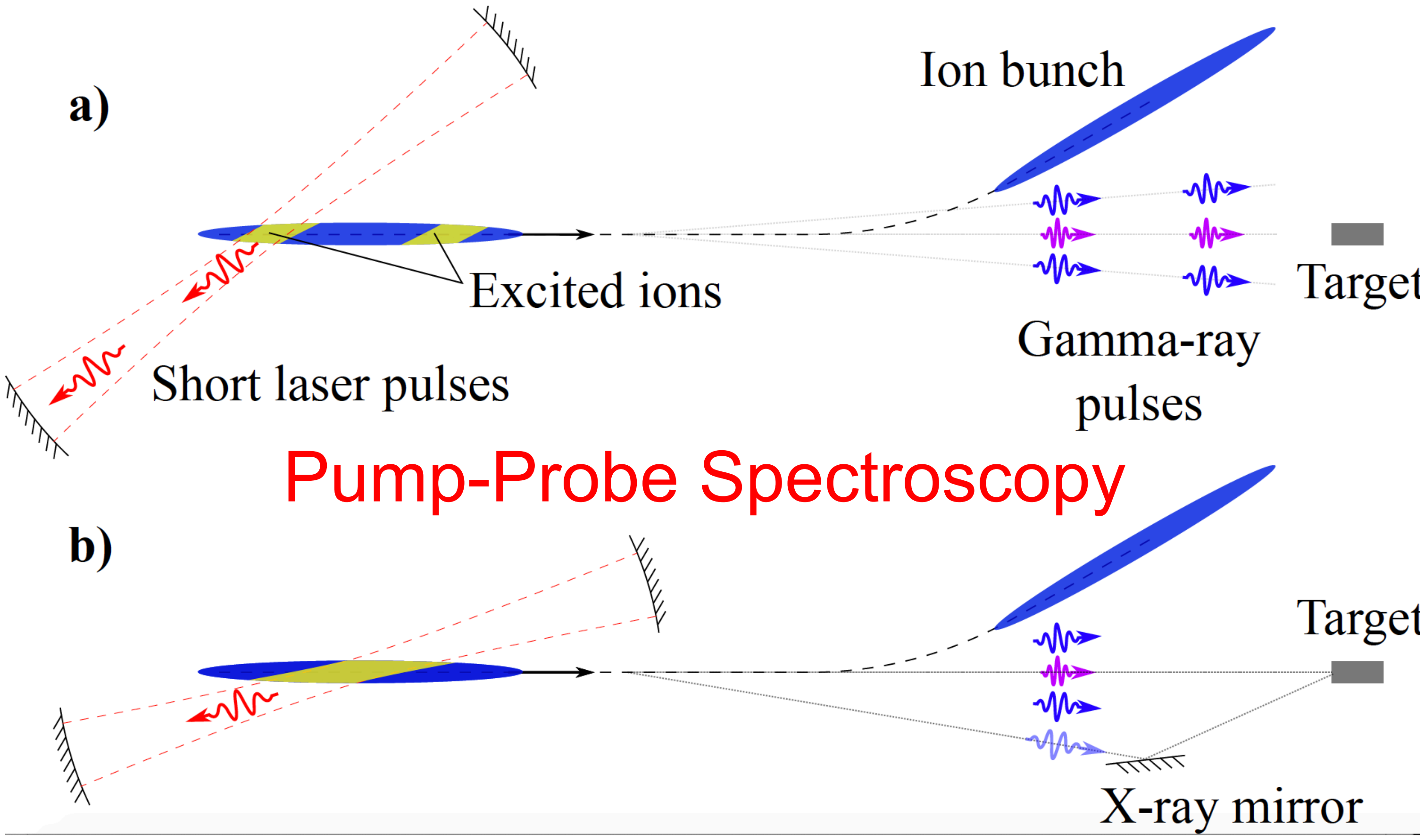


Fixed-target experimental configurations



Parallel Spectroscopy

Fixed-target experimental configurations



Applied physics and enabling technologies

- Production of medical isotopes and isomers
- Nuclear waste disposal
- Gamma-ray lasers ?
- Precision gamma polarimetry
- …

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ARTICLE

Proposal for selective isotope transmutation of long-lived fission products using quasi-monochromatic γ-ray beams

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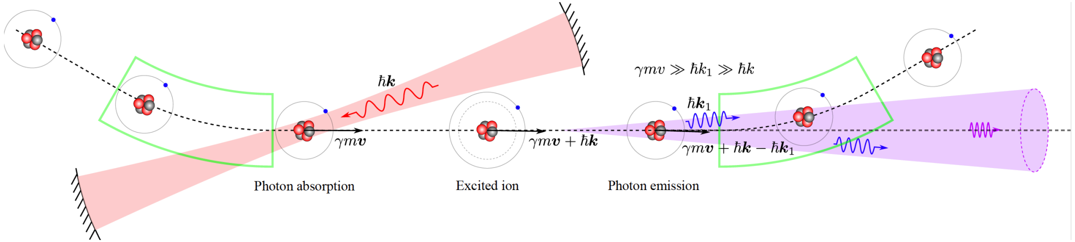
Conclusion


$\hbar \boldsymbol{k}$
$\gamma m \boldsymbol{v}$
Photon absorption
$\gamma m \boldsymbol{v} + \hbar \boldsymbol{k}$
Excited ion
$\gamma m v \gg \hbar k_1 \gg \hbar k$
$\hbar \boldsymbol{k}_1$
$\gamma m \boldsymbol{v} + \hbar \boldsymbol{k} - \hbar \boldsymbol{k}_1$
Photon emission