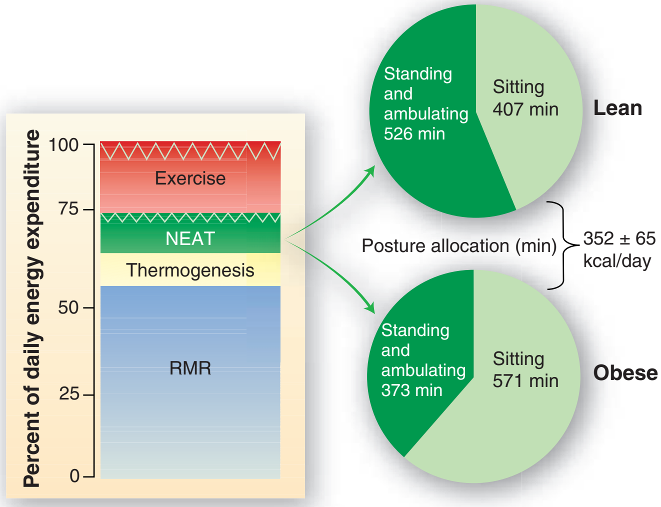
How to Create a Spin Current

Prashant Sharma

Science **307**, 531 (2005);
DOI: 10.1126/science.1099388



A moratorium on sitting. (**Left**) Total daily energy expenditure can be divided into three main components: resting metabolic rate (RMR), thermogenesis, and the cost of physical activity, both planned (exercise; red) and unplanned (NEAT; green). RMR represents 50 to 70% of daily energy expenditure and covers the energy necessary for body maintenance, including cellular metabolism and whole-body functions such as ventilation, circulation, and tissue oxygen uptake. RMR seems to be "fixed" for a given person, although it does decline with age. Because humans have evolved behavioral strategies (clothing) to maintain body temperature in cold environments, thermogenesis (yellow) accounts for only 10% of daily energy expenditure and encompasses the energy required to digest, absorb, transport, and store ingested food. This leaves 20 to 40% of daily energy expenditure for the most variable component, physical activity. The energy cost of physical activity can be divided into planned physical activity, such as sport and exercise, and spontaneous physical activity or NEAT, which includes all nonvolitional muscle activities such as fidgeting, muscle tone, and maintenance of posture. When people decide to increase energy expenditure for weight control purposes, usually only structured exercise is included in their calculations. Levine *et al.* propose that concentrating on modifying NEAT behaviors (standing instead of sitting, fidgeting instead of keeping still, or simply walking) can burn the necessary extra calories to control weight (*1*, *2*). In other words, targeting inactivity may be sufficient to fill the "energy gap" that leads to a creeping up of body weight (*6*). (**Right**) Time spent sitting versus standing and ambulating in 20 self-proclaimed "couch potatoes," both lean (top) and mildly obese (bottom) (*1*). If the obese volunteers substituted a mere 164 min of sitting for standing or walking around, they would expend an extra 352 kcal/day on average. This could prevent the addition of extra pounds, assuming energy intake is unchanged.

is worth emphasizing that the "energy gap" required to explain the increased prevalence of obesity is only 100 to 200 kcal/day (*6*). This suggests that a sustained small change in either energy intake or energy expenditure is all that is required to prevent obesity in most of us (see the figure). Therefore, the difference in NEAT observed between obese and lean individuals is significant and implies that obesity might be prevented through simply limiting sedentary activities, or increasing behaviors such as standing, walking, and fidgeting. Indeed, a half-century ago, Widdowson (*7*) found that fidgeting is important for energy expenditure. In a 1986 study, spontaneous physical activity equivalent to NEAT and measured within the confines of a respiratory chamber accounted for an average energy expenditure of 348 kcal/day (*8*). The energy cost of spontaneous physical activity varied among study participants from 100 to 700 kcal/day and accounted for a major portion of individual differences in 24-hour energy expenditure. Interestingly, these values are almost the same as those reported in the Levine *et al*. study in which extra "couch potato" time accounted for energy savings of 352 kcal/day on average.

The underlying mechanisms responsible for an individual's propensity to fidget are unknown. However, studies in families (*9*) have shown that although the degree of spontaneous physical activity is highly variable, it is more similar among siblings than among unrelated individuals. This provides indirect evidence for the idea that NEAT is genetically determined. Furthermore, in a prospective study, weight gain was inversely related to the level of NEAT, at least in males (*9*). Unfortunately, if genes do determine the true "coach potato," then encouraging an exchange of time spent sitting for time spent standing, as suggested, is unlikely to help to control body weight. Instead, one could progressively change the environment to discourage sitting behaviors. What Levine and colleagues clearly demonstrate is that small but sustained changes in the activities of daily living can profoundly affect energy balance.

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10.1126/science.1108597

PHYSICS

How to Create a Spin Current

Prashant Sharma

We usually think of a current as a flow of particles, such as the flow of electrons in a charge current generated by a battery. However, besides its charge, the electron also carries a spin, whose projection along the spin axis can point up or down. Conventional electronic devices ignore this property of the electron, but new devices are now being built that rely on the spin (*1*, *2*). Such devices should have faster switching times and lower power consumption than conventional devices, mainly because spins can be manipulated faster and at lower energy cost than charges can.

All currently available spin-based devices are memory devices that use the spin to store information. Spin-based electronic (spintronic) devices such as transistors (*2*) require spin currents, just as conventional electronic devices require charge currents. Unfortunately, it is very difficult to generate and transport a spin current.

To understand what is meant by a spin current, consider an electron current that flows through a channel and contains only up-spin polarized electrons. Add to this a similar current in which all electrons are down-spin polarized and flow in the opposite direction. The result is a current of spins only; there is no net particle transfer across any cross section of the channel.

A spin current differs from a charge current in two important ways. First, it is invariant under time reversal: If the clock ran backward, spin current would flow in the same direction. Second, spin current is associated with a flow of angular momen-

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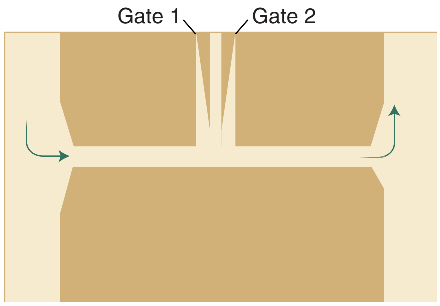
tum, which is a vector quantity. This feature allows quantum information to be sent across semiconducting structures, just as quantum optics involves distribution of information across optical networks via polarization states of the photon.

Most methods currently under investigation use ferromagnets to inject a spin current into a nonmagnetic material. However, this process is inefficient. For practical applications, the generation and detection of spin currents should not require strong magnetic fields and interfaces between semiconductors and ferromagnets.



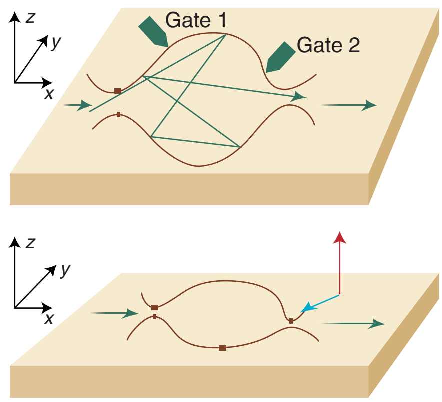
Creating a spin current through spin pumping I. A single channel of electrons is formed in a 2D electron system through electrostatic confinement. When out-of-phase ac voltages are applied to the two gates, the channel is perturbed, resulting in a dc electron current. If one of the gates is replaced by an oscillating magnetic field, a spin current is pumped.

One method that meets these requirements is spin pumping, which involves the scattering of electrons off a small region (a quantum cavity). In the cavity, electrons with different spins take dissimilar paths and therefore scatter differently off the cavity walls. Through modulating the shape of the cavity periodically in time, a constant spin current can be generated.

The theory of pumping electrons without changing their spin state is based on the idea (*3*) that one can create a traveling wave potential for electrons to ride on. At any moment, the electrons sit in the minima of the wave and move along with it. The efficiency of this mechanism depends on the depth of the traveling wave: The deeper the potential, the greater the chance that the electrons remain trapped and are transported along with the wave.

One practical way to create such a traveling wave is to periodically modulate the transmission of the electron flow at two points in space (*4*). This can be done by applying two metal gates on a channel (see the first figure) or on a quantum cavity (second figure, top panel). Experimentally, these structures are created in a two-dimensional (2D) layer of electrons (an electron gas), which forms in semiconducting heterostructures typically made from GaAs and AlGaAs. Switkes *et al.* have shown experimentally that a quantum cavity can indeed be modulated in time (*5*).

These ideas have recently been generalized to create spin currents. The earliest proposal (*6*) was to create a traveling wave for up spin-polarized electrons that is opposite in direction to that for down spin-polarized electrons. Creation of such spin-selective traveling waves requires the use of some externally controllable mechanism to break spin-rotation symmetry—that is, to define a unique spin axis in space. This can be achieved by replacing one of the metal gates in the first figure with an external, time-dependent magnetic field. To obtain efficient spin transport, one must increase the depth of the minima in the traveling waves by restricting the electrons to a long narrow channel—a quantum wire (*7*)—such that they repel each other.



Creating a spin current through spin pumping II. (Top) A quantum cavity is perturbed through out-of-phase ac voltages applied to the two gates. Electrons entering the cavity scatter off the cavity walls several times before leaving. **(Bottom)** In a sufficiently large cavity, pumping leads to a spin current with a tunable direction of spin polarization. Both in-plane (green arrow) and out-of-plane (red arrow) polarizations are possible.

However, the picture of a single traveling wave is inadequate for describing pumping in a finite cavity, because the electron follows a complicated path before exiting the cavity. The direction of the current is therefore determined by the details of the scattering in the cavity (*8*). This sensitivity to the electron's path in the cavity is an essential feature of mesoscopic semiconductor devices, which can be up to several tens of micrometers in size.

In a theoretical proposal (*9*) for spin pumping, this dependence of the current through the cavity on externally controllable parameters is used to generate a spin current. The proposal is to modulate the shape of a quantum cavity through the use of two magnetic fields. A strong magnetic field applied in the plane of the cavity (see the second figure, top panel) couples only to the spin of the electrons. For such a strong in-plane magnetic field, there are more up-spin electrons (whose spins are aligned with the magnetic field) than down-spin ones inside the cavity. As a result, the pumped current is spin-polarized along the direction of the strong magnetic field and in the cavity plane; that is, it is a mixed charge and spin current.

To achieve only a spin current, a second, weak magnetic field is added. The field is weak enough not to affect the spin of an electron, but the Lorentz force exerted by this field affects the spatial motion of the charged electrons. One would therefore expect (on average) the up-spin charge current to flow in one direction while the down-spin charge current flows in the opposite direction. Spin currents have recently been produced experimentally with such a device (*10*).

An alternative to using magnetic fields in the cavity has also been proposed (*11*). It is based on the fact that the spin state of an electron moving inside a semiconductor is not independent of its momentum state. Because the quantum cavity is formed in a semiconductor—typically a GaAs/AlGaAs heterostructure—the spin of the electron is coupled to its motion inside the cavity. Because of this spin-orbit coupling, the direction of the spin of an electron follows the electron's motion. As a result, the direction of the spin polarization coming out of the cavity depends on the details of the scattering in the cavity (*12*). By increasing the number of times an electron scatters off the cavity walls, the in-plane spin projection of the electron can be made small, and its spin can be made to point in a direction perpendicular to the plane of the electron gas (see the second figure).

This approach should allow spin currents to be pumped through a quantum cavity without an in-plane magnetic field. Because of spin-orbit coupling, the outgoing current will be spin-polarized. By either applying a weak perpendicular magnetic field [as in the experiments in (*10*)] or by inducing small changes in the density of electrons in the cavity, a pure spin current can be obtained. In this method of pumping, the direction of polarization of the spin current can be changed from in-plane to out-of-plane by altering the shape and size of the quantum cavity (second figure, bottom panel). The approach has not yet been realized experimentally.

Spin pumping in mesoscopic systems allows the spin-polarization direction of currents to be manipulated without the use of strong magnetic fields and ferromagnets. However, some experimental challenges remain before this method is ready for use in actual spintronic devices. One difficulty lies in efficiently detecting spin currents whose polarization direction is arbitrary.

Spin currents polarized in the plane of the 2D electron system have been detected electrically (*10*). Out-of-plane polarization in a 2D electron system may be detected (*11*) via the spin Hall effect. Because of this effect, an electron with its spin polarized perpendicular to its momentum is deflected in a direction orthogonal to both its momentum and its spin. Reversing the direction of either the momentum or the spin polarization reverses the direction of deflection. As a result, a spin current with an out-of-plane polarization generates a transverse electric field in a material that shows the spin Hall effect. Recently, the spin Hall effect has been observed for the first time in a semiconducting GaAs/InGaAs heterostructure (*13*).

We have yet to create a spin pump that can generate spin currents with any chosen direction of spin polarization. Nonetheless, recent experimental and theoretical advances give hope that devices relying on spin currents will soon be realized.

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10.1126/science.1099388

ASTRONOMY

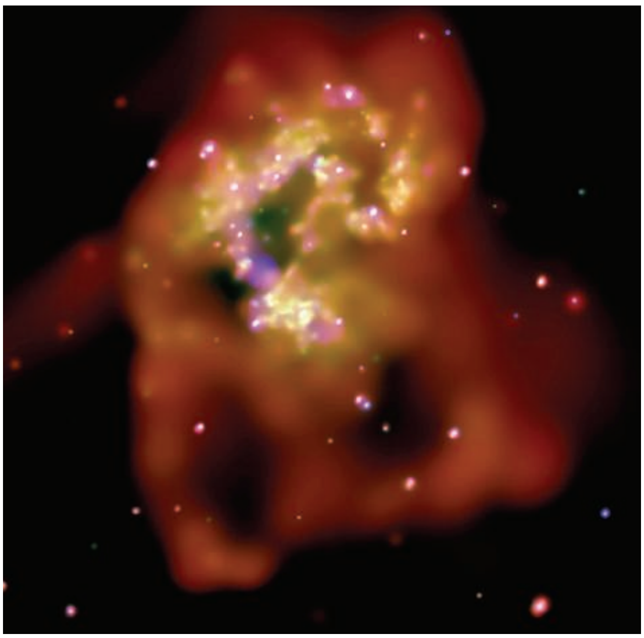
The Hunt for Intermediate-Mass Black Holes

Giuseppina Fabbiano

All known black holes fall into two classes. Stellar black holes are born in the collapse of massive stars and have masses several times that of the Sun. They were discovered thanks to the x-ray emission that arises from the accretion of the outer layers of a nearby orbiting star. Supermassive black holes such as quasars have masses of millions to billions of solar masses. They are ubiquitous in elliptical galaxies and galaxy bulges. Our own Milky Way hosts both stellar black holes and a nuclear supermassive black hole.

Why have no black holes with intermediate masses of hundreds to tens of thousands of solar masses been found to date? Such black holes are thought to be produced by primordial collapse in the early universe (*1*) and by the gravitational collapse of the cores of dense star clusters in galaxies (*2*). Some astronomers have suggested that ultraluminous x-ray sources (see the figures) (*3*) may be the elusive intermediate-mass black holes (*4*, *5*), but the evidence to date is inconclusive.

Ultraluminous x-ray sources are rare, pointlike x-ray sources found in galaxies farther away than our own Milky Way and its companion galaxy, Andromeda. Their x-ray luminosities are 10 to 1000 times the "Eddington luminosity" of a normal x-ray binary containing a neutron star; such binaries are the most common x-ray source in galaxies. (The Eddington luminosity is the maximum luminosity achievable by a black hole powered by accretion from a companion star.) Ultraluminous x-ray sources are thus exceptionally bright objects, which might be powered by accretion onto black holes with masses of a few hundred solar masses or more. They could represent the missing mass range in the black hole mass distribution. But do they?



An abundance of ultraluminous x-ray sources. In this Chandra image of the "Antennae," the 14 most luminous sources are ultraluminous x-ray sources.

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In the past few years, observations with NASA's Chandra x-ray observatory and the European Space Agency's XMM-Newton have greatly increased the number of known ultraluminous x-ray sources and have further elucidated their properties. The data have rekindled the debate on what these sources might be. The main alternative to intermediate-mass black holes is that they are normal black-hole x-ray binaries that only appear to exceed the Eddington luminosity because of direction-dependent (beamed) emission (*6*, *7*). It has also been suggested that the ultraluminous x-ray emission is caused by inhomogeneities in the accretion disk, which would allow the Eddington limit to be exceeded (*8*).

Although the intermediate-mass black hole hypothesis has not been disproved, it is not needed to explain most of the data. Stellar-evolution calculations can account for black holes as massive as 70 solar masses, placing the fainter ultraluminous x-ray sources in the realm of stellar black holes. Evolutionary calculations of x-ray binaries can also produce luminosities in the range observed for ultraluminous x-ray sources (*9*). Only the brightest ultraluminous x-ray sources cannot be explained by the Eddington emission of a stellar black hole.

Variations in the intensity and color of ultraluminous x-ray sources (*10*) are also consistent with x-ray binaries, but this behav-

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