QUANTUM PHYSICS

New spin on the Hall effect

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The spin Hall effect occurs when electrons with opposite spins go their separate ways in an electric field. The phenomenon is crucial to spin-based electronics, and its electrical signal has just been spotted.

Just as manipulating electron charge is central to conventional electronic circuitry, so creating, moving and measuring electron spin is essential to spin-based electronics, or spintronics. Page 176 of this issue, Valenzuela and Tinkham report a significant breakthrough in spin control, with the first detection by electrical means of the ‘spin Hall effect’ — the separation, or polarization, of electrons of opposite spin (up and down) under the influence of an electric field.

Normally, electron spins are polarized by magnetic fields. Electrons in so-called ferromagnetic materials (iron is the classic example) are naturally spin-polarized, so generating currents of spin in non-magnetic materials has typically involved careful engineering of ferromagnetic contacts that can act as a source of polarized electrons. Alternatively, in semiconductors, polarized laser light has been used to create spin polarization.

But in fact, spin currents may appear wherever there are conventional charge currents. This comes about through the interplay of an electron's spin and its direction of propagation, an effect known as the spin–orbit interaction. An electron moving forwards in an electric field experiences a magnetic field, with the result that the trajectories of spin-up and spin-down electrons are bent in different directions. A spin current and a spin imbalance are induced: this is the spin Hall effect.

So how can we detect this effect? In the conventional Hall effect, discovered in 1879 by Edwin Hall, positive and negative charges are separated by a transverse magnetic field, creating a voltage at right angles to the current flow. The Hall effect, however, does not naturally produce such an obvious electrical signal. Two research groups have detected the spin imbalance using optical methods. But an electrical signature would open new opportunities for the study and control of spin currents.

Valenzuela and Tinkham’s detection relies on the fact that, if a current is initially unpolarized as it flows through a sample of material, the spin–orbit interaction causes equal numbers of electrons to end up on each side, and no transverse voltage results (Fig. 1a). But if the current is initially spin-polarized, different numbers of electrons migrate to each side of the sample. In this case, a charge imbalance results — and so a voltage. Thus, the key to the successful electrical detection of the spin Hall effect is creating a spin current in an otherwise non-magnetic material.

In the case in hand, that material is aluminium. The authors use a set-up known as a tunnel junction, consisting of a ferromagnetic electrode from which electrons, polarized in the direction of the electrode’s magnetization, are injected into an aluminium strip through a thin intervening insulating layer. This injection of spin-polarized electrons creates a spin imbalance in the aluminium strip that must be counterbalanced by a flow of spins: a spin current is induced in an open circuit where no charge current is flowing (Fig. 1b). In this region, voltage contacts are laid out in a ‘Hall cross’ geometry, enabling measurement of a transverse voltage.

In the authors’ experimental geometry, the spins must have a component pointing at right angles to the plane of the strip for any effect to be observed. And indeed, when Valenzuela and Tinkham applied a magnetic field to force the magnetization of the ferromagnetic electrode into a perpendicular orientation, voltage contacts registered a transverse voltage that is the signature of the spin-Hall effect.

The voltage signal decayed exponentially with the distance between the tunnel junction and the Hall cross. That is an expected consequence of spin–orbit coupling: as spins precess around an axis that varies with the electrons’ direction of propagation, their initial polarization decays. Thus the spin current, and the resulting voltage, will diminish over a characteristic length, known as the spin diffusion length. Importantly, the authors find that the decay of the spin Hall voltage they measure is consistent with their independent measurements of the spin diffusion length.

The spin Hall voltage is small — of the order of 10 nV in this experiment, equivalent to a conductivity some 10^4 times smaller than values for conventional electrical conductivity. But it is easily measurable, as is the conventional Hall effect in metals. Soon after the discovery of that effect, an article in the popular press stated that ‘The new force is exceedingly feeble, so that we cannot predict any practical applications for it’. That author was not to know of the effect’s many uses in precision sensors for fluid flow, power and pressure in the era of integrated circuits, or in sensitive Hall magnetometers. The quantum-mechanical version of the Hall effect is now also used as the standard measure of resistance.

The spin Hall effect could be similarly useful. Now that electrical measurements of the effect are possible, we can expect to gain a deeper understanding of spin–orbit interactions in metals and semiconductors. Fundamental questions about the origin of the spin Hall effect that have generated considerable debate — such as whether the effect might be intrinsic, and so occur in pure materials, or whether it is always associated with impurities — can also be addressed. Furthermore, transverse voltages much larger than those in the aluminium strips used by Valenzuela and Tinkham should appear in semiconductor structures. Thus, the potential for generating and detecting spin currents electrically looks promising.

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Figure 1: Seeking the spin Hall effect. a. Charge current flows from left to right through a so-called Hall cross made from a conductor such as aluminium. Spin–orbit interactions will cause a separation of electron spins — the spin Hall effect. If the charge current is unpolarized (with equal numbers of spin-up and spin-down electrons), the spin imbalance does not induce a charge imbalance or transverse voltage at the Hall cross. b. If electrons polarized in the direction of magnetization M are injected from a ferromagnetic electrode while a circuit drives a charge current (I) to the left, a spin imbalance is created. This produces a spin current (I_s) without a charge current to the right of the electrode.

Spin–orbit interactions again separate spin-up and spin-down electrons, but now the numerical superiority of one spin type means that a transverse charge imbalance and a spin Hall voltage, \( V_{SH} \), are created. As the distance, \( L \), between the electrode and the Hall cross increases, the voltage signal decreases, allowing the decay length of spin currents (spin diffusion length) to be measured.
10. The Nation **44** (25 December 1879).