Spin–orbit coupling goes global

Viewpoint

Spin-orbit coupling goes global

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Editor's note. This Viewpoint relates to an article by Bychkov and Rashba (1984 *J. Phys. C: Solid State* **17** 6039) and was published as part of a series of Viewpoints celebrating 50 of the most influential papers published in the *Journal of Physics* series, which is celebrating its 50th anniversary.

There are such instances in the development of science when experiment becomes not only ripe to absorb concepts already existing in the theory but directly requires them. Such an instant happened in physics of two-dimensional (2D) systems in 1983 when two prominent experimental groups reported data indicating splitting of electron and hole energy bands by spin-orbit coupling (SOC) in GaAs heterostructures.[1,2] This is why the 1984 paper by Bychkov and Rashba[3] that appeared in response to these findings and described them from a unified standpoint attracted immediate attention inside the community and strongly influenced future developments in physics of heterostructures. Currently its impact goes far beyond this field. This 1984 paper is closely related to the papers of my group on wurtzite-type crystals published back around 1960.[4–6] It was also preceeded by a 1984 paper of the same authors that is currently featured in the "*Golden Archive*" of JETP Letters. I discuss below the principal concepts and the effect of the whole group of papers.

The basic requirements are uniaxial symmetry of the system and absence of inversion symmetry. They are satisfied for hexagonal wurtzite-type crystals and for heterostructures grown from cubic crystals due to the breaking of cubic symmetry by asymmetric confinement of 2D electrons. Whenever these conditions are fulfilled, SOC contributes to the electron Hamiltonian a term $H_R = \alpha(\boldsymbol{\sigma} \times \mathbf{k}) \cdot \hat{\mathbf{z}}$ known currently as the Rashba term. Here $\hat{\mathbf{z}}$ is the unit vector along the symmetry axis, $\mathbf{k}$ is a 2D momentum in the plane perpendicular to it, $\boldsymbol{\sigma}$ is the vector of Pauli matrices, and α is the strength of SOC. Because $\mathbf{k}$ enters into H_R linearly, in the lower order than into the kinetic energy $\hbar^2\mathbf{k}^2/2m$, topology of the energy spectrum changes. Instead of the parabolic spectrum with a minimum at $\mathbf{k} = 0$, there appear two $E(\mathbf{k})$ surfaces with a self-crossing conical (Dirac) point at $\mathbf{k} = 0$ and the minimum at a circle of the radius $k_0 = m\alpha/\hbar^2$. At small E, constant-energy surfaces are tori with a topological transition to spindle-tori at the Dirac-point energy when the orifice of the torus closes. The term H_R locks electron spin $\mathbf{s}$ to $\mathbf{k}$ as $\mathbf{s} \parallel (\mathbf{k} \times \hat{\mathbf{z}})$.

Equivalently, one can change $\mathbf{k} \to \mathbf{k} + k_0(\boldsymbol{\sigma} \times \hat{\mathbf{z}})$ in the traditional formula for kinetic energy. Comparing this $\mathbf{k}$ with the kinematic momentum $\mathbf{k}_{\rm kin} = \mathbf{k} - (e/\hbar c)\mathbf{A}$ shows that $(\boldsymbol{\sigma} \times \hat{\mathbf{z}})$ plays the role of a vector-potential $\mathbf{A}$ but with noncommuting components. Hence, the theory is non-Abelian. This property is manifested in the Aharonov-Casher effect.

Among the most prominent early results were also the electric dipole spin resonance (EDSR) and topological quantum phase transition in 3D in a magnetic field $\mathbf{B} \parallel \hat{\mathbf{z}}$. The first is strong electron-spin resonance driven by resonant electric field $\tilde{\mathbf{E}}(t)$ and the second is abrupt switching from paramagnetism to diamagnetism when Fermi level crosses the Dirac point. And an exotic Landau level falling out from the serial dependence is a progenitor of the zero-energy level in graphene. SOC causes beats in Shubnikov-de Haas and de Haas-van Alphen oscillations that allow measuring α. EDSR provided a clue to and initiated interest in electrical manipulation of electron spins, the focus of the current field of spintronics.

Precession of electron spins in the effective spin-orbit field $\mathbf{B}_{\rm so} \propto \alpha(\mathbf{k} \times \hat{\mathbf{z}})$ at a characteristic length $\ell_{\rm so} \approx \pi/k_0$ underlines the concept of the Datta-Das spin transistor. Their suggestion stimulated research on SOC in low-dimensional systems, in particular, in gate control of α, and emergence of spintronics as a branch of science and technology aimed in integrating electron spin into information processing.

SOC that originally played only marginal role in condensed matter physics is currently at its heart and penetrates all its branches including applications. Concepts and methods developed in condensed matter physics propagated already into other areas of physics and even beyond it. Recent developments based on SOC and influenced by Ref. [3] include but are not restricted by:

Topological insulators with insulating bulk and spin-momentum locked edge states,

Helical Tomonaga-Luttinger liquids,

Fast qubits driven by EDSR,

Spin transistor-class devices including their all-electric all-semiconductor versions,

Spin injection and spin interference,

Charge, spin, and heat transport in SOC media and photogalvanic effect,

Bulk spin polarization by current and spin-Hall effect, including its Quantum and Anomalous versions,

SOC torques in ferro- and antiferromagnetic memory devices, including SOC torque oscillators,

Josephson junctions with controlled-α barrier layers,

Noncentrosymmetric superconductors including spin-polarized supercurrents and Majorana fermions,

Superconductivity and magnetism of 2D electrons at high-α interfaces of $LaAlO_3/SrTiO_3$-type ceramics, including superconductor-to-insulator transition,

Kondo effect in SOC systems,

Giant-α compounds such as BiTeI, ferroelectric GeTe, multiferroics, organic-inorganic perovskites, and Pt nanowires with $\alpha \gtrsim 1\,{\rm eV\AA}$,

ARPES, SARPES, and STM study of the bulk, surface, and interfaces of high-atomic-number Z compounds and high-Z overlayers, including Fermi arcs and closed surfaces at terminations of Weyl semimetals,

Graphene-family few-layer high-Z compounds,

Ultra-cold Bose and Fermi gases with artificial SOC including BCS-to-Bose-Einstein condensate transition,

SOC and spin-polarized transport in biological systems due to their intrinsic chirality,

SOC of light in noncentrosymmetric metamaterials,

Generalized high-energy theories involving H_R-type terms.

Recent progress in some of the above fields is covered by review papers[7–9] and reported in Topical journal issues.[10,11]

In conclusion, SOC that played only a marginal role in solid state physics in 1959 when the Hamiltonian H_R has been originally derived[4] and even in 1984 when it was applied to heterostructures,[3] is currently at the heart of it. Moreover, research on SOC propagated widely to various areas of science, and H_R became the most popular model Hamiltonian of SOC. Spin-orbit is currently expected to become a cornerstone of future technologies.

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