

## SPIN-ORBIT COUPLING IN CONDENSED MATTER PHYSICS.

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The subject of our paper [1] with Yuri A. Bychkov is two-fold spin splitting of the band spectrum of two-dimensional charge carriers, electrons and holes, in asymmetric heterostructures, and manifestation of it in two independent experiments. Heterostructures are artificial crystals carefully grown as systems of layers of a few different semiconductors and engineered in such a way to achieve a desirable electron energy spectrum. Such structures were developed for semiconductor optoelectronics, in particular, semiconductor lasers beginning from 1960s. Electrons in them behave as nearly two-dimensional (2D). In early 1980s, two fundamentally new physical phenomena were discovered in 2D systems, the Integer and Fractional Quantum Hall Effects (IQHE and FQHE). These discoveries deeply influenced all following developments in the low-dimensional physics of semiconductors, transforming it from an applied to a fundamental field of research, and promoted qualitatively new theoretical concepts. IQHE demonstrated the first topological phase transition, and FQHE indicated that electron-electron interaction can produce exotic quasiparticles that carry fractional charges (fractions of the fundamental electron charge  $e$ ) and obey a fractional statistics (that differs from the textbook Fermi and Bose statistics).

I attribute the success of our paper to four factors. First, it stood at a firm theoretical ground. Second, it was timely. Third, it included interesting physics which had impact on the future developments. And, last but not the least, it was published in JETP Letters, with a follow-up paper [2] in J. Phys. C: Solid State Phys., two journals that were easily available and widely read then.

I begin with the second factor. Our paper was a fast response to two papers [3, 4] that were published one next to the other in the same issue of the Physical Review Letters and reported manifestation of spin-orbit (SO) coupling in spin and cyclotron resonances in two different 2D systems. It is worth mentioning that both papers came from prominent experimental groups, and Klaus von Klitzing and Horst Stormer who would become Nobel Laureates for the discovery of the IQHE and FQHE, respectively, were among the authors. In our paper, we proposed an unified approach for estimating SO coupling constants from both sets the experimental data. Our fast response was only possible because we were already

actively involved in physics of 2D systems for a couple of years.

Now I turn to the first factor that requires a more detailed explanation. Electrons possess charge and spin, and existence of spin follows from the relativistic Dirac theory. As a result, SO coupling is also a relativistic effect. Formally, it is weak in the fine structure constant  $\alpha_f = e^2/\hbar c \approx 1/137$ . But in crystals it is multiplied by the atomic number  $Z$ , and in the middle of the periodic system  $Z\alpha_f$  is not weak. Therefore, SO coupling essentially modifies the energy spectrum. In the late 1950s, we embarked with my student Valentin Sheka on finding energy spectrum of uniaxial non-centrosymmetric crystals of the CdS type by group-theoretical methods, and arrived at the relativistic part of the Hamiltonian

$$\hat{H}_{so} = \alpha(\boldsymbol{\sigma} \times \mathbf{k}) \cdot \boldsymbol{\nu}. \quad (1)$$

Here  $\alpha$  is a SO coupling constant,  $\boldsymbol{\sigma}$  is a vector of Pauli matrices,  $\mathbf{k} = \mathbf{p}/\hbar$  is the electron quasi-momentum, and  $\boldsymbol{\nu}$  is a unit vector directed along the symmetry axis. When added to a nonrelativistic Hamiltonian  $H_0 = \hbar^2 \mathbf{k}^2 / 2m$ ,  $\hat{H}_{so}$  splits the spin-degenerate spectrum into two branches. The lower branch reaches its minimum at a circle in the  $\mathbf{k}$ -space with a radius  $k_{so} = m\alpha/\hbar^2$  rather than in a single point, as distinct from all energy spectra known by then. The branches intersect, at the energy  $\epsilon = 0$ , in a conical point known as the Dirac point, and isoenergy surfaces are toroidal at  $\epsilon < 0$  and spherical at  $\epsilon > 0$ . We were excited by the result but unlucky with the paper. A short version of it was rejected by JETP as being of no general interest, and a full version was published by Solid State Physics (in 1959) in a "Collection of Papers" issue that has never been translated into English. Meantime, we found that the Hamiltonian  $\hat{H}_{so}$  has a dramatic effect on spin resonance [5] As distinct from the textbook concept, spin resonance of free electrons is predominantly excited by the electrical, rather than by magnetic, component of electromagnetic field, and under proper conditions this statement is also true for localized electrons. This prediction was initially met with scepticism, and my talk at the Landau Seminar was interrupted by Vitaly L. Ginzburg who exclaimed: "Because the final result is definitely wrong, there should be some error there". Landau' immediate response:

"Vitya, don't you see what kind of Hamiltonian he has?"settled the problem. Currently, this resonance is known as Electric Dipole Spin Resonance (EDSR); it was observed and investigated in numerous systems [6]. Therefore, using the Hamiltonian  $\hat{H}_{so}$  for describing SO coupling in asymmetrical heterostructures was well justified.

Illuminating the third factor is most challenging because of the multitude of directions in which spin physics developed during two last decades. The concept of spintronics is focused on applications and is based on the perception that the Si based electronics is approaching its fundamental limits. Spintronics relies on adding spin degree of freedom to charge based devices and electrical control of electron spin [7] The spin transistor proposed by Datta and Das is its paradigmatic device [8]. This interference device is based on spin precession in a SO coupled conductor connecting two ferromagnetic electrodes, and electric current across it is controlled by the gate-potential-dependent parameter  $\alpha$ . As a result of huge efforts, a proof of the principle InAs device has been recently demonstrated [9]. Modifications of it, as well as spin injection devices based on SO and Aharonov-Bohm controlled interference, have been also proposed. Creating perfect crystal surfaces covered by submonolayers of high- $Z$  elements allowed producing 2D electron gases with giant  $\alpha$ 's that were directly measured by the Spin Angular Resolved Photo-Emission Spectroscopy (SARPES). In Pt nanowires grown on Si substrate  $\alpha$  is of atomic scale,  $\alpha = 1.36$  eVÅ[10]. Such systems are considered as prospective candidates for creating spin devices with nanoscale interference lengths  $l_{so} \approx 1/k_{so}$ . Meantime, there was a remarkable progress in the magnetic memory technology based on the discovery of giant magnetoresistance celebrated by the Nobel Prizes for Albert Fert and Peter Grünberg. As a result, fast transport of magnetic domains by electric current rather than by mechanical motion emerged as an urgent problem, and the torques exerted onto domain walls by SO coupling of the  $\hat{H}_{so}$  type and the spin-Hall effect predicted by D'yakonov and Perel' [11] are considered as relevant mechanisms [12]. Recently, 2D electron gases with strong SO coupling were discovered in a new class of systems, conducting LaAlO<sub>3</sub>/SrTiO<sub>3</sub> interfaces separating two insulating ceramics [13]. These interfaces demonstrate coexistence of superconductivity and magnetism, and their exotic properties are ascribed to SO coupling; they are considered as candidates for new devices. One more field emerged due to the discovery of non-centrosymmetric superconductors. In them, SO coupling admixtures a triplet component to singlet Cooper pairs and in this way raises the Pauli limit for pair breaking by magnetic field [14]. Discovery of topological insulators, [15, 16] the substances with insulating bulk and topologically protected conducting channels at the surface, provided a powerful stimulus for growing

crystals with strong SO coupling, mostly from high- $Z$  compounds. Among them is BiTeI with  $\alpha = 3.85$  eVÅ. I admire experiments of the Tokyo group which managed, by moving the Fermi level  $\mu$  across the Dirac point, to observe a topological transition from toroidal to two spherical Fermi surfaces, and the related paramagnet-to-diamagnet phase transition [17]; we predicted it back in 1960 by analytical calculations [18]. A closely related subject are low-dimensional topological superconductors that host Majorana fermions: particles that constitute their own antiparticles and are prospective candidates for topologically protected quantum computation [19]. The simplest construction includes a low-dimensional semiconductor with a Hamiltonian  $\mathcal{H} = H_0 + \hat{H}_{so}$  that is a subject to a moderate magnetic field and turned into superconductor by the proximity effect [20]. It eliminates the Dirac point, creates a gap in the internal spectrum branch, and renders the system become "spinless" when  $\mu$  is inside the gap. While intensive search for Majoranas is underway, a number of currently available fast qubits (elements of prospective quantum computers) are driven by EDSR. And seemingly unrelated but conceptually closely connected systems are ultracold atoms in atomic traps with laser-produced artificial SO coupling [21]. High density of states near the spectrum bottom of the Hamiltonian  $\mathcal{H}$  results in enhanced attraction between particles, and experiments with atomic traps provide unique perspective onto the effect of strong SO coupling on the competition between the BCS (Bardeen, Cooper, Schrieffer) and BEC (Bose-Einstein condensate) mechanisms of the transition into superconducting state. Finally, I mention emergence of SO metamaterials for spin-controlled photonics [22]. They bridge spin physics of electrons and light.

In conclusion, physics of spin-orbit coupling penetrated into numerous branches of condensed matter physics and unified them into an extensive, interconnected, and exciting field including both fundamental problems and practical applications. I guess that our paper became successful because it was one of the first, and timely, steps of this journey.

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