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Condensed Matter Highlight

Spin-Hall effect: Back to the beginning at a higher level

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Abstract

The phenomena of the spin-Hall effect, initially proposed over three decades ago in the context of asymmetric Mott skew scattering, was revived recently by the proposal of a possible intrinsic spin-Hall effect originating from a strongly spin–orbit coupled band structures. This new proposal has generated an extensive debate and controversy over the past 2 years. On August 2006 the first workshop on the spin-Hall effect was held at the Asian Pacific Center for Theoretical Physics. Its purpose was to bring together many of the leading groups in this field to resolve such issues and identify future challenges. We offer this short summary to clarify formerly controversial issues now settled and help refocus the research efforts in new and important avenues.

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1. Introduction

The spin Hall effect (SHE) is the generation in a paramagnetic system of a spin current perpendicular to an applied charge current leading to spin accumulations with opposite magnetization at the each edges. This effect was first predicted over three decades ago by invoking the phenomenology of the earlier theories of the anomalous Hall effect in ferromagnets, which associated its origin with asymmetric Mott-skew and side-jump scattering from impurities due to spin–orbit coupling [1,2].

Recently, the possibility of an intrinsic (dependent only on the electronic structure) SHE has been put forward [3,4] predicting the presence of a spin current generated perpendicular to an applied electric field in semiconducting systems with strong spin–orbit coupling, with scattering playing a minor role. This proposal has generated an extensive theoretical debate in a very short time motivated by its novel physical concept and potential as a spin injection tool [5]. The interest has also been dramatically enhanced by recent experiments by two groups reporting the first observations of the SHE in n-doped semiconductors [6,7] and in 2D hole gases (2DHG) [8].

These experiments measure directly the spin accumulation induced at the edges of the examples through different optical techniques. On the other hand, most of the early theory has focused on the spin-current generated by an electric field, which would drive such spin-accumulation. In most studies this spin current and its associated conductivity has been defined as $j_y^z \equiv \{v_y, s_z\}/2 = \sigma^{\mathrm{SHE}} E_x$. This choice is a natural one but not a unique one in the presence of spin–orbit coupling since there is no continuity equation for spin density as is the case for charge density. The actual connection between the spin-accumulation and the induced spin-current is not straight forward in the situations where spin–orbit coupling is strong and this relation is the focus of current research and one of the key challenges ahead.

Although two model Hamiltonians with strong spin–orbit coupling have been considered initially, the p-doped 3D valence band system [3] and the 2DEG with Rashba coupling [4], the one that has attracted the most attention, perhaps due to its simplicity, is the latter one which has the form $H_{\mathrm{R-SO}} = \lambda(\sigma_x k_y - \sigma_y k_x)$. In such systems, in a clean sample, where the transport scattering rate τ^{-1} is small compared to the spin–orbit splitting $\lambda k_{\mathrm{F}}/\hbar$, one finds an intrinsic value $e/8\pi$ for the spin Hall conductivity, which is valid at finite frequencies in the range $\tau^{-1} < \omega < \lambda k_{\mathrm{F}}/\hbar$, independent of details of the

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impurity scattering, in the usual case where both spin–orbit split bands are occupied. The prediction for the dc spin Hall effect in this model has been examined and debated extensively. It was first noticed that contributions to the spin-current from impurity scattering, even in the limit of weak disorder, seemed to cancel exactly the intrinsic contribution [9,10]. This lead to speculation that this cancellation destroys the effect in other model as well. On the other hand, it is now understood through recent efforts, culminating in this workshop, that such cancellation only occurs for this very particular model, due to the linearity of the spin–orbit coupling and the parabolic band dispersion [11–13].

This motivates the title of this summary: after our initial excitement and our initial worries that such a beautiful effect may not exist, we are back to the original proposal but at a higher level of understanding: that an intrinsic contribution to the SHE is present in many systems with strong enough spin–orbit coupling [3,4]. This contribution is in addition to the usual extrinsic contribution predicted earlier and recently attributed to some of the experiments in n-doped systems [6,7] through theoretical treatments based on the related extrinsic contributions to the anomalous Hall effect [14,15]. What follows is a summary of the issues agreed upon and debated during the open discussion sessions of the workshop; it is not meant as a summary of all the topics presented in the workshop. Even though feedback from all the speakers in the workshop has been solicited in composing this summary, any ommisions or unnintentional unbalance is ultimately the responsability of the organizers. For further information on this workshop and to view the slides of the talks given and other topics discussed which are not mentioned here we encourage the reader to visit the workshop website [16].

2. Agreement and consensus

Within the open sessions of this workshop, several key points were discussed and agreement was reached on their conclusions. This is an important and intended result of this workshop, to bring together several of the leading researchers in the field to clarify the now extensive debate in the literature which can be overwhelming to a newcomer.

The agreed upon statements are as follows:

- The dc spin Hall conductivity, defined through $j_y^z \equiv \{v_y, s_z\}/2 = \sigma^{\mathrm{SHE}} E_x$, does not vanish in general and it includes both intrinsic and non-intrinsic contributions.
- The dc spin Hall conductivity for the model Hamiltonian, $\mathcal{H}_{\mathrm{R}} = \hbar^2 k^2/2m + \lambda(\sigma_x k_y - \sigma_y k_x)$, vanishes in the absence of a magnetic field and spin-dependent scattering, even in the limit of weak scattering. This cancellation is due to the particular relation in this model between the spin dynamics $\mathrm{d}S_y/\mathrm{d}t$ and the induced spin-Hall current, i.e. $\mathrm{d}s_y/\mathrm{d}t = i[\mathcal{H}_{\mathrm{R}}, s_y] \propto j_y^z$, which in a steady state situation indicates a vanishing spin-Hall current. No such relation exists in more complicated models, where the spin–orbit coupling is not simply linear in the carrier momentum.

The effects of disorder on the induced spin-current, within linear response, come in the form of self-energy lifetime corrections and vertex corrections. The life time corrections only reduce this induced current through a broadening of the bands without affecting its nature. On the other hand, vertex corrections have been the source of important debate since they make the intrinsic SHE vanish in the Rashba 2DEG system for any arbitrary amount of scattering [9,10,12]. For p-type doping in both 3D and 2D hole gases the vertex corrections vanish in the case of isotropic impurity scattering [17–20]. This result is now understood in the context of the specific relation of the spin-dynamics within this particular model as stated above [11,12]. This spin-dynamics are linked to the magneto-electric effect producing a homogeneous in-plane spin polarization by an electric field in a Rashba 2DEG [21,22]. These results have recently been found to be consistent with numerical treatments of the disorder through exact diagonalization finite size scaling calculations [23–25].

It is important to point out, however, that in the mesoscopic regime, where spin Hall conductance of finite size systems rather than conductivity of infinite size systems is considered and the finite width can lead to spin-Hall edge states [26], the SHE seems to also be present and robust against disorder even in the 2DEG Rashba system although its link to the bulk regime is still unclear [26–29].

3. Semantics

Given the extensive literature it was deemed useful to agree upon several definitions and notations in order not to create confusion due only to imprecise communication. With this in mind it was agreed that:

- The spin Hall effect is the antisymmetric spin accumulation in a finite width system driven by an applied electric field.
- The word intrinsic is reserved for the intrinsic contribution to the spin-current generated in the absence of scattering. This contribution can be calculated through the single bubble diagram within the diagrammatic technique and corresponds to the ac-limit of $\omega\tau \to \infty$ where scattering does not play a role. For example, the intrinsic spin Hall conductivity of the Rashba model is $e/(8\pi)$ and for the p-doped valence system it is $(e/6\pi^2)(k_{\mathrm{F}}^{h.h} - k_{\mathrm{F}}^{l.h.})(1 + \gamma_1/(2\gamma_2))$.

4. Future challenges

4.1. Theoretical

Although there is wide agreement within the theoretical community that a spin Hall effect similar in magnitude to the predicted intrinsic contribution should occur in p-doped and in mesoscopic samples, there are still many remaining challenges in order to fully understand this novel effect and related effects in spintronics in strongly spin–orbit coupled systems. At the top of the agenda seems to be a need to better understand the spin-accumulation induced by the spin-Hall effect at a more quantitative level and its relation to the spin-current generated. Some of the issues raised during these open session were:

- What is the effect of scattering on the induced spin-currents and spin coherence in a strongly spin–orbit coupled system in general and in specific model at a quantitative level (including the sign of the effect in the several experimental set-ups)?
- Can the spin-current density seemingly arising from the Fermi sea lead to spin-accumulation and/or spin transport?
- A clearer understanding of the different contributions and their scaling with respect to disorder (strength, types, range, etc.) to the induced spin current is needed.
- How does spin relax in relation to scattering and to the fact that spin is not a conserved quantity in the strongly spin–orbit coupled regime? How does spin relax near the baoundry?
- Is the effect more readily observable at mesoscopic scales and is there a relation between the mesoscopic and bulk regime?
- Are there other spin-current definitions which give a clearer picture and can be more readily connected to spin-accumulation?
- There is a need for a full theory of spin-accumulation (and detection) in strongly spin–orbit coupled systems.

These are some of the key issues and questions raised but not by all means the only ones that are being considered in current research. It is important to realize that besides the SHE, there is a plethora of effects, linked to spin-transport dynamics in semiconductors, which are important to understand in the context of strongly spin–orbit coupled systems. One in particular is the spin Coulomb drag [30], which is an intrinsic friction mechanism between opposite spin populations studied in non-spin–orbit coupled systems, and is important in degenerate systems where electron–electron interactions are relevant.

4.2. Experimental

On of the clear achievements of spintronics in recent years has been the experimental observation of this novel effect through optical means. Spin transport in spin–orbit coupled systems is governed by characteristic length scales (mean free path, $l=v_F\tau$, spin precession length $l_{so}=\hbar v_F/\Delta_{so}$), time scales (lifetime, τ, spin coherence time, τ_s) and by the relative strength of spin–orbit coupling, Δ_{so} and disorder. From these scales it is generally believed that the SHE observed by Awschalom et al. [6] is in the extrinsic regime, attributed to Mott-scattering mechanisms [14,15], and the one observed by Wunderlich et al. [8] in 2DHG is in the intrinsic regime.

Some of the experimental issues raised during the open discussion session were:

- A key remaining experimental challenge is the detection of the effect through electrical means, which could lead to actual useful devices. This detection has to be done in coordination with careful realistic theoretical modeling of particular devices.
- It is important to understand and model in further detail the effects of edge electric field induced spin-polarization vs. the spin-Hall effect, and the angle dependence of the luminescence induced in the present set-ups and their relation to the spin magnetization.
- Is it possible to measure spin current in the bulk; i.e. not indirectly through spin accumulation?

5. Outlook

The past 2 years have seen a tremendous amount of research achievement and advances in the area of spintronics which continuous to generate many novel ideas and phenomena. Besides a good and healthy competitiveness, it has been a field (as it is demonstrated by organizing this conference) which moves forward in unison to clarify debates rather than allow them to linger for many years, helping it to move forward to explore interesting new physics.

As illustrated by the topics debated throughout the workshop, there are many remaining challenges and a very healthy outlook of the field, and not just simply of the spin-Hall effect which is a very small part of the whole semiconductor spintronics field.

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Appendix A: Workshop Participants

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