Where have I been? where am I now? where am I going?

"Universal" intrinsic spin-Hall effect: the strange story of the anomalous Hall effect and its new trick in spintronics.

Jairo Sinova
TAMU
October 15th 2003
WHERE HAVE I BEEN?

- QHE: flatland of electrons in a magnetic field (Skyrmions, IQHE, disorder)
- Spin Glasses: to RSB or not RSB, that was my question.
- Superconductivity in organic transistors: yes, the fraud thing!
The report of the death of QHE has been greatly exaggerated.

- Excitation gap; too low: LL mixing, finite width, disorder, dynamical screening, etc.
- Polarization issue: role of disorder on plateaus near \( n=1 \), Skyrmion localization?
- What type of disorder (source) is most relevant?

PRB 62, 13579 (00); PRB 61, 2749 (00); PRB 62, 2008 (00); PRL 87, 046901 (01)
Excitonic condensate/ easy-plane ferromagnet/ composite bosons condensate

**Superfluid current:** dissipationless counter propagating current in each layer cancels drag current

\[ I_T = 0 \]

\[ I_B = I_{QP} + I_{SF} \]

Need to understand the effects of disorder on current carrying states: the vortex formation and critical current

\( \nu = 1, \quad Q_lB = 0.838, \quad V_0 / (e^2/\varepsilon l_B) = 3.0, \quad N_\Phi = 36, \quad \text{Symmetric Disorder} \)

\( d/l_B = 0.5 \)
SPIN GLASSES: to RSB or not to RSB, that was my main question

Nature of Ergodicity Breaking in Ising Spin Glasses as Revealed by Correlation Function Spectral Properties

Jairo Sinova,1,2 Geoff Canright,1,2 and A. H. MacDonald2
1Department of Physics, University of Tennessee, Knoxville, Tennessee 37996
2Department of Physics, Indiana University, Bloomington, Indiana 47405
(Received 24 May 2000)

In this Letter we address the nature of broken ergodicity in the low temperature phase of Ising spin glasses by examining spectral properties of spin correlation functions \( C_{ij} \equiv \langle S_i S_j \rangle \). We argue that more than one extensive [i.e., \( O(N) \)] eigenvalue in this matrix signals replica symmetry breaking. Monte Carlo simulations of the infinite-range Ising spin-glass model, above and below the Almeida-Thouless line, support this conclusion. Exchange Monte Carlo simulations for the short-range model in four dimensions find a single extensive eigenvalue and a large subdominant eigenvalue consistent with droplet model expectations.

Questions: how to distinguish between RSB and RS scenarios

Analogy between ODLRO in QM and spin correlation function
• Emerging serious field of electronics (many funding possibilities and inter-field collaborations)
• Need to understand transport and optical limits
• A large number of experiments but not in depth
• Physical effects dominated by collective behavior in new generation devices
• Current theory is behind advanced and more experimentally testable predictions

J. Sinova et al, PRL 87, 226802 (2001)
MAIN INTEREST: COLLECTIVE EFFECTS IN INTERACTING SYSTEMS AND NOVEL SPIN TRANSPORT EFFECTS

- Study of broken symmetry states, collective effects, and phase transitions in strongly correlated systems: SC, ferromagnetism, QHE, ...
- Transport (charge and spin) and optical properties of interacting electron systems.
- Focus on manmade materials: reduced dimensionality, nanostructures, spintronics, material engineering.

Where am I now and where am I going?
CURRENT PROGRAMS

- Diluted Magnetic Semiconductors (30%): well established effort, many things to do
- Spin Hall Effect and anomalous Hall effect (30%): recently started but very promising
- Rotating BECs (15%): connecting AMO with CM
DMS Ferromagnetism: a spintronics tango

- Analogy with (II,Mn)VI
diluted magnetic semiconductors

Tomasz Dietl et al.: (Phys. Rev. B ’97)

Hole-mediated ferromagnetism

Mn is an acceptor in (III,Mn)V
DMS Ferromagnetism: I

**Mn = Local Moments + Holes**

FERROMAGNETISM MEDIATED BY THE CARRIERS!!!

\[ J_{pd} \sum_I S_I \cdot s(R_I) \]
Ga$_{1-x}$Mn$_x$As

As anti-site defect: $Q=+2e$

Substitutional Mn: acceptor + Local 5/2 moment

Interstitial Mn: double donor

Low Temperature - MBE

Ferromagnetic: $x=1-8\%$
courtesy of D. Basov
MBE Growth of (III,Mn)V Semiconductors


Mn provides localized spin (S=5/2) and hole
1. One could solve the full many body S.E.: not possible AND not fun

2. Combining phenomenological models (low degrees of freedom) and approximations while checking against experiments

“This is the art of condensed matter science, an intricate tango between theory and experiment whose conclusion can only be guessed at while the dance is in progress”

Quantitative success of the effective Hamiltonian (MF) and weak scattering theories (no free parameters)

- Ferromagnetic transition temperature ✓
- Magneto-crystalline anisotropy and coercivity ✓
- Domain structure ✓
- Anisotropic magneto电阻ance ✓
- Anomalous Hall effect ✓
- MCD in the visible range ✓
- Non-Drude peak in longitudinal ac-conductivity ✓
- Ferromagnetic resonance ✓

- Infrared and visible range magneto-optics
- Heterostructures and multilayers (spin-transfer, TMR, etc.)
- . . .

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It IS true that *it takes two to tango*.

**BUT it takes MANY to do the spintronics tango!!**

TAMU, U Texas, Nottingham, Prague, SIU, Berlin, Tokyo, UCSB, UCSD, Buffalo, Penn State, U Maryland, Rice, Poland, Madrid, Indiana U, Karlsruhe, ...
Quantum Melting and Absence of Bose-Einstein Condensation in Two-Dimensional Vortex Matter

Jairo Sinova,1 C. B. Hanna,2 and A. H. MacDonald1
1Department of Physics, University of Texas, Austin, Texas 78712-1081
2Department of Physics, Boise State University, Boise, Idaho 83725-1570
(Received 29 December 2001; published 28 June 2002)

We demonstrate that quantum fluctuations suppress Bose-Einstein condensation of quasi-two-dimensional bosons in a rapidly rotating trap. Our conclusions rest in part on the derivation of an exact expression for the boson action in terms of vortex position coordinates, and in part on a solution of the weakly interacting boson Bogoliubov equations, which simplify in the rapid-rotation limit. We obtain analytic expressions for the collective-excitation dispersion, which is quadratic rather than linear. Our estimates for the boson filling factor at which the vortex lattice melts are consistent with recent exact-diagonalization calculations.

Measuring the Condensate Fraction of Rapidly Rotating Trapped Boson Systems: Off-Diagonal Order from the Density Profile

Jairo Sinova,\textsuperscript{1} C. B. Hanna,\textsuperscript{2} and A. H. MacDonald\textsuperscript{1}
\textsuperscript{1}Department of Physics, University of Texas at Austin, Austin, Texas 78712-1081
\textsuperscript{2}Department of Physics, Boise State University, Boise, Idaho 83725-1570
(Received 16 September 2002; published 24 March 2003)

We demonstrate a direct connection between the density profile of a system of ultracold trapped bosonic particles in the rapid-rotation limit and its condensate fraction. This connection can be used to probe the crossover from condensed vortex-lattice states to uncondensed quantum-fluid states that occur in rapidly rotating boson systems as the particle density decreases or the rotation frequency increases. We illustrate our proposal with a series of examples, including ones based on models of realistic finite trap systems, and comment on its application to freely expanding boson density profile measurements.
“UNIVERSAL” INTRISIC SPIN HALL EFFECT: the strange story of the anomalous Hall effect and its new trick in spintronics

Jairo Sinova, Nikolai Sinitsyn, Ewelina Hankeiwcz, Winfried Tiezer, Tomas Jungwirth, Allan H. MacDonald, Qian Niu, Dimitri Culcer

Texas A&M University
Oct. 15th 2003

References (TAMU et al): Sinova et al cond-mat/0307663, Culcer et al con-mat/0309445, Sinitsyn et al cond-mat/0310315

Other references: Murakami et al Science 301, 1248 (2003), cond-mat/0310005, Jiangping Hu et al cond-mat/0310093, Schliemann et al cond-mat/0310108
1879: Edwin Hall discovers the Hall effect. By driving a current through a metal in a magnetic field there is a voltage perpendicular to the current.

\[ \rho_{xy} = R_0 B \]

Ordinary and anomalous Hall effect.

But in many ferromagnets:

\[ \rho_{xy} = R_0 B + 4\pi R_s M \]
Spin-orbit coupling interaction

Ingredients:
- “Impurity” potential $V(r)$
- Motion of an electron

Produces an electric field

$$\vec{E} = -\left(\frac{1}{e}\right)\nabla V(r)$$

In the rest frame of an electron the electric field generates and effective magnetic field

$$\vec{B}_{\text{eff}} = -\left(\frac{\hbar}{cm}\right) \times \vec{E}$$

This gives an effective interaction with the electron’s magnetic moment

$$H_{so} = -\mu \cdot B_{\text{eff}} = -\left(\frac{e\vec{S}}{mc}\right) \cdot \left[ \frac{\hbar}{mc} \times \vec{r} \left(\frac{1}{er} \frac{dV(r)}{dr}\right) \right] = \alpha \vec{S} \cdot \vec{L}$$

CONSEQUENCES

- If part of the full Hamiltonian quantization axis of the spin now depends on the momentum of the electron!!
- If treated as scattering the electron gets scattered to the left or to the right depending on its spin!!
The troubled history of anomalous Hall effect: side jump, skew scattering, no AHE in pure crystals, . . . .

Basic idea OK: scattering from impurities with SO coupling gives a Hall contribution

In ferromagnet $n_{↑} > n_{↓} \Rightarrow$ charge imbalance across sample

- Original study by Luttinger and Karpulus: scattering of Bloch electrons
- Smit questions their result: introduces skew scattering, claims $R_s=0$ for periodic lattice ($R_s \sim \rho$)
- Berger introduces yet another type of scattering: side jump ($R_s \sim \rho^2$)
Recently it was realized that in ferromagnetic systems where SO coupling is intrinsic and strong the Kubo formalism in the weak scattering limit and a semiclassical (but correct) treatment of Bloch wave-packet dynamics captures a nonzero anomalous Hall conductivity of

\[ \text{Re}[\sigma_{xy}] = -\frac{e^2\hbar}{V} \sum_{\vec{k} \ n \neq n'} \left( f_{n'\vec{k}} - f_{n\vec{k}} \right) \frac{\text{Im} \left[ \langle n'\vec{k} | \hat{v}_x | n\vec{k} \rangle \langle n\vec{k} | \hat{v}_y | n'\vec{k} \rangle \right]}{(E_{n\vec{k}} - E_{n'\vec{k}})^2} \]

ANOMALOUS HALL EFFECT

AHE without disorder!!

anomalous velocity:

$$\dot{x}_c = \frac{\partial \epsilon}{\hbar \partial k_x} + \left(\frac{e}{\hbar}\right) \mathbf{E} \times \hat{\Omega}.$$

Berry curvature:

$$\Omega_z = 2 \text{Im} \left[ \left\langle \frac{\partial u}{\partial k_y} \left| \frac{\partial u}{\partial k_x} \right\rangle \right. \right].$$

$$\sigma_{AH} = -\frac{e^2}{\hbar} \sum_n \int \frac{d\vec{k}}{(2\pi)^3} f_{n,\vec{k}} \Omega_z(n, \vec{k}),$$

ANOMALOUS HALL EFFECT WITH DISORDER

Experiments

Clean limit theory

Minimal disorder theory
Carriers with same charge but opposite spin are deflected by the spin-orbit coupling to opposite sides.

Spin imbalance perpendicular to current

Refs: Dyakonov and Perel (71), J. E. Hirsch (99), S. Zhang (00)

Experimental effort: WINFRIED TEIZER!!!
Let's try with a simple model: Rashba SO coupling in a 2DEGs

But just as there is an intrinsic AHE there should be an intrinsic spin-Hall effect!!!
2DEG+Rashba SO coupling

\[ H_k = \frac{\hbar^2 k^2}{2m} \sigma_0 + \lambda (k_x \sigma_y - k_y \sigma_x) = \frac{\hbar^2 k^2}{2m} \sigma_0 + \lambda \vec{\sigma} \times \vec{k} \]

Inversion symmetry \(\Rightarrow\) no R-SO

Broken inversion symmetry \(\Rightarrow\) R-SO

Bychkov and Rashba (1984)
A heuristic argument of how it works

\[ \mathbf{E} = \mathbf{E}_x \hat{x} \]

\[ \begin{align*}
\text{t=0} & \quad \text{p}_z \\
\text{t=t}_0 & \quad \text{p}_z
\end{align*} \]
‘Universal’ spin-Hall conductivity

\[ \sigma_{xy}^{sH} = \frac{e\hbar}{mV} \sum_{k,n \neq n'} \left( f_{n',k} - f_{n,k} \right) \times \frac{\text{Im}\left[ \langle n'k|\hat{j}_{\text{spin}}^z|nk\rangle \langle nk|\hat{p}_y|n'k\rangle \right]}{(E_{nk} - E_{n'k})^2} \]

\[ \hat{j}_{\text{spin}}^z = \frac{\hbar}{4} \{ \tau_z, \vec{v} \}, \quad \hbar\vec{v} = \hbar\partial H(k)/\partial \vec{p} \]

For most systems one is always in the universal value regime
SOME LAST THOUGHTS/CONCLUSIONS

- Other work not talked about: generalization to the semiclassical formalism (cond-mat/0309475), Rashba+Dresselhaus spin-Hall effect (cond-mat/0310315)
- Address issues with the boundary conditions and specific system calculation.
- Is the current being considered from a conserved quantity.
- R+ linear D+ cubic D generalization.