

Transport signatures of Dirac states in topological insulator - ferromagnet heterostructures

HILARY M. HURST

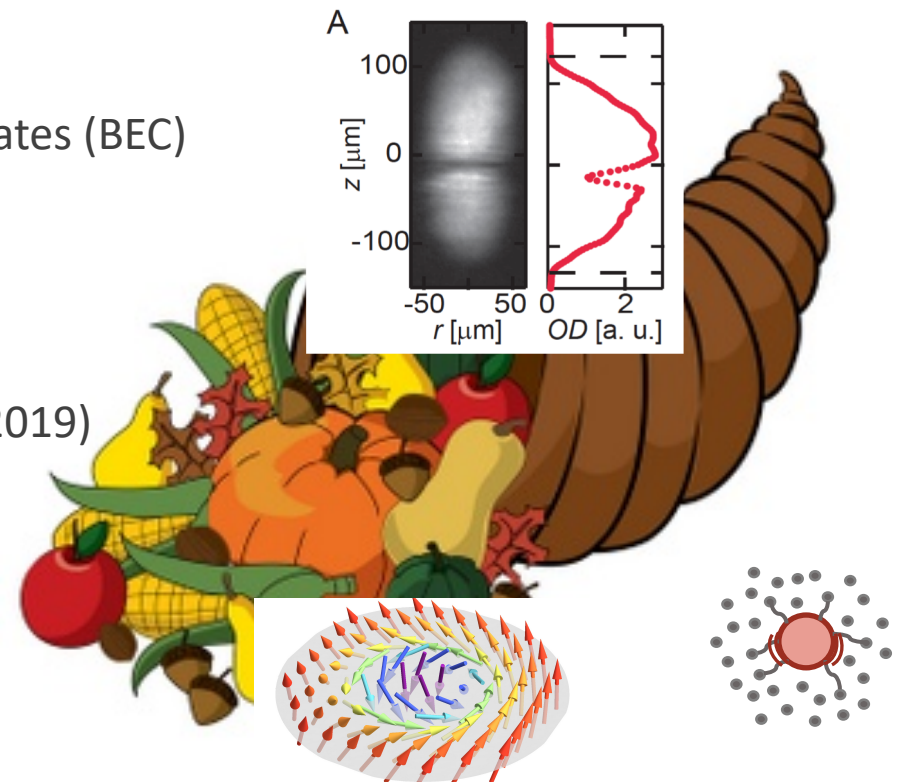
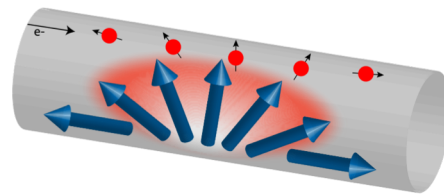
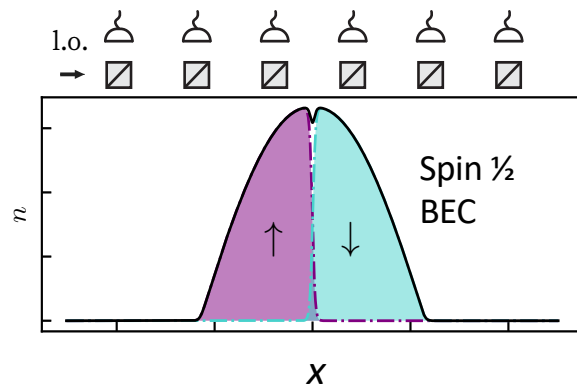
KITP: SPIN AND HEAT TRANSPORT IN QUANTUM AND TOPOLOGICAL MATERIALS

NOVEMBER 27, 2019



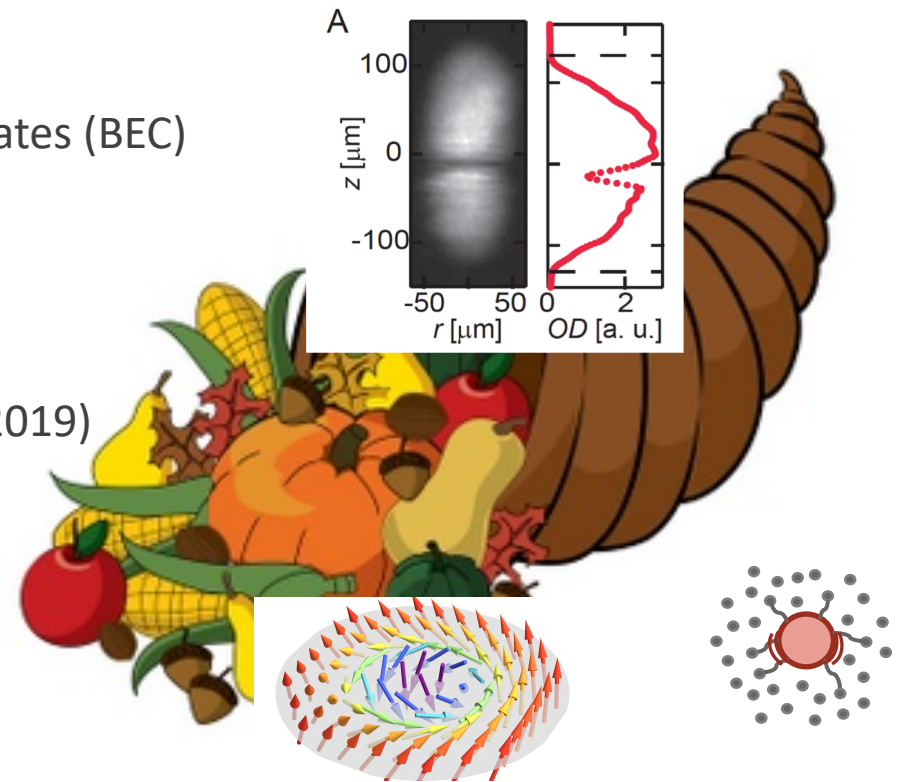
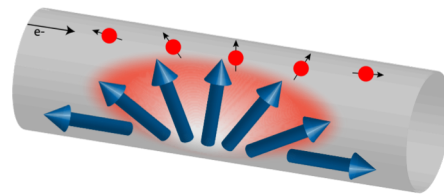
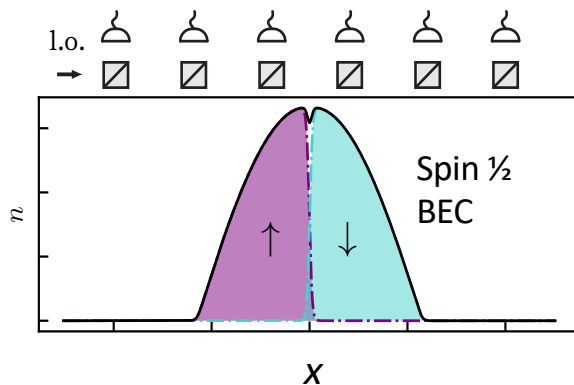
My Research: A Cornucopia of Topological Defects

- magnetic textures interacting with Dirac surface states
 - XY model vortices: PRB, **93**, 245111, (2016)
 - skyrmions: PRB, **91**, 060401(R), (2015)
- Brownian dynamics of dark solitons in Bose-Einstein condensates (BEC)
 - L. M. Aycok, HMH, et al PNAS, **114**, 2503-2508, (2017).
 - PRA, **95**, 053604, (2017).
- stochastic domain wall dynamics
 - in magnetic nanowires: arXiv:1908.02299
 - in BEC subject to weak measurement: PRA **99**, 053612 (2019)



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NATIONAL PHYSICAL SCIENCE CONSORTIUM



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Dmitry Efimkin

UMD →
UT Austin →
Monash U

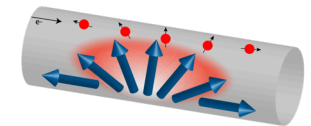


Victor Galitski
JQI / UMD

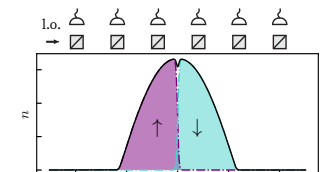
Other collaborators:



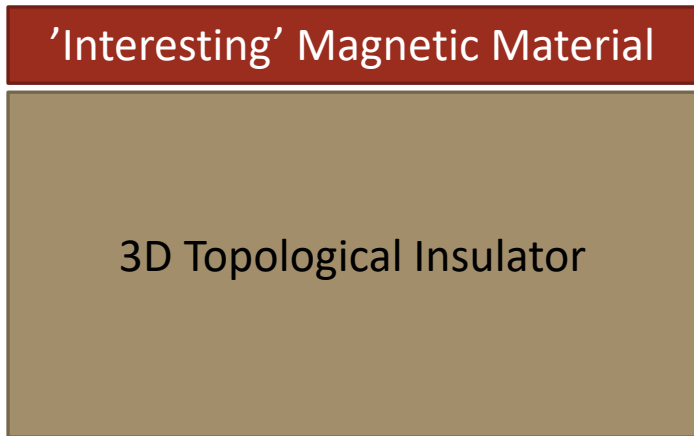
Tero Heikkilä – JYU (Finland)



Ian Spielman – NIST, JQI



Magnetic Patterning on 3D Topological Insulators



Clean interface exchange model

$$\mathcal{H} = v_F [(\mathbf{p} - e\mathbf{A}) \times \boldsymbol{\sigma}]_{\hat{z}} - \Delta \mathbf{m}(\mathbf{r}) \cdot \boldsymbol{\sigma} - g\mu_b B \sigma^z - \mu$$

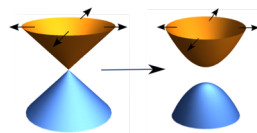
External magnetic field

Spatially dependent magnetization in top layer

$$\mathcal{H} = v_F [(\mathbf{p} - e\mathbf{A} - e\mathbf{a}(\mathbf{r})) \times \boldsymbol{\sigma}]_{\hat{z}} - (\Delta m_z(\mathbf{r}) + g\mu_b B) \sigma^z - \mu$$

Out-of-Plane Magnetization

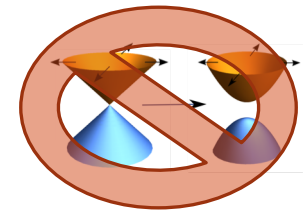
- acts as an effective mass
- leads to gap-opening on TI surface
- interesting physical effects: AQHE, magnetic confinement, etc.



In-Plane Magnetization

- acts as an effective gauge field
- no gap opening*

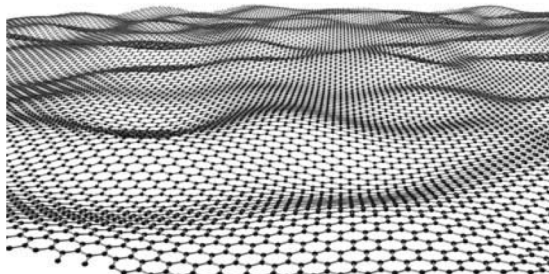
$$\mathbf{a}(\mathbf{r}) = \frac{\Delta}{ev_F} [\mathbf{m}(\mathbf{r}) \times \hat{z}]$$



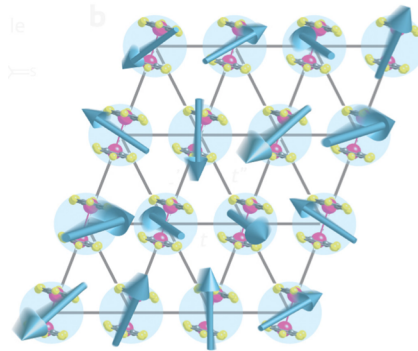
Model I: In-Plane Magnetization Only

$$\mathcal{H} = v_F [(\mathbf{p} - e\mathbf{a}(\mathbf{r})) \times \boldsymbol{\sigma}]_{\hat{z}} - \mu$$

$$\mathbf{a}(\mathbf{r}) = \frac{\Delta}{ev_F} [\mathbf{m}(\mathbf{r}) \times \hat{z}] \quad \Delta \ll \mu$$



Ripples in Graphene



Spin Liquids

Consider a 2D magnetic system with the following properties:

$$\langle \mathbf{m}(\mathbf{r}) \rangle = 0$$

$$\langle m_\alpha(\mathbf{r}_1) m_\beta(\mathbf{r}_2) \rangle = \Lambda^{\alpha\beta} f(\mathbf{r}_1 - \mathbf{r}_2)$$

$$\mathcal{H}_{\text{int}} \sim \Delta^2 s^\alpha(\mathbf{r}_1) \langle m_\alpha(\mathbf{r}_1) m_\beta(\mathbf{r}_2) \rangle s^\beta(\mathbf{r}_2)$$

$$s^\alpha(\mathbf{r}_1) = \psi_{\mathbf{r}_1}^\dagger \sigma^\alpha \psi_{\mathbf{r}_1}$$

magnetic correlations: proxy for static or dynamical gauge field disorder

tunable magnetic properties = tabletop realization of Dirac models with tunable vector disorder

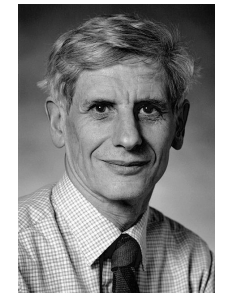
2D Magnetic XY-model



V. Berezinskii



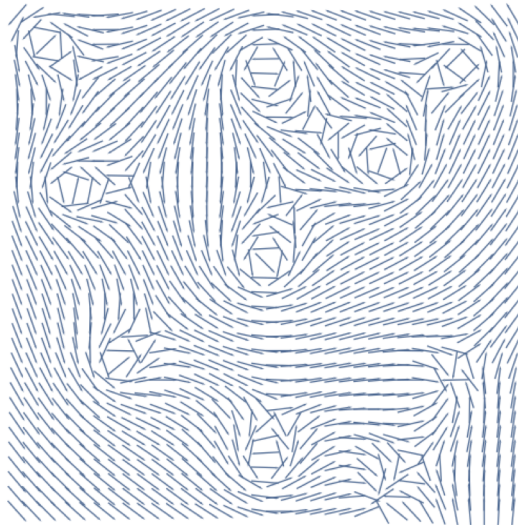
J. M. Kosterlitz



D. Thouless

No net magnetization at finite temperature

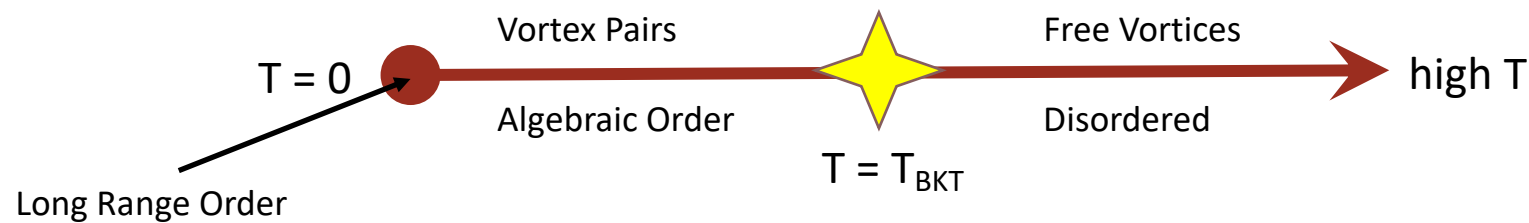
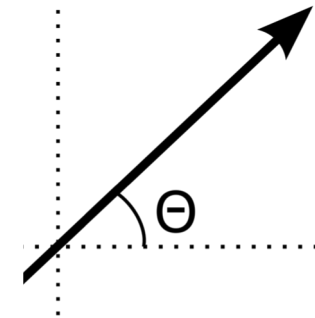
$$\langle \mathbf{m}(\mathbf{r}) \rangle = 0$$



$$\mathbf{m}(\mathbf{r}) = \{ \cos \Theta(\mathbf{r}), \sin \Theta(\mathbf{r}) \}$$

$$\mathcal{H}_{XY} = \frac{\rho_s}{2} \int d\mathbf{r} (\nabla \Theta)^2$$

$$\Theta = \Theta + 2\pi$$



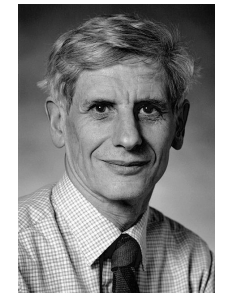
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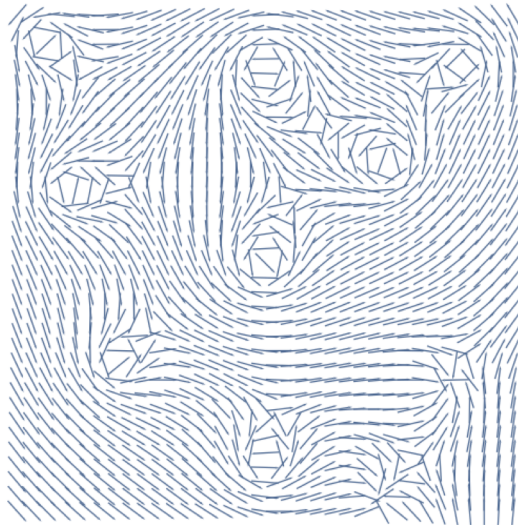
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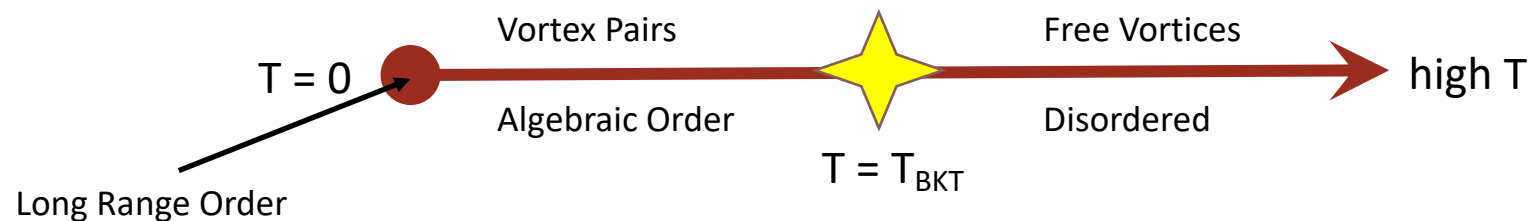
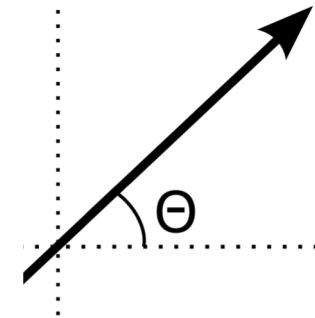
$$\langle \mathbf{m}(\mathbf{r}) \rangle = 0$$



$$\langle m(\mathbf{r})m(0) \rangle \sim \left(\frac{|\mathbf{r}|}{a} \right)^{\eta(T)} ; T < T_{\text{BKT}}$$

$$\langle m(\mathbf{r})m(0) \rangle \sim e^{-r/\xi_0} ; T > T_{\text{BKT}}$$

$$\eta(T) = \frac{T}{4T_{\text{BKT}}}$$

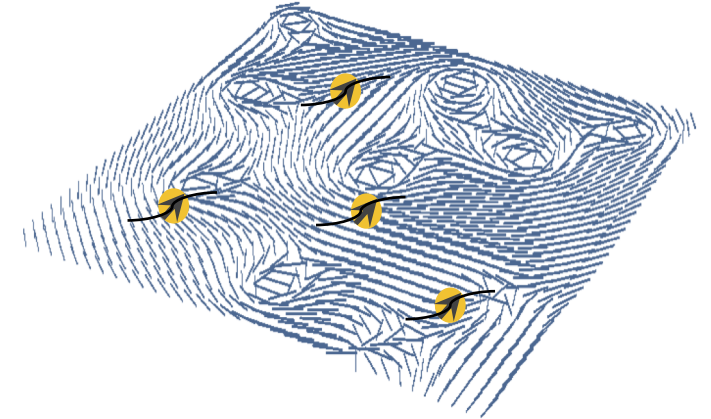


Surface States Coupled to XY-Model

$$\mathcal{H} = v_F [(\mathbf{p} - e\mathbf{a}(\mathbf{r})) \times \boldsymbol{\sigma}]_{\hat{z}} - \mu \quad \mathbf{a}(\mathbf{r}) = \frac{\Delta}{ev_F}(m_y, -m_x)$$

$$\text{Effective electric field: } E = -\partial_t \mathbf{a}^l = -\frac{\Delta}{v_F} \partial_t \mathbf{m}^t \rightarrow 0 \quad (\text{static magnet})$$

$$\text{Effective magnetic field: } B_z = [\nabla \times \mathbf{a}^t]_{\hat{z}} = \nabla \cdot \mathbf{m}^l$$

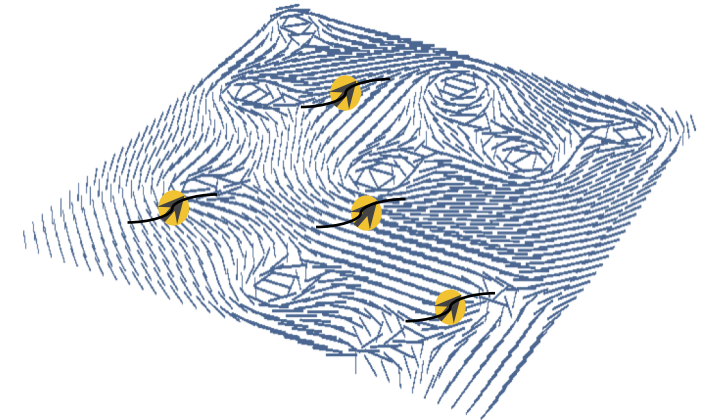


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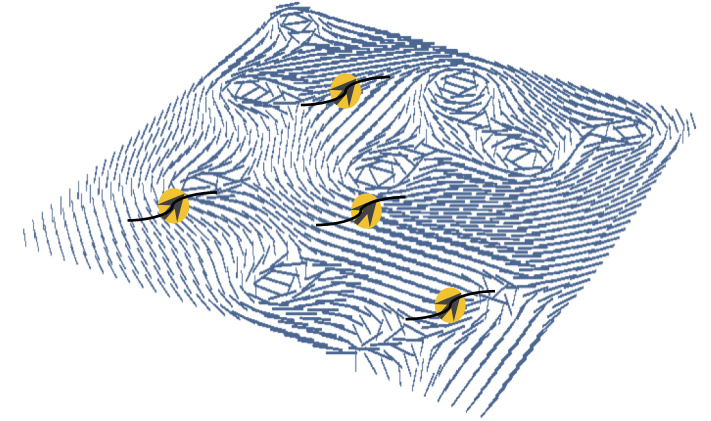
Magnetic field generated by vortices is nonlocal and leads to random magnetic field (RMF) $B_z^v(\mathbf{r}) \propto \sum_i q_i \frac{\cos(\Theta_i)}{|\mathbf{r} - \mathbf{r}_i|}$

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Effective interaction between fermions:

$$V_0^{\alpha\beta}(\mathbf{q}) = -\Delta^2 \langle m_\alpha^l(\mathbf{q}) m_\beta^l(-\mathbf{q}) \rangle = V_0(\mathbf{q}) \Lambda_{\mathbf{q}}^{\alpha\beta} \quad V_0(\mathbf{q}) = -\frac{v_F^2}{q^2} \langle B_z(\mathbf{q}) B_z(-\mathbf{q}) \rangle \quad ; \quad \Lambda_{\mathbf{q}}^{\alpha\beta} = \frac{q_\alpha q_\beta}{q^2}$$

Effect of RMF on Electron Transport

Perturbative disorder regime $\Delta, \gamma \ll \mu$

Two experimental knobs

- temperature tunes the **range** of disorder
- doping tunes disorder **strength**

$$\rho = \frac{h}{e^2} \frac{2\hbar}{\mu\tau_{\text{tr}}}$$

$$\tau_{\text{tr}}^{-1} \propto \int_q |V_0(\mathbf{q})| f(\varphi_{\mathbf{q}}) \delta(\xi_{\mathbf{p}-\mathbf{q}} - \xi_{\mathbf{p}})$$

$$V_0(\mathbf{q}) \sim \frac{1}{(q^2 + 1/\xi_0^2)^{1-\eta(T)/2}} \quad T > T_{\text{BKT}}$$

$$V_0(\mathbf{q}) \sim \frac{1}{q^{2-\eta(T)}} \quad T < T_{\text{BKT}}$$

strong temperature dependence

unscreened interaction below BKT transition temperature

*can be regularized by including band curvature

Effect of RMF on Electron Transport

Resistivity Peak at T_{BKT}

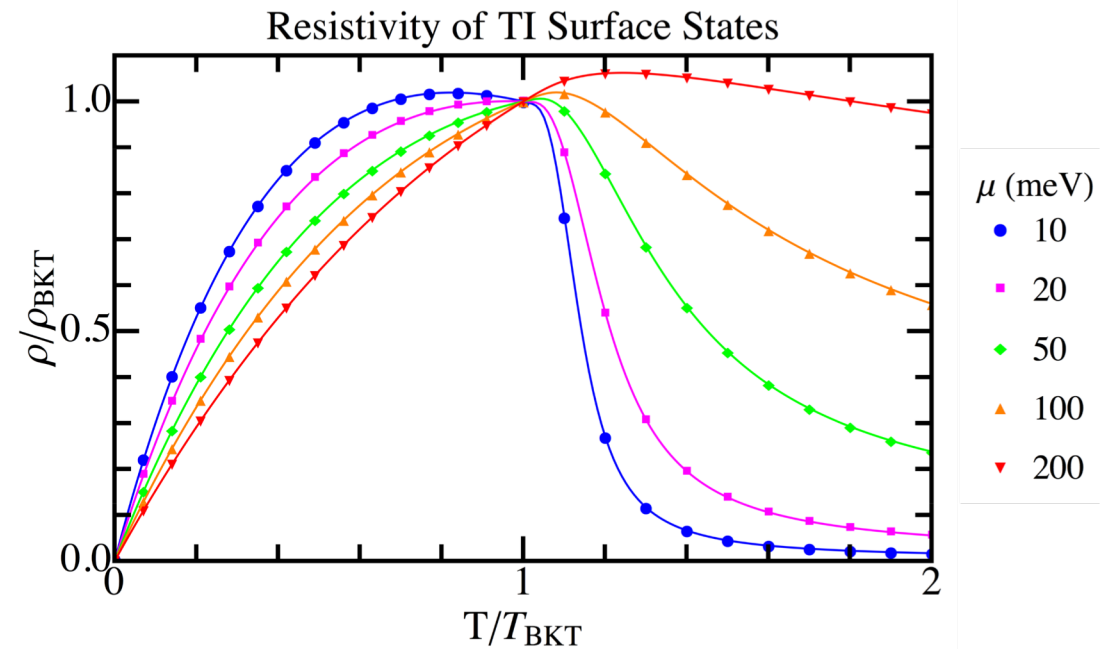
Linear scaling of resistivity with temperature

- manifestation of RMF physics
- distinguishable from other scattering

$$\rho(T \rightarrow 0) \sim f_{1,\mu} T$$

$$\rho(T \rightarrow T^-) \sim f_{2,\mu}(T - T_{\text{BKT}})$$

$$\rho(T \rightarrow T_+) \sim f_{3,\mu}(T - T_{\text{BKT}})$$



Effect of RMF on Electron Transport

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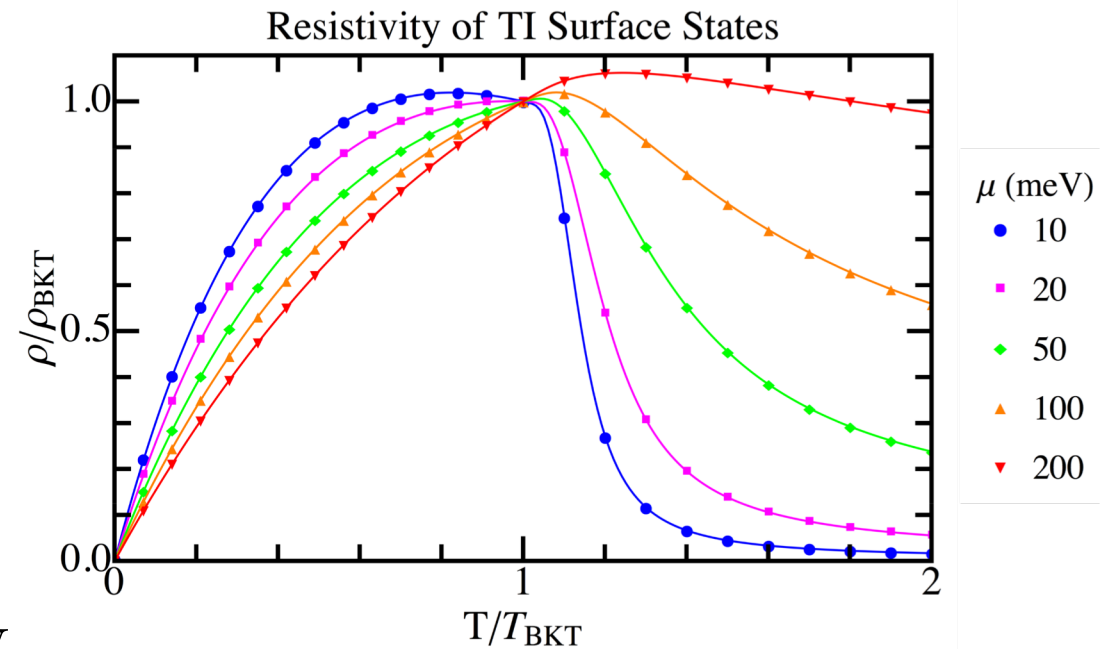
$$\rho(T \rightarrow T^-) \sim f_{2,\mu}(T - T_{\text{BKT}})$$

$$\rho(T \rightarrow T_+) \sim f_{3,\mu}(T - T_{\text{BKT}})$$

“Real” numbers:

$$\mu \approx 50 \text{ meV} \quad \Delta \approx 10 \text{ meV}$$

$$\rho_{\text{BKT}} \approx 1.8 \text{ k}\Omega$$



Conclusions I

PRB, **93**, 245111, (2016)

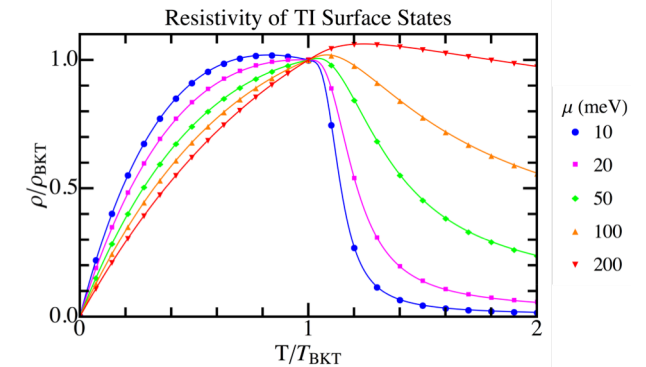
TI + magnetic material heterostructures offer opportunity to study fermion-gauge field models

- need TI property of spin-momentum locking
- simple mapping from magnetization to gauge field, but broken in presence of band curvature

Signatures of the RMF can be seen in transport for 3 disorder regimes

- (near) long-range disorder as $T \rightarrow 0$
- quasi long-range for $T < T_{\text{BKT}}$
- disordered for $T > T_{\text{BKT}}$
- linear resistivity within Fermi Liquid theory

Disorder range and strength tunable by temperature and doping



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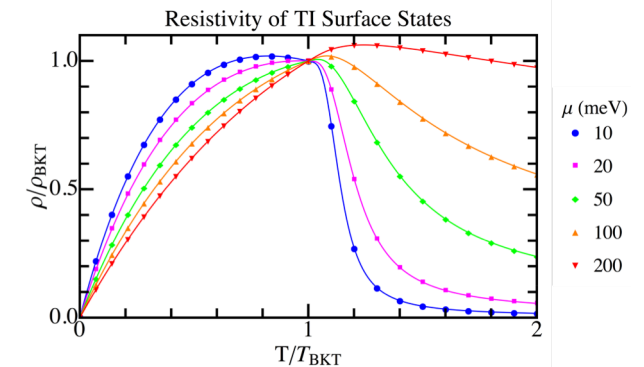
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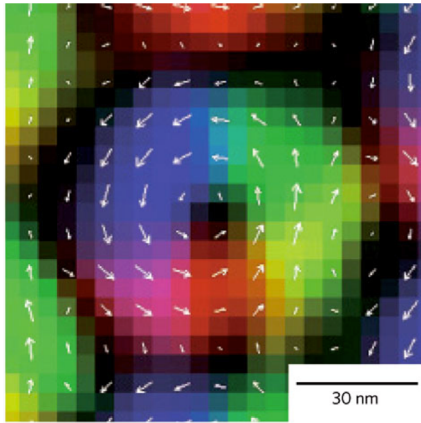
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See Also: Dynamical magnetic fluctuations can induce pairing

- Amperian Pairing at the Surface of Topological Insulators
- Kargarian, Efimkin, Galitski PRL **117**, 076806 (2016)



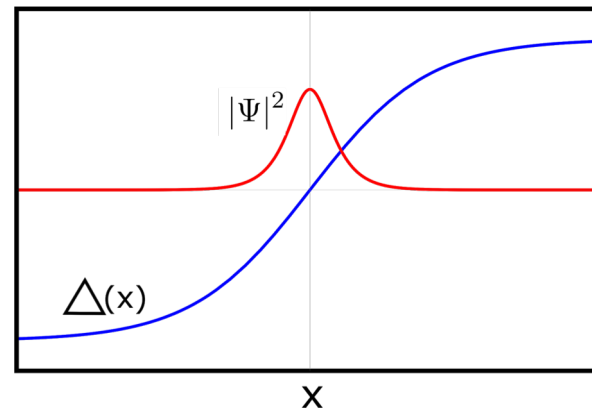
Model II: Single Magnetic Skyrmion



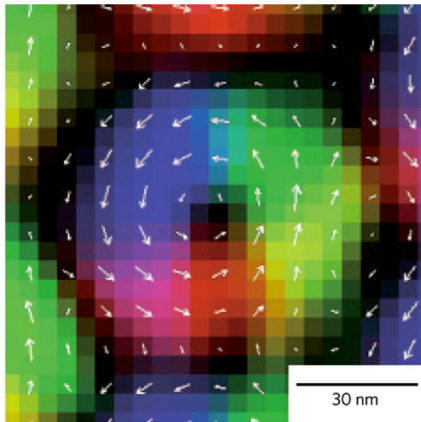
XZ Yu, *et al* Nature 2010

$$\mathcal{H} = v_F [(\mathbf{p} - e\mathbf{A} - e\mathbf{a}(\mathbf{r})) \times \boldsymbol{\sigma}]_{\hat{z}} - (\Delta m_z(\mathbf{r}) + g\mu_b B)\sigma^z$$

Skyrmion \rightarrow position-dependent Dirac mass



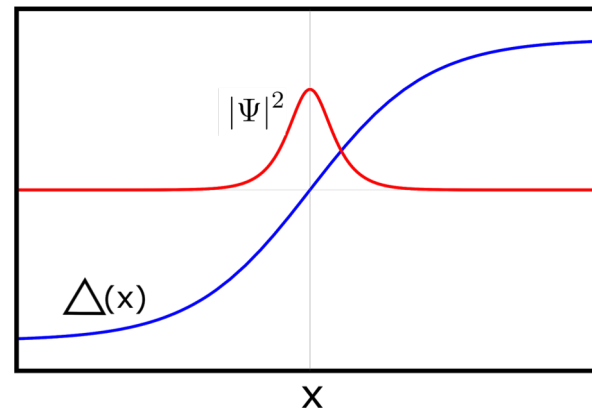
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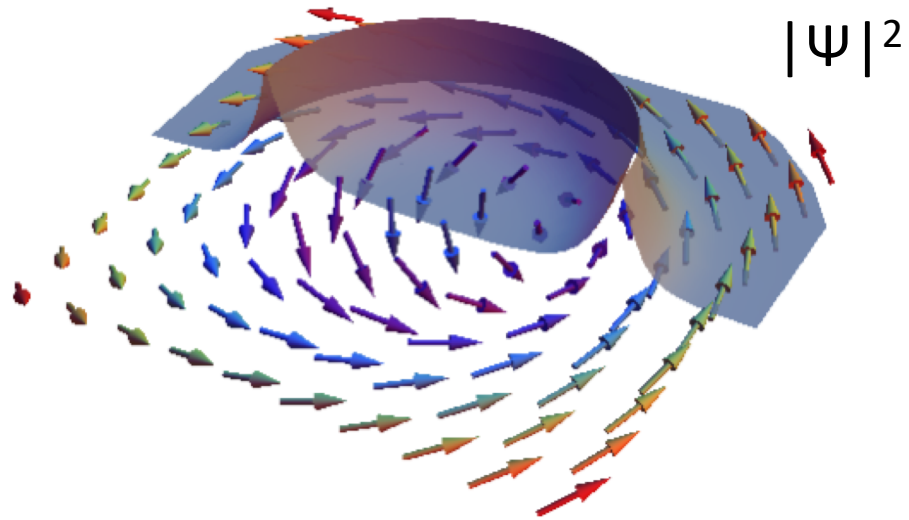


$$n_z(\mathbf{r}) = 2\Theta(r - R_S) - 1$$

consider only m_z component

Energy Spectrum as a Function of Skyrmion Radius

Analytically find in-gap states localized at skyrmion radius



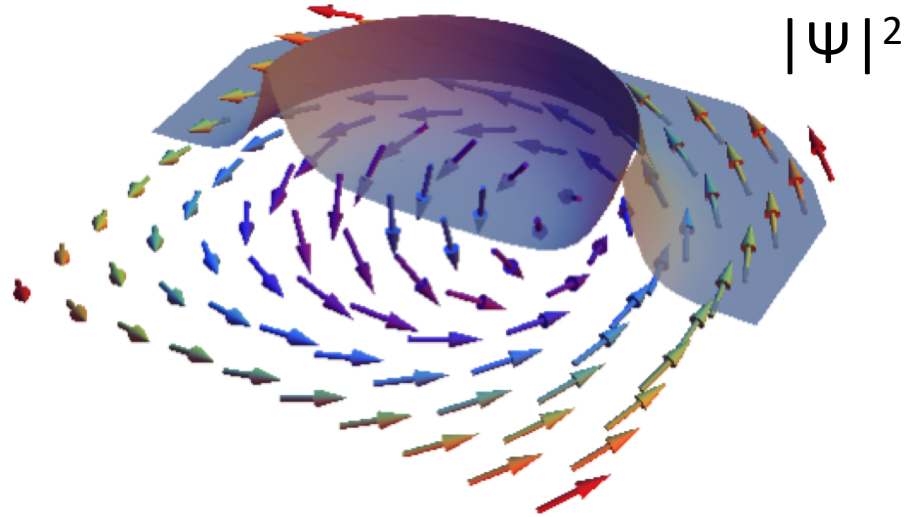
Parameters for Bi_2Se_3

$$\Delta_S = 10 \text{ meV}$$

$$v_F \approx 0.5 \times 10^6 \text{ m/s}$$

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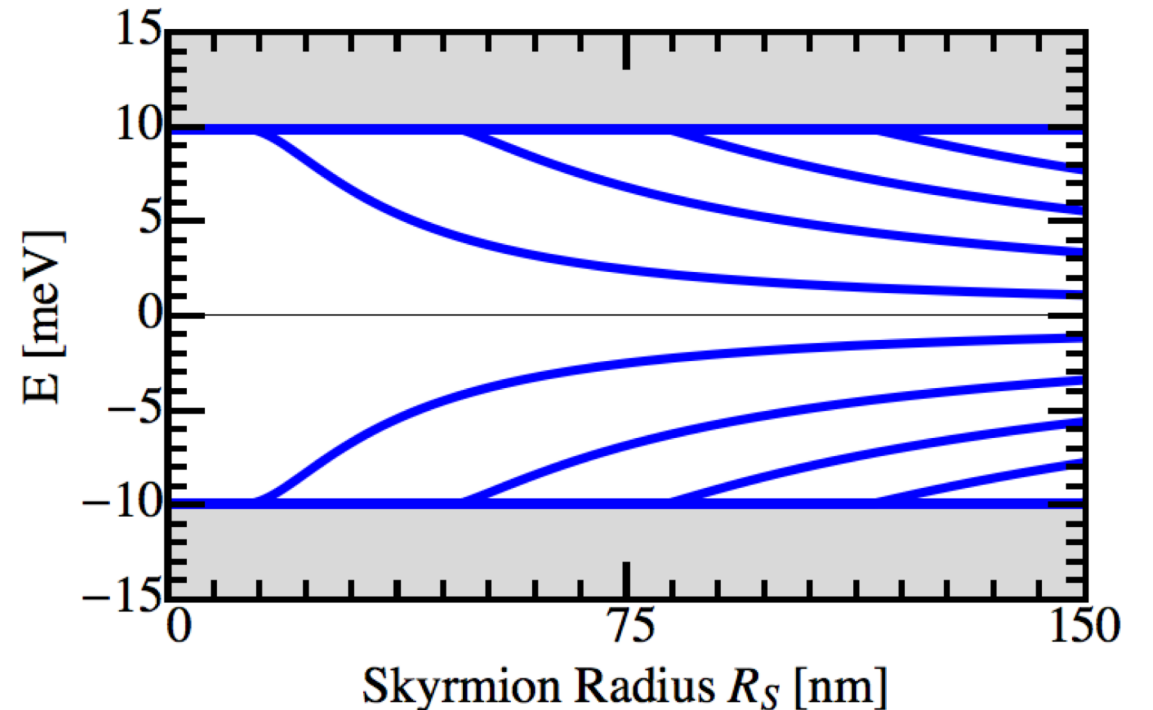


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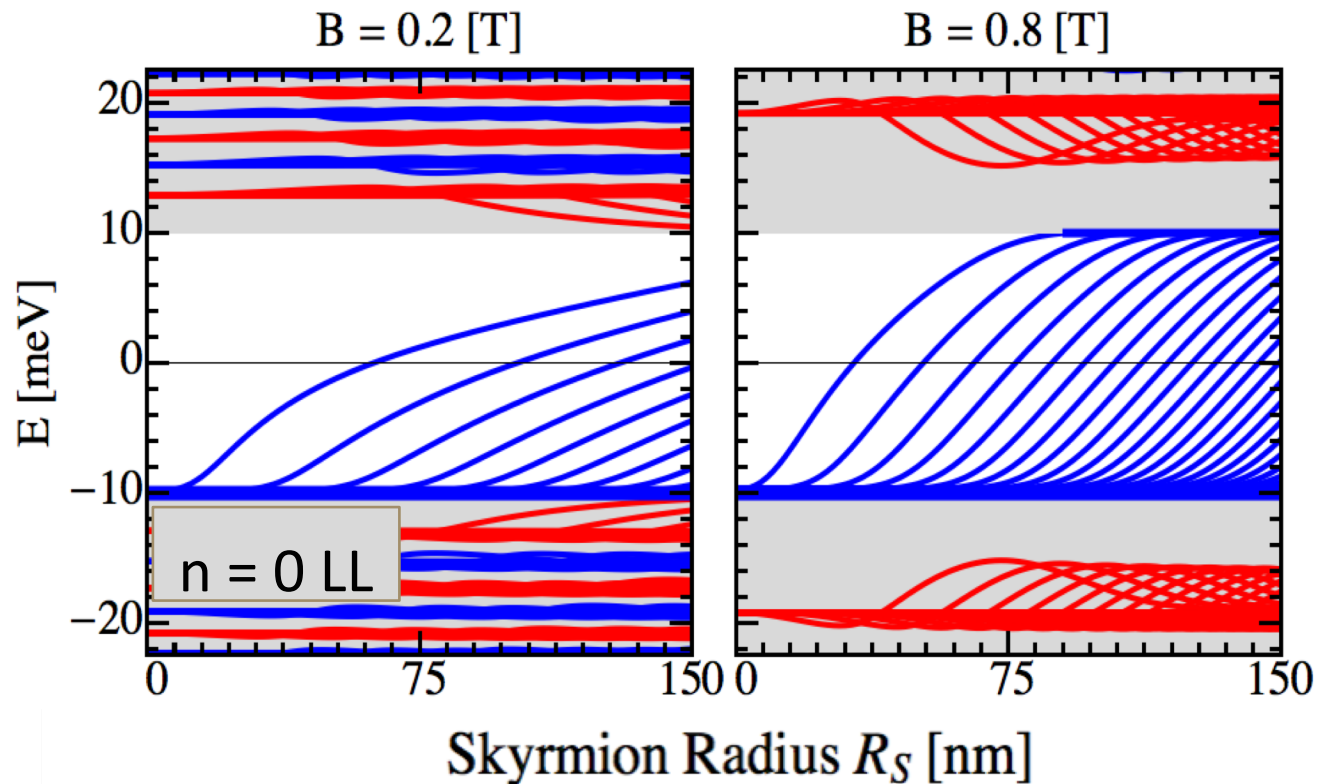
$$\Delta_S = 10 \text{ meV}$$

$$v_F \approx 0.5 \times 10^6 \text{ m/s}$$

Critical Skyrmion Radius $R^* \approx 16 \text{ nm}$
Localized states, no zero mode



External Magnetic Field + Skyrmion



- Broken electron - hole symmetry
- States form Landau Levels
- In-gap states possible for $\Delta_S > \Delta_Z$
- External parameters
 - Skyrmion radius R_S and B
- $n = 0$ Landau Level Splitting:

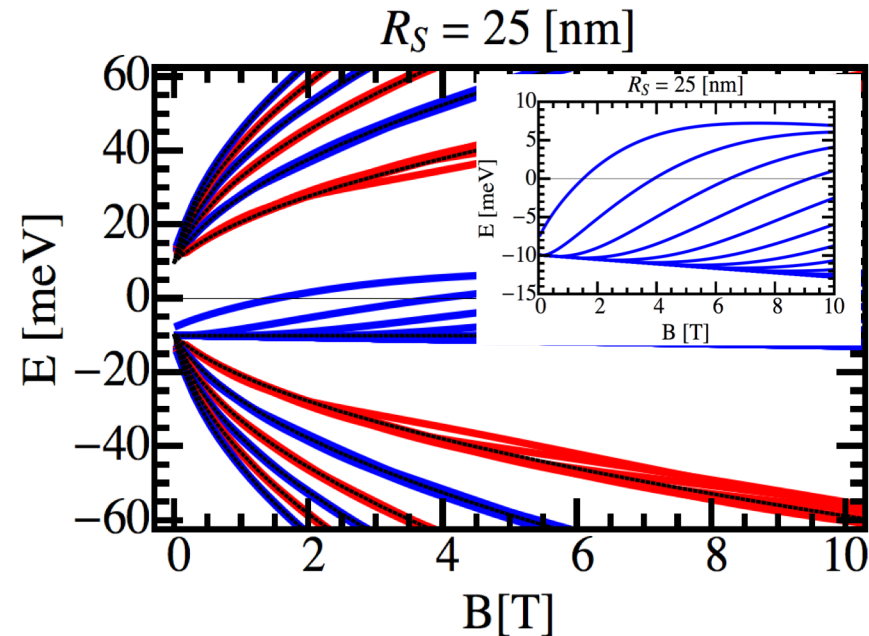
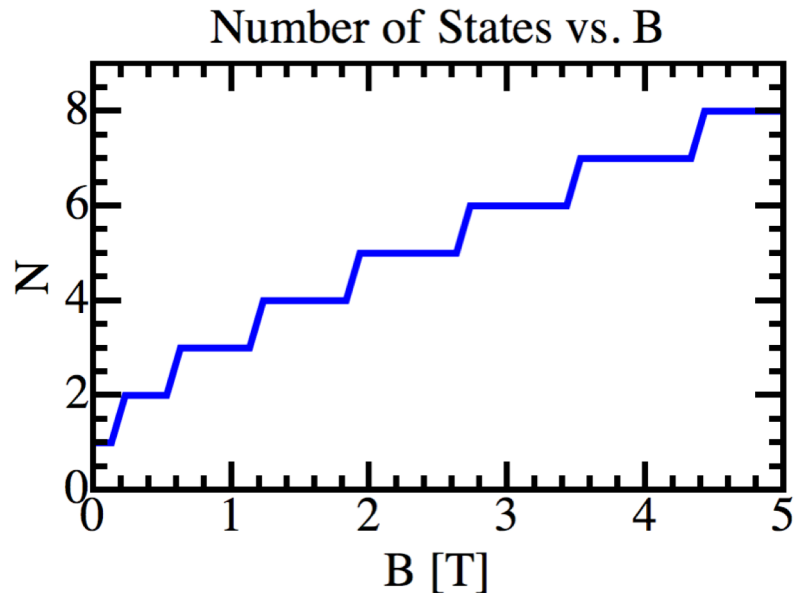
$$E_{0m} = -sgn(B)(\Delta_Z + \Delta_S n_z(\mathbf{r}))$$
- Robust in-gap states
- States with $R_m \sim R_S$ most affected

$$R_m \approx \sqrt{\frac{2\hbar c}{eB}}(m + 1)$$

Energy vs. Magnetic Field Strength

- States with $|n| > 0$ weakly affected
- In gap states are well split from $n = 0$ LL as magnetic field is increased
- LLs are macroscopically degenerate
- Can tune number of states

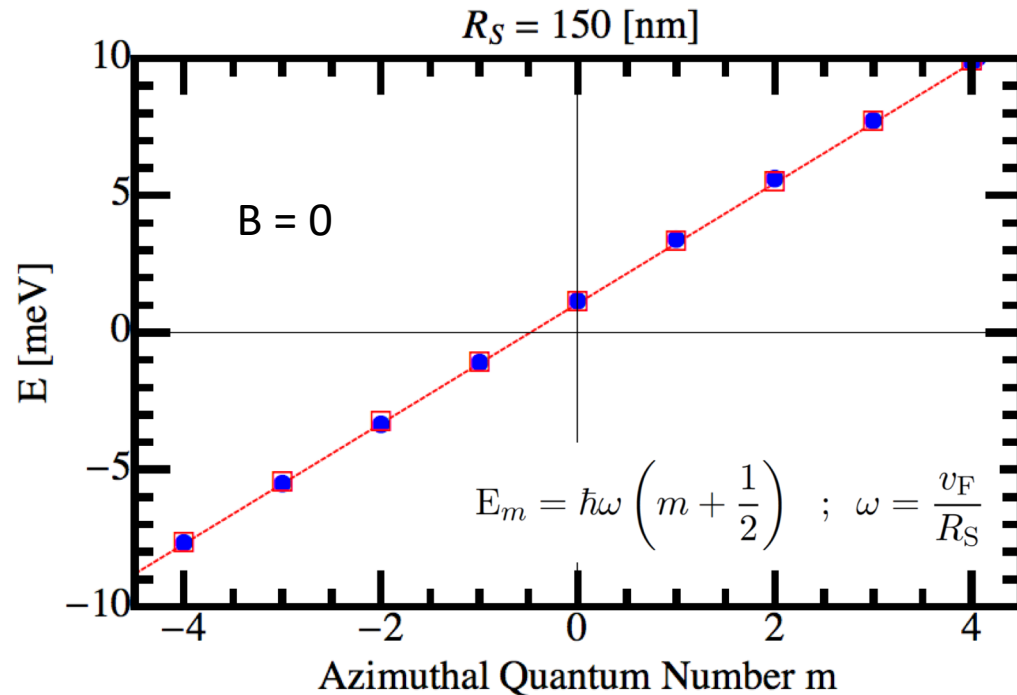
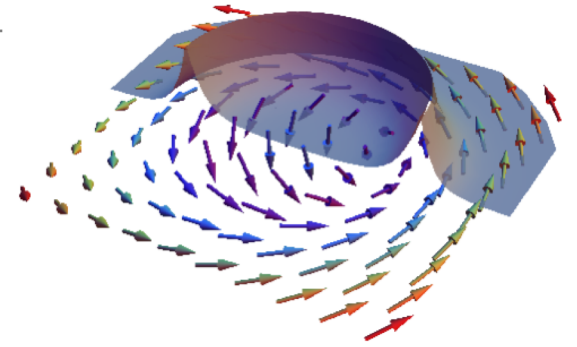
$$E \propto \sqrt{B|n|}$$



Energy Spectrum at Large Skyrmion Radius

- Spectrum follows semiclassical quantization
- Weakly dependent on texture shape
- More states at larger radius

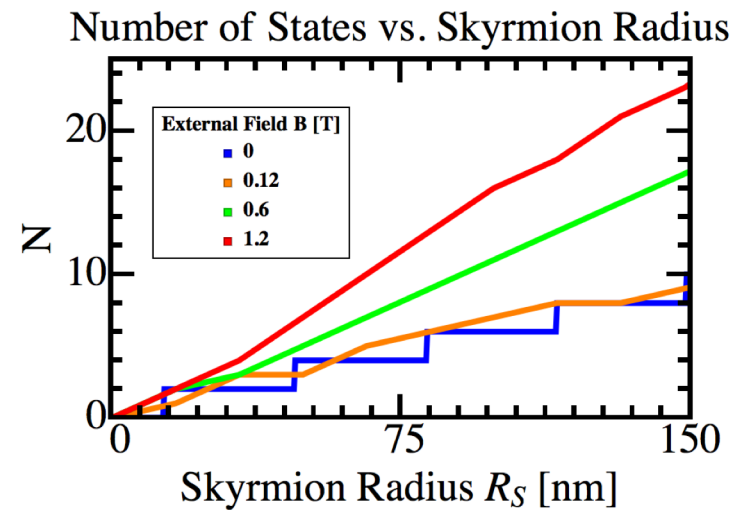
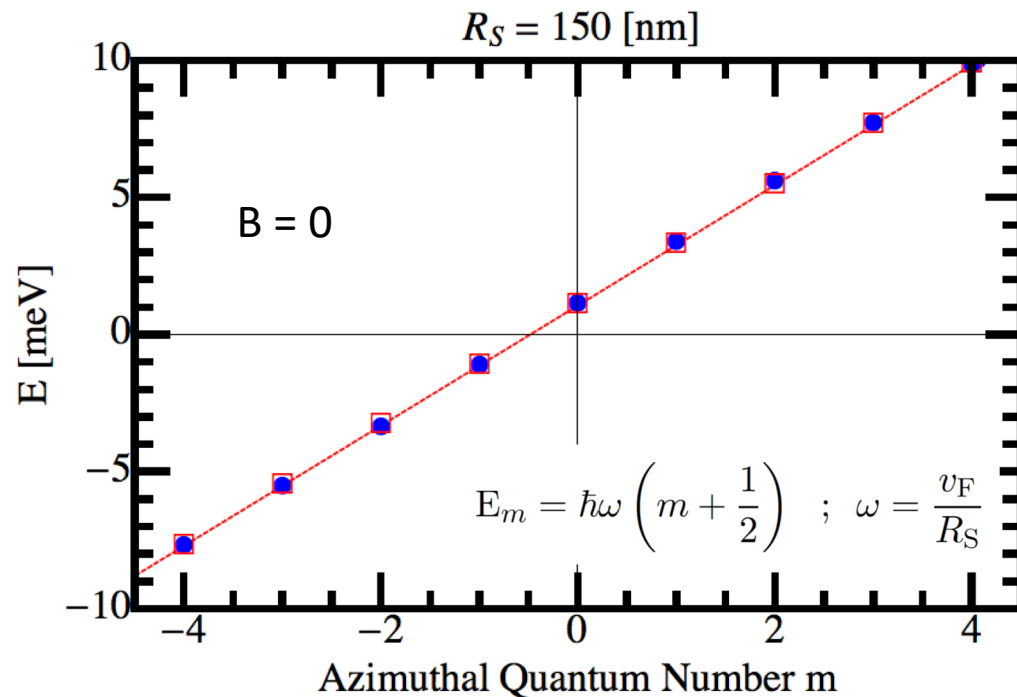
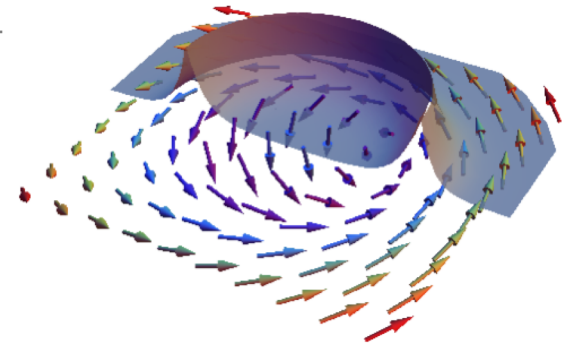
$$\oint p_i dq_i = nh$$



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$$\oint p_i dq_i = nh$$



Charged Skyrmion Dynamics

Charged Skyrmions can be manipulated by an electric field

Skyrmion charge is eN_B with N_B number of additional occupied states

$$\mathcal{L} = \lambda \left[\dot{\mathbf{R}} \times \mathbf{R} \right]_z + eN_B \left(\phi(\mathbf{R}) - \frac{\dot{R}}{c} A(\mathbf{R}) \right) + \frac{m_S \dot{R}^2}{2}$$

$$\begin{cases} \dot{R}_y \approx - \left[\frac{eN_B c}{2\lambda c + eN_B B} \right] E_x = -\mu_s E_x \\ \dot{R}_x \approx 0 \end{cases}$$

- Small damping in insulating systems
- Hall motion occurs due to Magnus Force term

Estimate of Cu_2OSeO_3 Skyrmion Mobility : $\mu_s \sim 1 \times 10^{-6} \text{ m}^2/\text{Vs}$ $R_S \approx 25 \text{ nm}$
 $N_B \approx 1$

Skyrmion Manipulation in Experiment

Our results:

Couple directly to electric field

$$E = 10^2 \text{ V/m} \Rightarrow v_H \sim 0.1 \text{ mm/s}$$

compare to STT

$$E = 10^5 \text{ V/m} \Rightarrow v_H \sim 0.1 \text{ m/s}$$

compare to thermal gradients

Efficient option for skyrmion manipulation... provided system can be grown

Conclusions II

PRB, **91**, 060401(R), (2015)

Individual magnetic textures can become charged due to magnetic confinement of surface states
provides interesting route toward electrical manipulation of otherwise neutral spin structures
in-gap states survive even with external magnetic field

