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Transport signatures of Dirac states in topological insulator - ferromagnet heterostructures

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Transport signatures of Dirac states in topological insulator - ferromagnet heterostructures

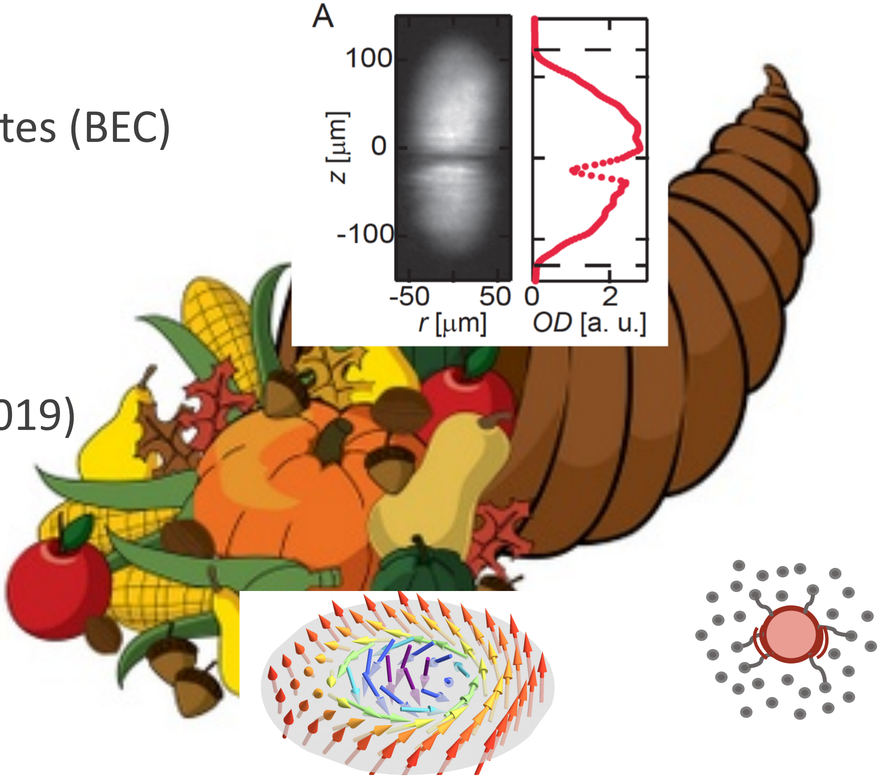
HILARY M. HURST

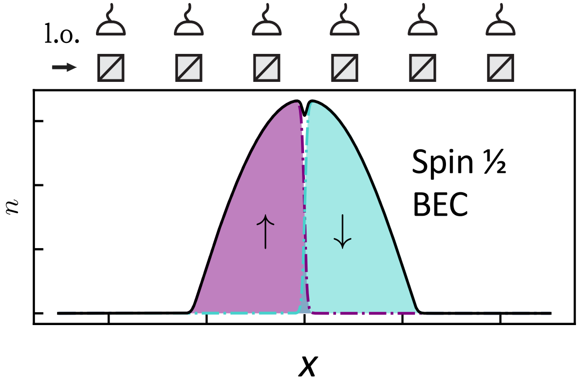
KITP: SPIN AND HEAT TRANSPORT IN QUANTUM AND TOPOLOGICAL MATERIALS

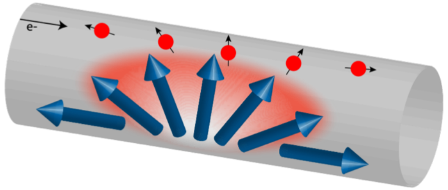
NOVEMBER 27, 2019

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. Aycock, 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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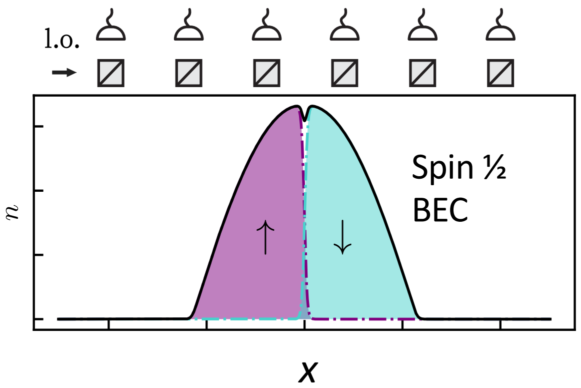

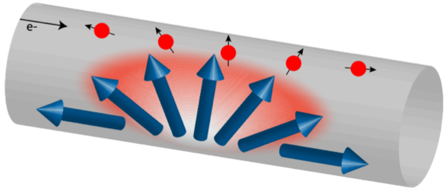

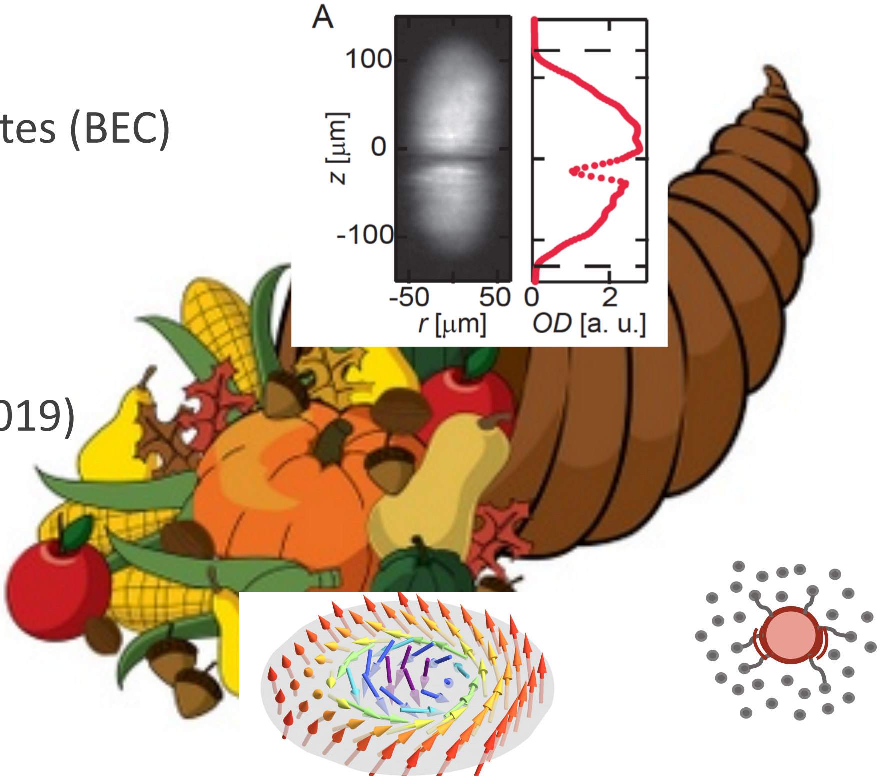

NATIONAL PHYSICAL SCIENCE CONSORTIUM

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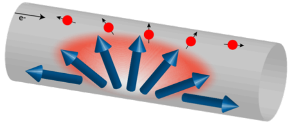

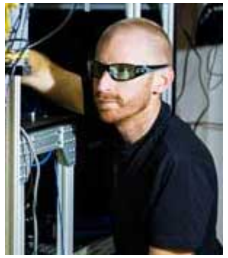

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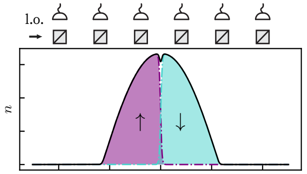
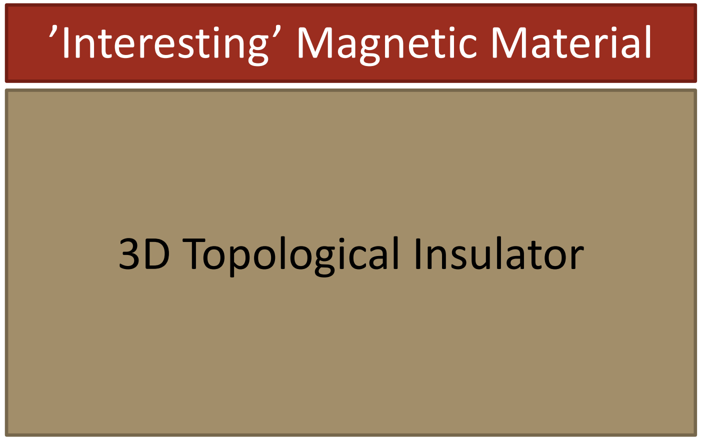


Magnetic Patterning on 3D Topological Insulators



Clean interface exchange model

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

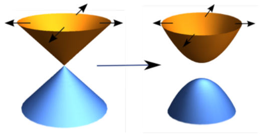
External magnetic field

Spatially dependent magnetization in top layer

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

Out-of-Plane Magnetization

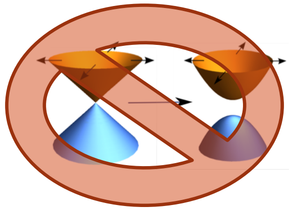
- acts as an effective mass
- leads to gap-opening on TI surface
- interesting physical effects: AQHE, magnetic confinement, etc.



In-Plane Magnetization

$$\mathbf{a}(\mathbf{r}) = \frac{\Delta}{e v_{\mathrm{F}}}\left[\mathbf{m}(\mathbf{r}) \times \hat{z}\right]$$

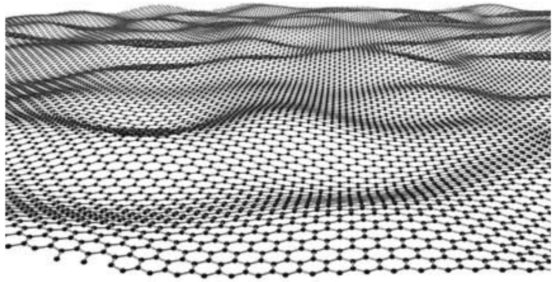
- acts as an effective gauge field
- no gap opening*



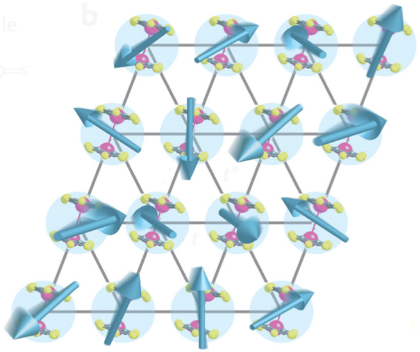
Model I: In-Plane Magnetization Only

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

$$\mathbf{a}(\mathbf{r}) = \frac{\Delta}{ev_{\mathrm{F}}}[\mathbf{m}(\mathbf{r}) \times \hat{z}] \qquad \Delta \ll \mu$$



Ripples in Graphene



Spin Liquids

Consider a 2D magnetic system with the following properties:

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

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

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

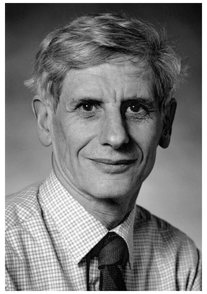
$$s^\alpha(\mathbf{r}_1) = \psi^\dagger_{\mathbf{r}_1} \sigma^\alpha \psi_{\mathbf{r}_1}$$

magnetic correlations: proxy for static or dynamical gauge field disorder

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

V. Berezinskii

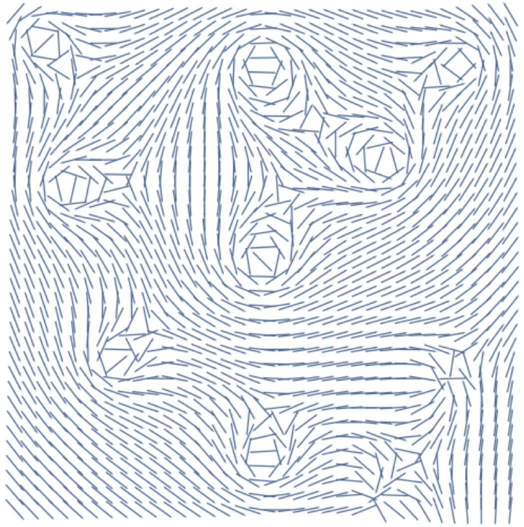
J. M. Kosterlitz



D. Thouless

2D Magnetic XY-model

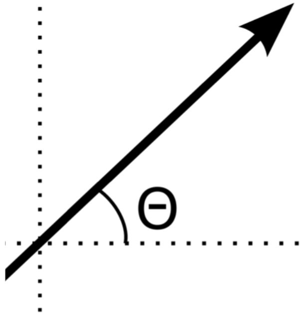
No net magnetization at finite temperature $\langle \mathbf{m}(\mathbf{r}) \rangle = 0$

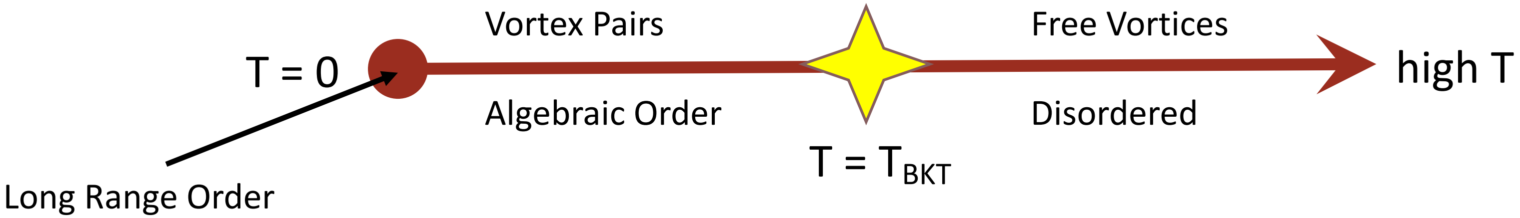


$$\mathbf{m}(\mathbf{r}) = \{\cos\Theta(\mathbf{r}), \sin\Theta(\mathbf{r})\}$$

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

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





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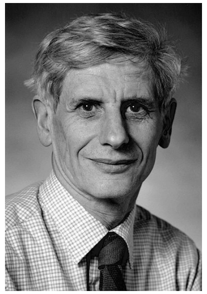

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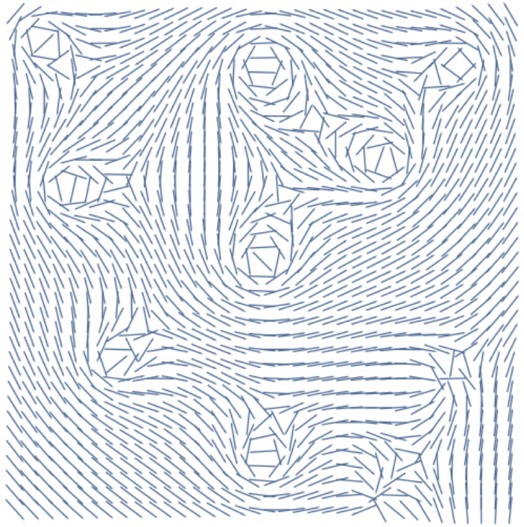
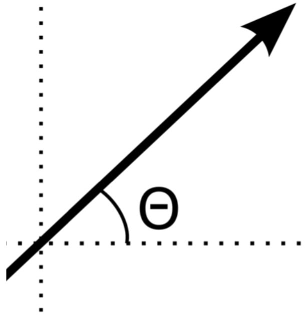
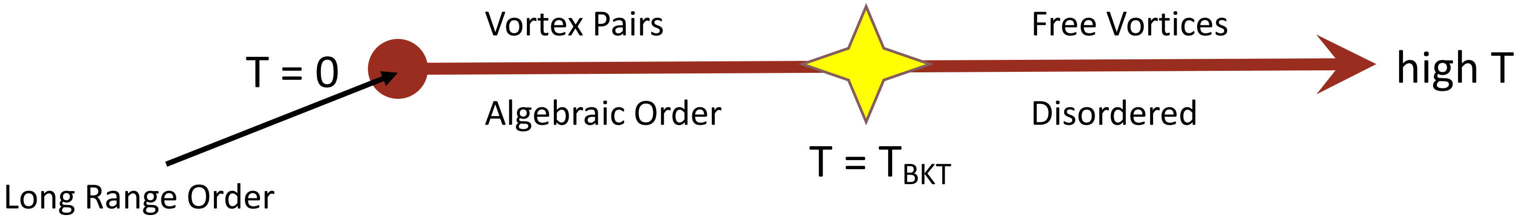


$$\langle m(\mathbf{r}) m(0) \rangle \sim \left(\frac{|\mathbf{r}|}{a} \right)^{\eta(T)} \quad ; \; T < T_{\mathrm{BKT}}$$

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

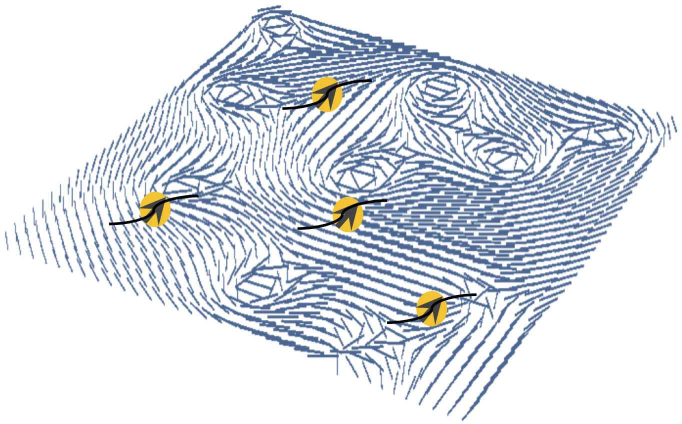
$$\eta(T) = \frac{T}{4T_{\mathrm{BKT}}}$$





Surface States Coupled to XY-Model

$$\mathcal{H} = v_{\mathrm{F}}\left[(\mathbf{p} - e\mathbf{a}(\mathbf{r})) \times \boldsymbol{\sigma}\right]_{\hat{z}} - \mu \qquad \mathbf{a}(\mathbf{r}) = \frac{\Delta}{ev_{\mathrm{F}}}(m_y, -m_x)$$



Effective electric field: $E = -\partial_t \mathbf{a}^l = -\frac{\Delta}{v_{\mathrm{F}}}\partial_t \mathbf{m}^t \to 0$ (static magnet)

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

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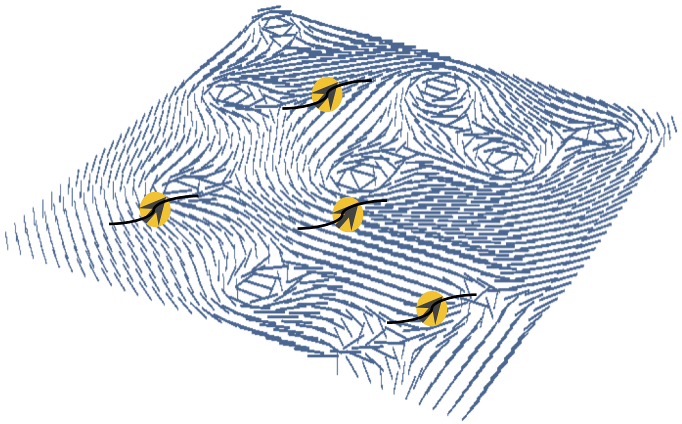

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Magnetic field generated by vortices is nonlocal and leads to random magnetic field (RMF) $B_z^v(\mathbf{r}) \propto \sum_i q_i \frac{\cos(\Theta_i)}{|\mathbf{r} - \mathbf{r}_i|}$

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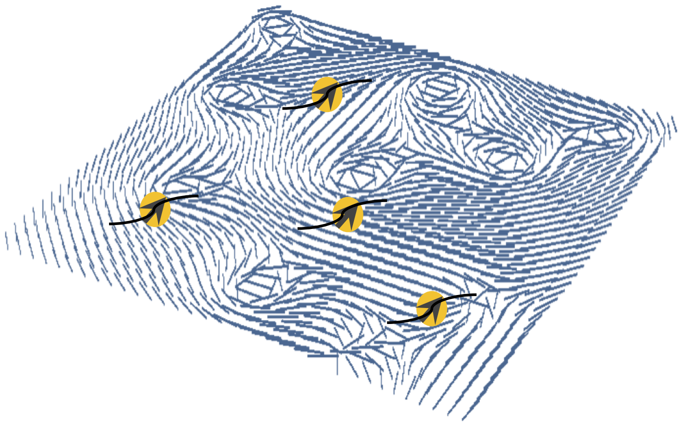

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Effective interaction between fermions:

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

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**

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

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

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

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

strong temperature dependence

unscreened interaction below BKT transition temperature
*can be regularized by including band curvature

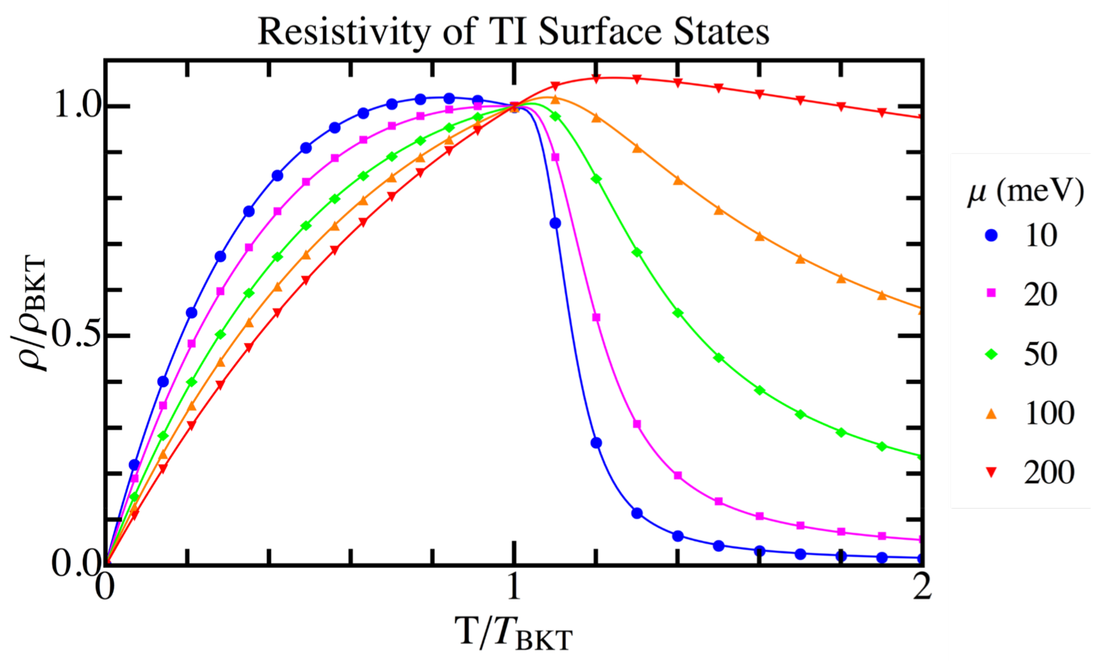
Effect of RMF on Electron Transport

Resistivity Peak at T_{BKT}

Linear scaling of resistivity with temperature

- manifestation of RMF physics
- distinguishable from other scattering

$$\rho(T \to 0) \quad \sim f_{1,\mu}\ T$$
$$\rho(T \to T^-) \sim f_{2,\mu}(T - T_{\mathrm{BKT}})$$
$$\rho(T \to T_+) \sim f_{3,\mu}(T - T_{\mathrm{BKT}})$$



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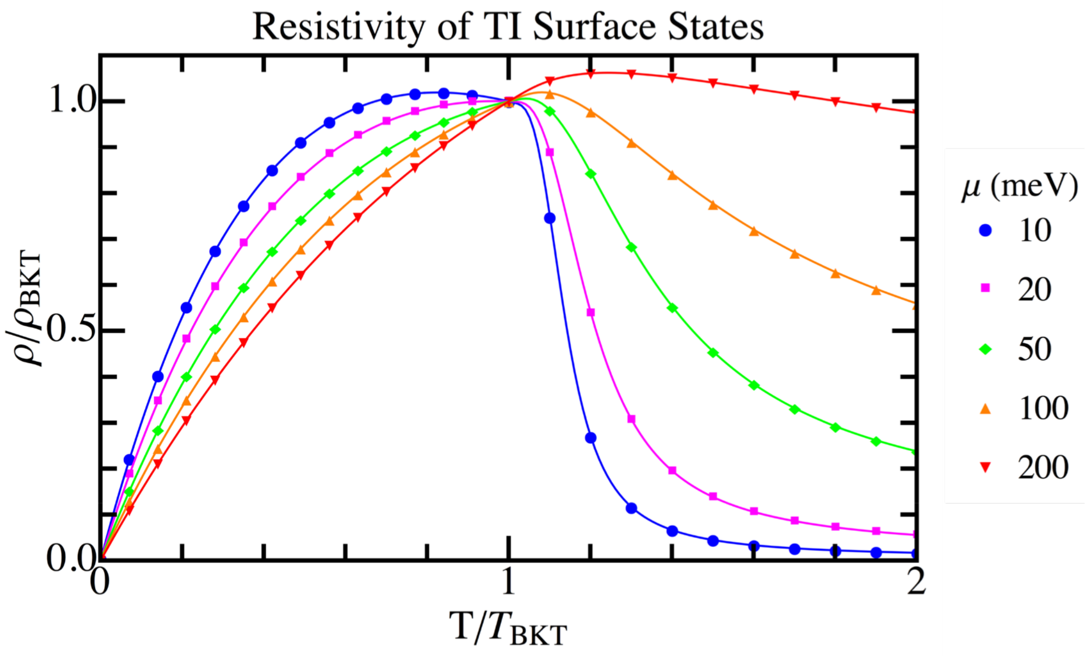
"Real" numbers:

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

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



Conclusions I

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

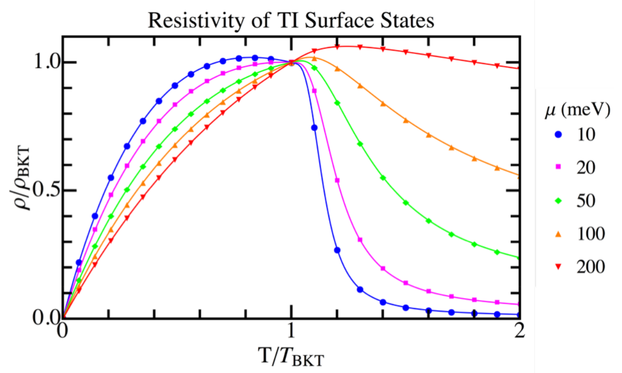
TI + magnetic material heterostructures offer opportunity to study fermion-gauge field models

- 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 $T < T_{BKT}$
- disordered for $T > T_{BKT}$
- linear resistivity within Fermi Liquid theory

Disorder range and strength tunable by temperature and doping



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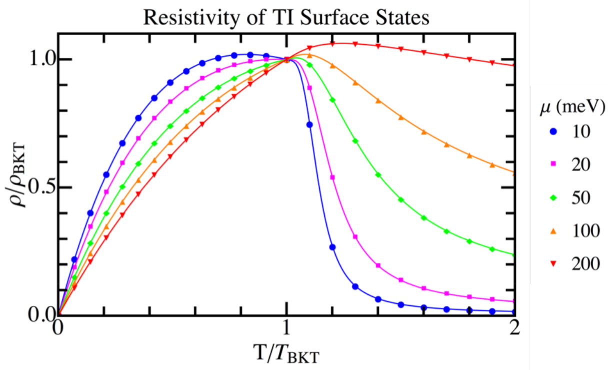
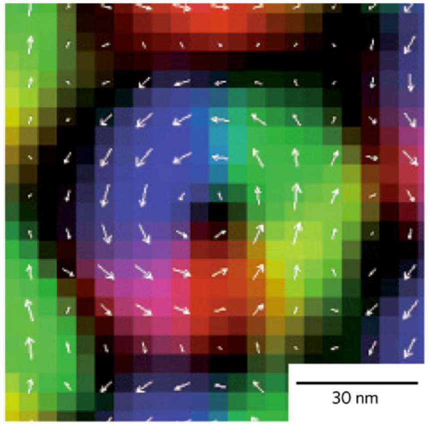


Disorder range and strength tunable by temperature and doping

See Also: Dynamical magnetic fluctuations can induce pairing

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

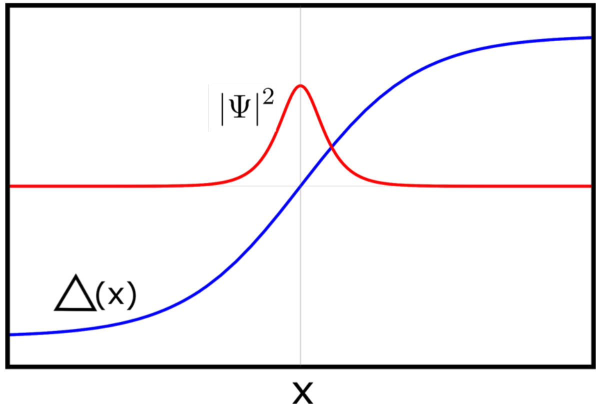
Model II: Single Magnetic Skyrmion



XZ Yu, *et al* Nature 2010

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

Skyrmion → position-dependent Dirac mass



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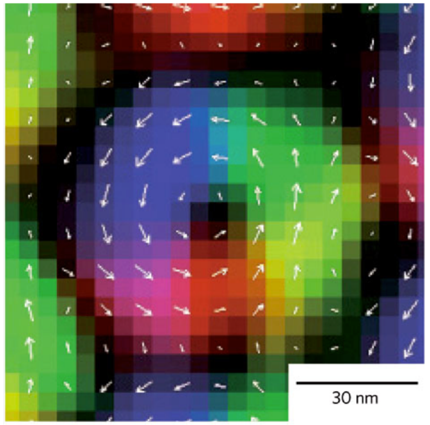

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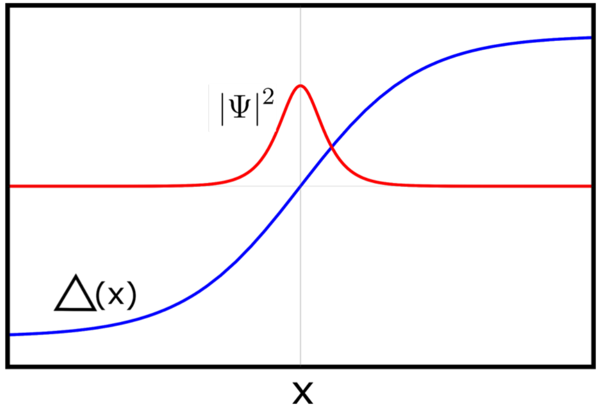
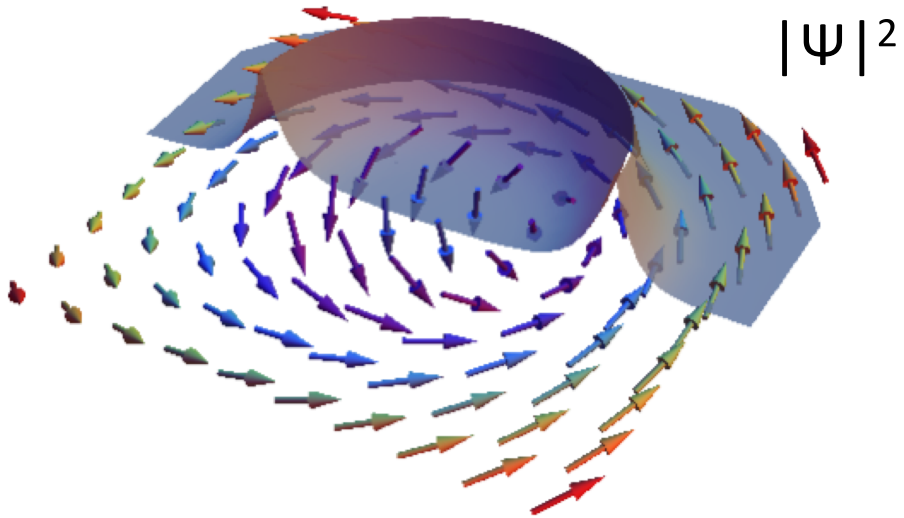


$$n_z(\mathbf{r}) = 2\Theta(r - R_{\rm S}) - 1$$

consider only mz 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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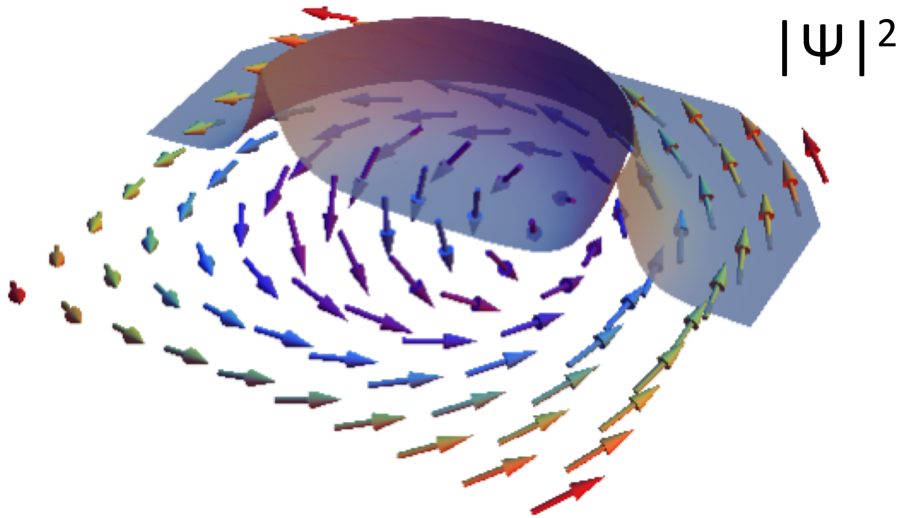

Parameters for Bi_2Se_3

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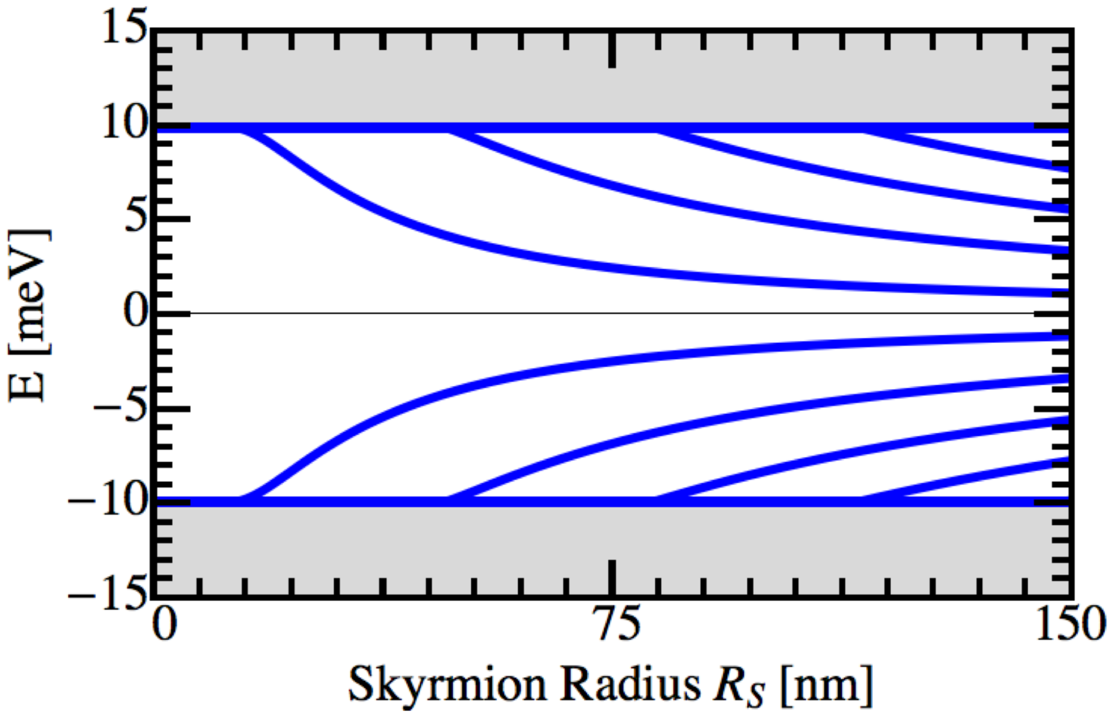
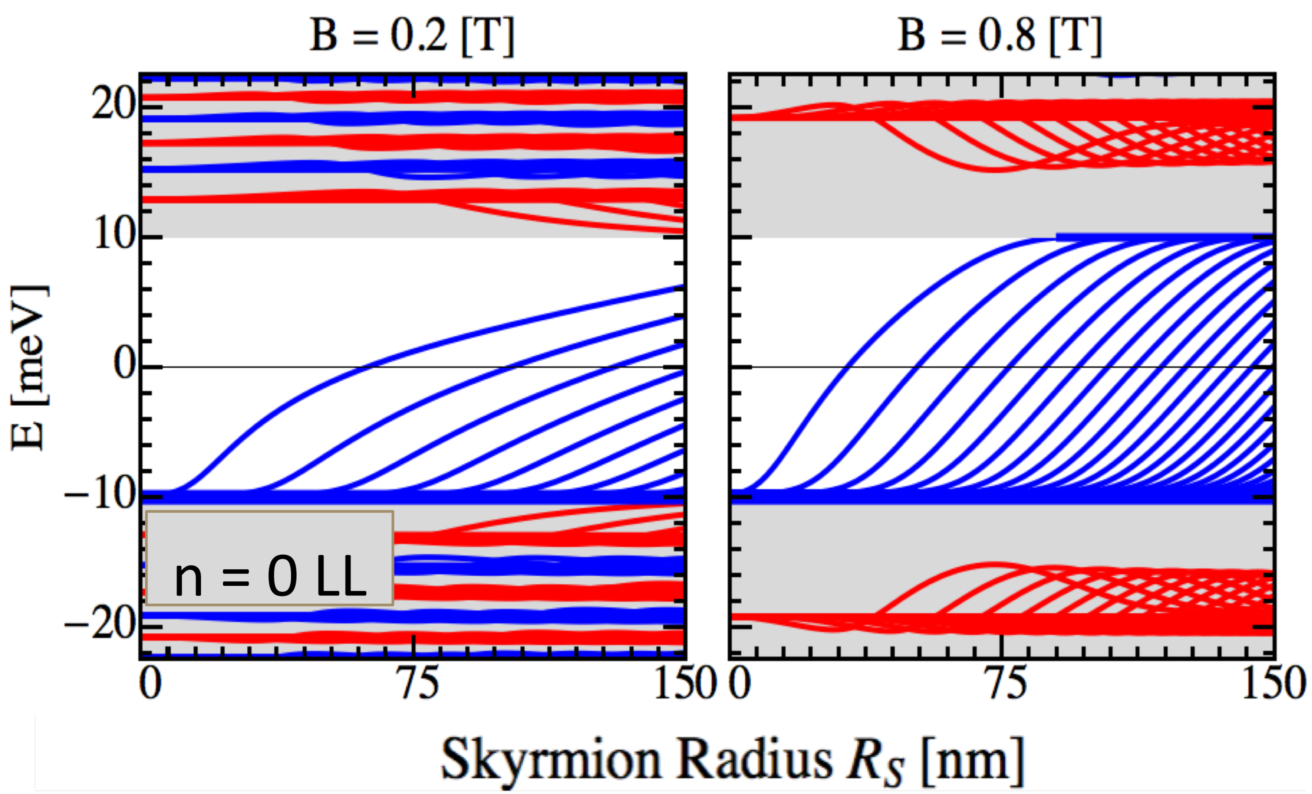
Critical Skyrmion Radius R* ≈ 16 nm

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 Rs and B
- n = 0 Landau Level Splitting:

$$E_{0m} = -sgn(B)(\Delta_Z + \Delta_S n_z(\mathbf{r}))$$

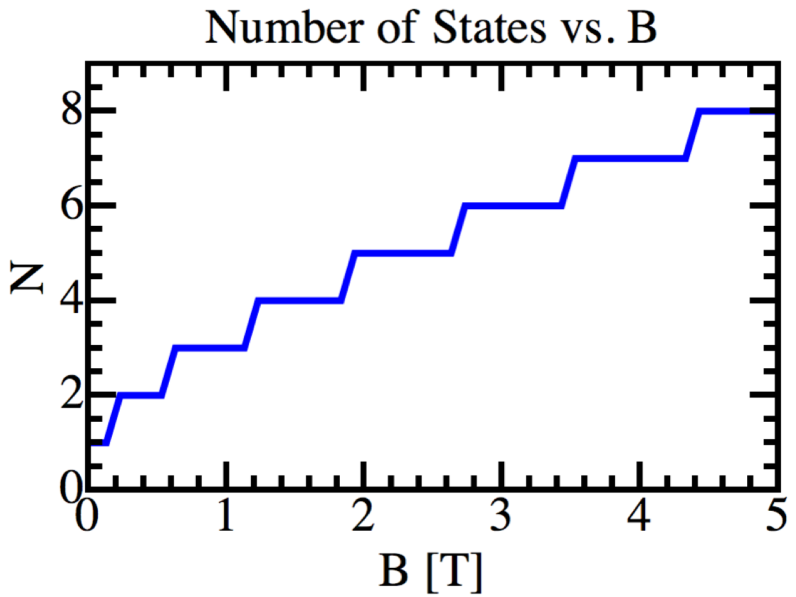
- Robust in-gap states
- States with $R_m \sim R_s$ most affected

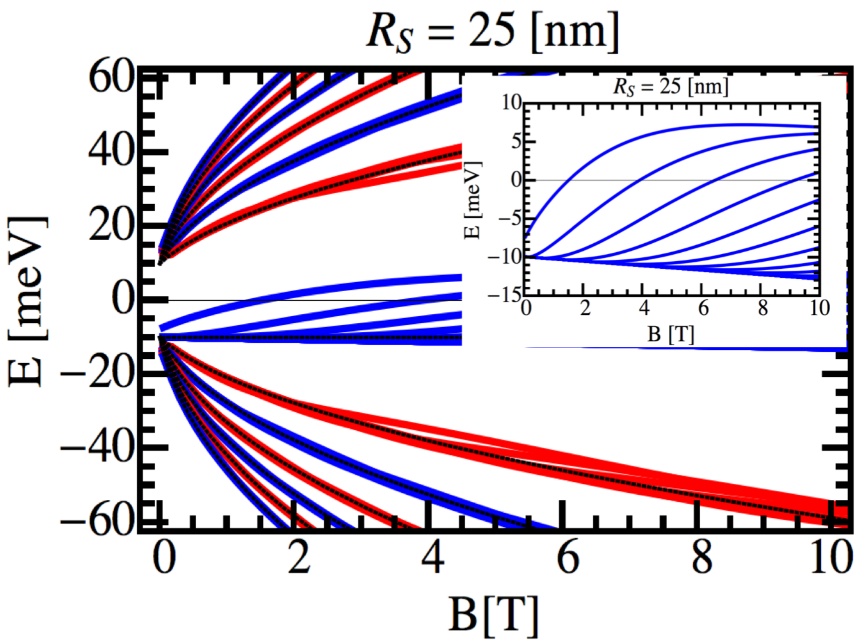
$$R_m \approx \sqrt{\frac{2\hbar c}{eB}(m+1)}$$

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

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

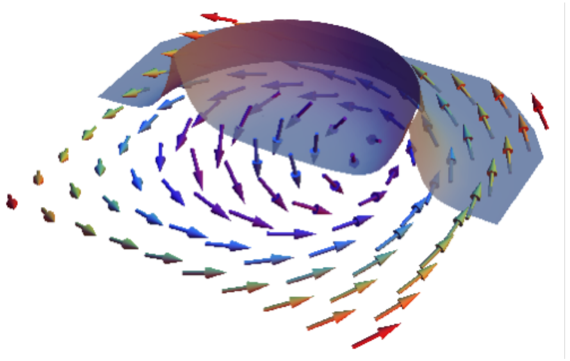


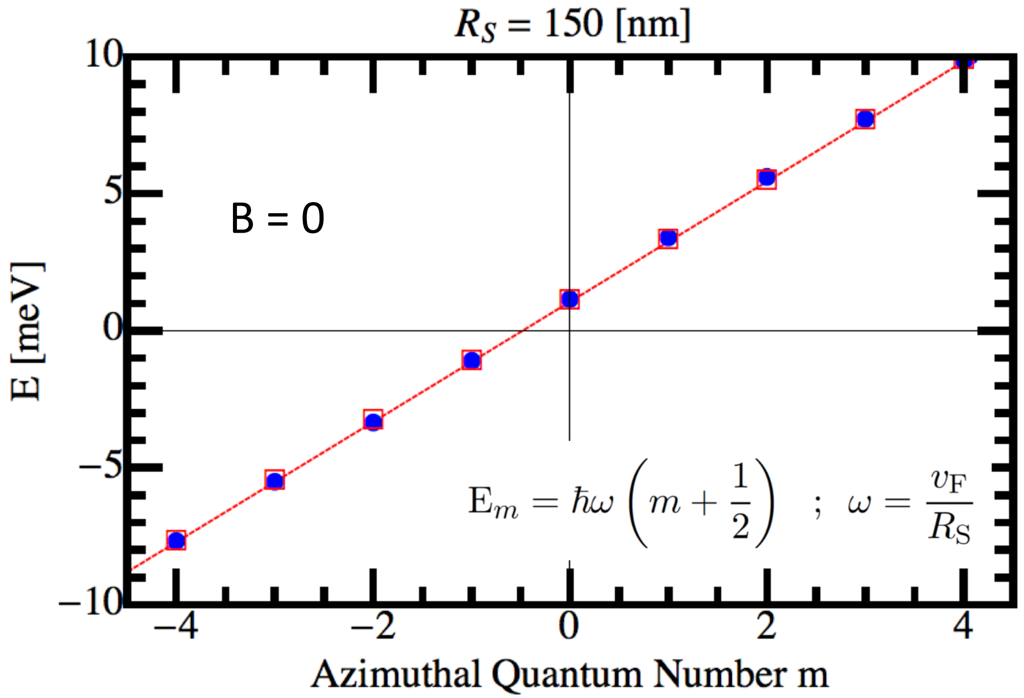


Energy Spectrum at Large Skyrmion Radius

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

$$\oint p_i dq_i = nh$$

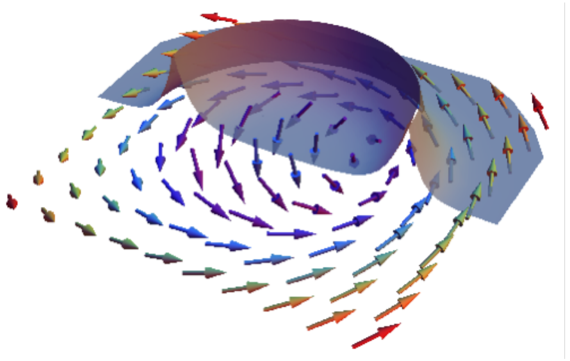


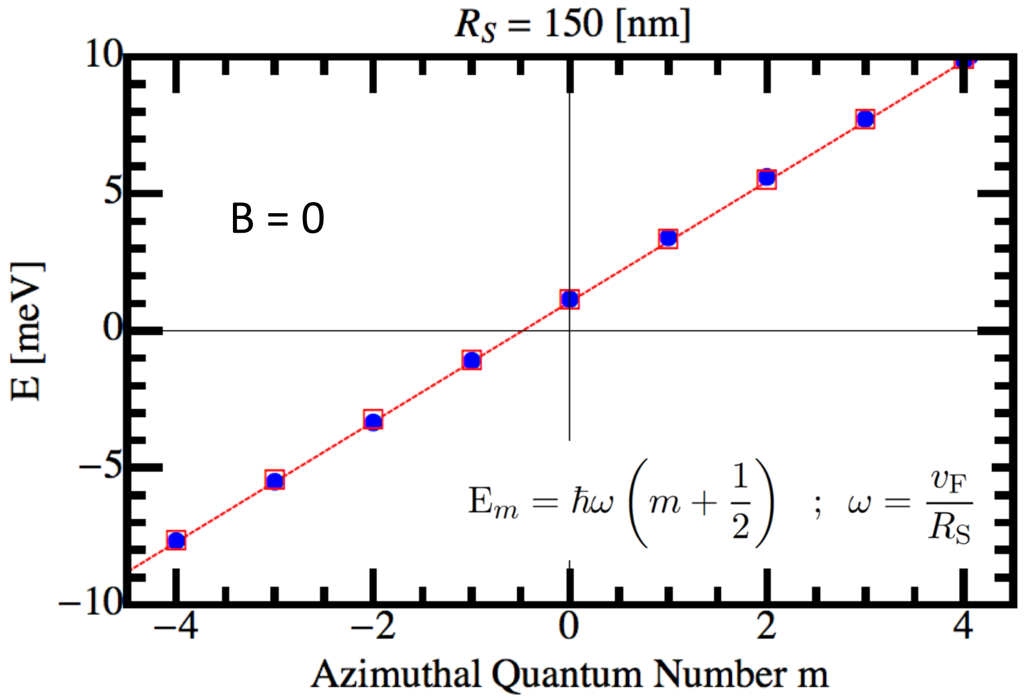


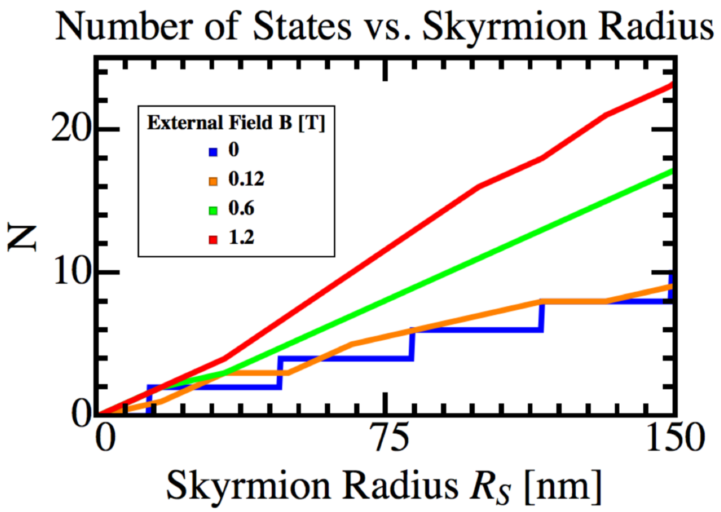
Energy Spectrum at Large Skyrmion Radius

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

$$\oint p_i dq_i = nh$$







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

$$\mathcal{L} = \lambda \left[\dot{\mathbf{R}} \times \mathbf{R}\right]_z + eN_\mathrm{B}\left(\phi(\mathbf{R}) - \frac{\dot{R}}{c}A(\mathbf{R})\right) + \frac{m_\mathrm{S}\dot{R}^2}{2}$$

$$\begin{cases} \dot{R}_y \approx -\left[\dfrac{eN_\mathrm{B}c}{2\lambda c + eN_\mathrm{B}B}\right] E_x = -\mu_\mathrm{s} E_x \\ \dot{R}_x \approx 0 \end{cases}$$

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

Estimate of Cu_2OSeO_3 Skyrmion Mobility : $\mu_\mathrm{s} \sim 1 \times 10^{-6}\ \mathrm{m^2/Vs}$

$R_\mathrm{S} \approx 25\ \mathrm{nm}$

$N_\mathrm{B} \approx 1$

Skyrmion Manipulation in Experiment

Our results:

Couple directly to electric field

E = 10^2 V/m ⇒ v_H ~ 0.1 mm/s

compare to STT

E = 10^5 V/m ⇒ v_H ~ 0.1 m/s

compare to thermal gradients

Efficient option for skyrmion manipulation… provided system can be grown

Conclusions II

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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