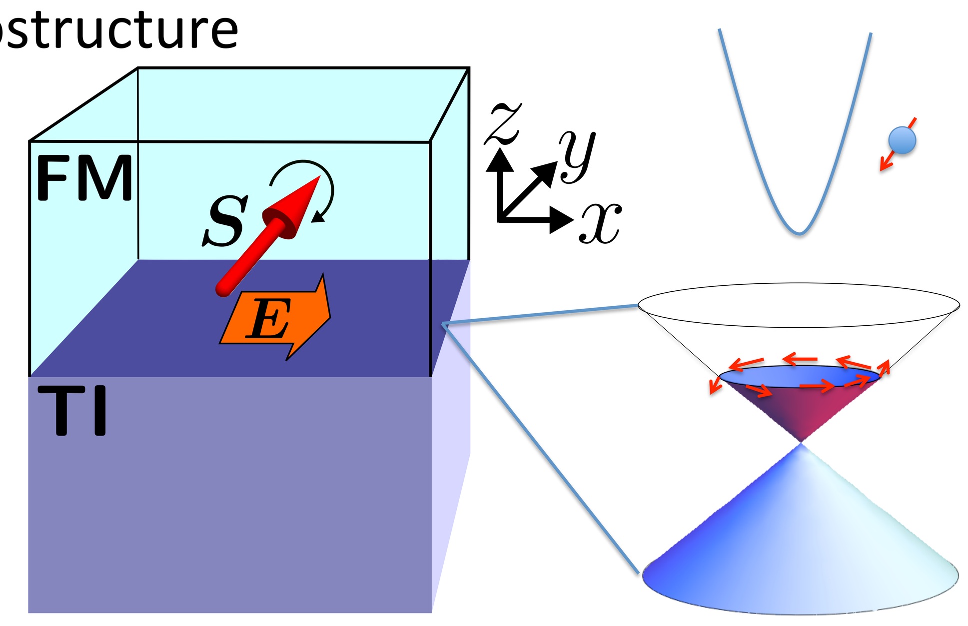
# Theoretical study of electron-magnon coupling in topological insulator/ferromagnet heterostructure

N. Okuma[1] and K. Nomura[2] / N.Okuma[1], M. Ramezani Masir[3], and A.H. MacDonald[3]

[1]Department of Physics, The University of Tokyo,
[2]Institute for Materials Research, Tohoku University,
[3]Department of Physics, The University of Texas at Austin

## 0. Introduction

Topological insulator/Ferromagnet heterostructure




**Magnon gas**

- Carrying y-component spin
- Quadratic dispersion

$$\omega_{\boldsymbol{q}} = D|\boldsymbol{q}|^2$$

**Dirac electron system**

- Spin-momentum locking (Spin accumulation=electric field)
- Linear dispersion $\xi_{\boldsymbol{k}} = v|\boldsymbol{k}| - \mu$

**Electron-magnon interaction**

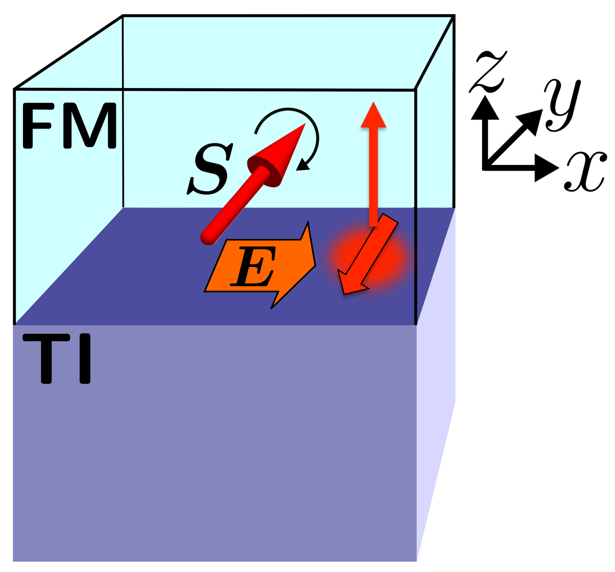
$$H_{em} = \alpha \int \frac{d^2p d^2q}{(2\pi)^2(2\pi)^2} \psi^\dagger_{\boldsymbol{p}} \hat{\sigma}^+ \psi_{\boldsymbol{p}+\boldsymbol{q}} a^\dagger_{\boldsymbol{q}}(z=0) + h.c.$$
$$= \alpha \sqrt{\frac{2}{L}} \sum_{\boldsymbol{p},\boldsymbol{q},q_n} \psi^\dagger_{\boldsymbol{p}} \hat{\sigma}^+ \psi_{\boldsymbol{p}+\boldsymbol{q}} a^\dagger_{\boldsymbol{q},q_n} + h.c.,$$

- Conversion between magnon and electron spin
- Total spin is conserved
- Origin is the s-d interaction

## 1. Electrical transport

(N. O. and K. Nomura, in preparation)

### Phenomenon under electric field

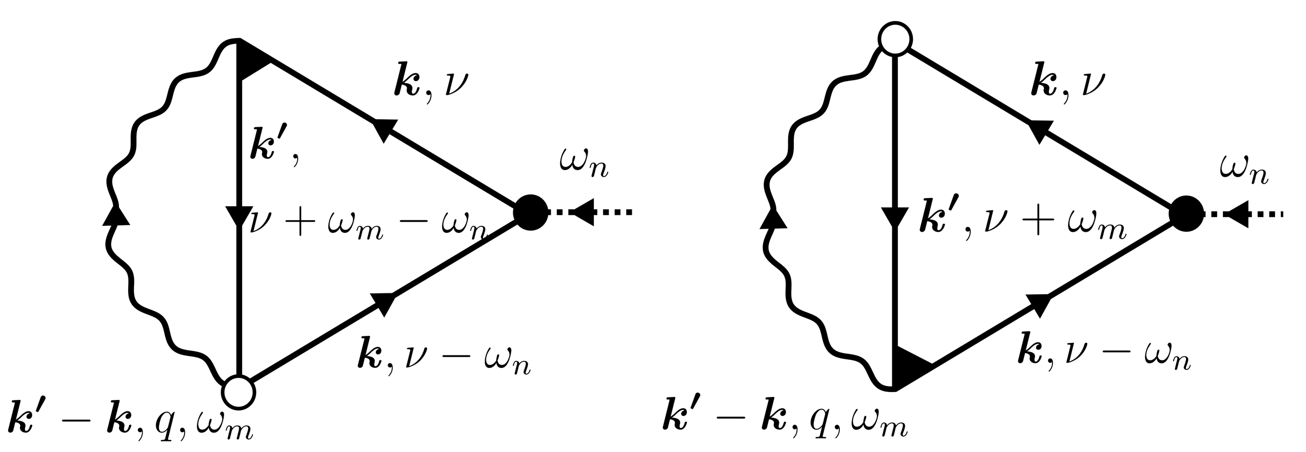



- Electron Spin accumulation (Edelstein effect)
- Conversion from electron spin to magnon spin
- Magnon spin current generation

### Spin current operator@interface

$$j_z^{S_y} = \frac{1}{i}\left[\frac{S^y_{tot}}{V}, H_{sd}\right] = -\frac{1}{i}\left[\frac{s^y_{tot}}{V}, H_{sd}\right]$$

### Microscopic calculation (Kubo formula)




● : Charge current operator

▲ : Spin current operator

○ : Electron-magnon interaction

### Result

$$\boxed{\frac{e\langle j_z^{S_y}\rangle_{cor}}{\langle j_x \rangle} \propto \frac{J_{sd}^2 a^5 S_0 T}{v^2 D}}$$

Ratio does not depend on $k_F$ and $\tau$

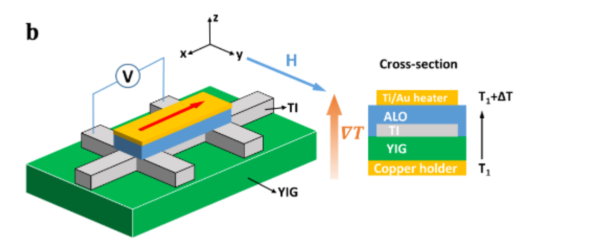
| Quantity | Symbol | Value |
|---|---|---|
| Fermi wave number | $k_F/\hbar$ | $10^9$ /m |
| Fermi velocity | $v$ | $5 \times 10^5$ m/s |
| Impurity relaxation time | $\tau$ | $10^{-13}$ s |
| *s*-*d* coupling | $J_{sd}$ | 10 meV |
| Lattice constant | $a$ | $10^{-9}$ m |
| Stiffness ($/a^2$) | $D/a^2$ | 5 meV |
| Spin | $S_0 a^2$ | 5/2 |
| Temperature | $k_B T$ | 30 meV |

$$j_z^{S_y}/E_x \sim 10^1\ (\hbar/e)\ (\Omega\ \mathrm{cm})^{-1}$$

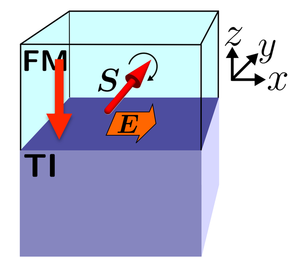
## 2. Thermal transport

(N.O., M.R. Masir, and A. H. MacDonald)

### Phenomenon under Temperature gradient

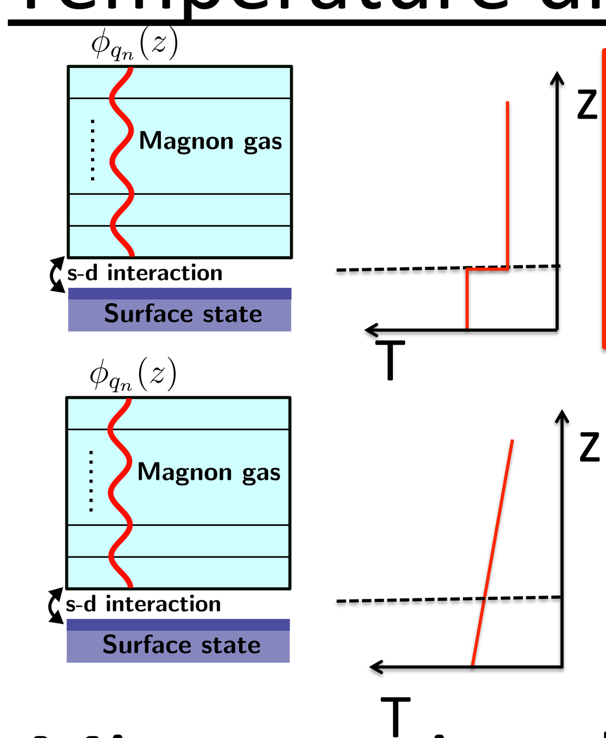


Z. Jiang, *et al.*, Nat. Commun. **7**, 11458 (2016).




- Spin seebeck effect (spin injection)
- Conversion from magnon spin to electron spin
- Electric field generation

### Temperature distribution




1. Step-like gradient
   Electron temperature: $T_e$
   Magnon temperature: $T_m$

This poster

2. Uniform gradient (Now calculating)

**Open question**

What is the correct treatment of the gradient?

### Microscopic calculation (Boltzmann eqn.)

$$\frac{\partial \delta n_{\boldsymbol{p}}}{\partial t} = \text{【Electron-magnon scattering】} + \text{【impurity scattering】}$$

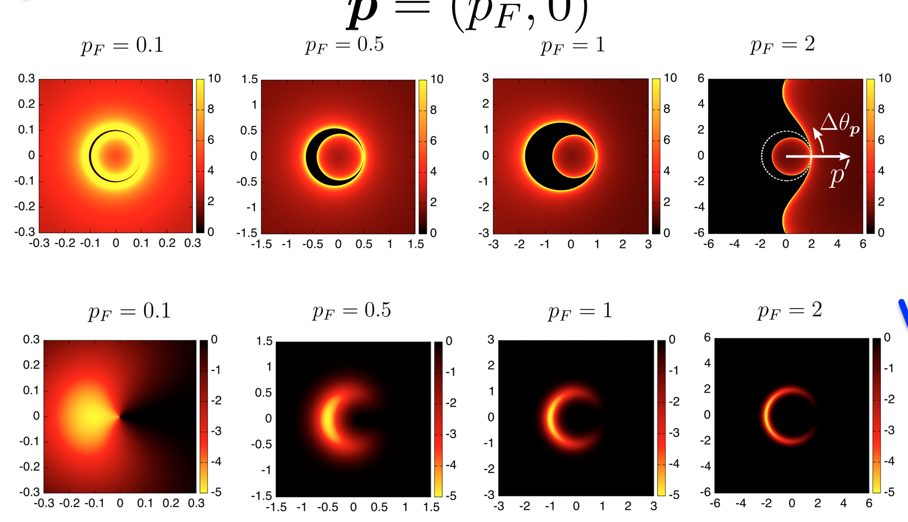
cf.) electrical transport

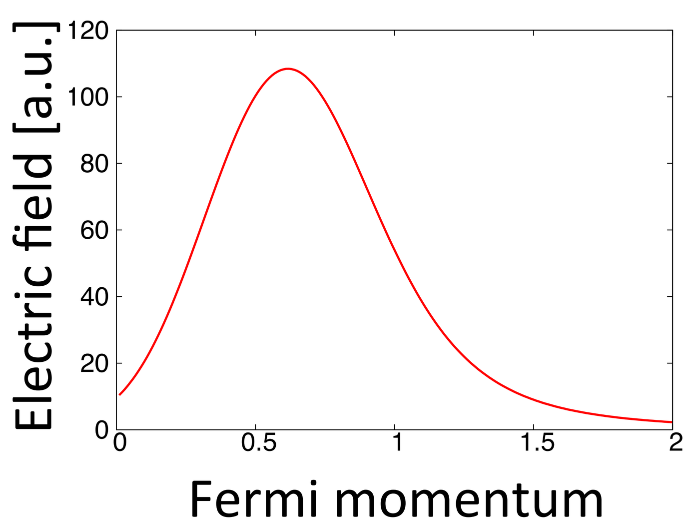
$$\frac{\partial \delta n_{\boldsymbol{p}}}{\partial t} + e\boldsymbol{E}\cdot\boldsymbol{v}_{\boldsymbol{p}}\frac{\partial f}{\partial \xi_{\boldsymbol{p}}} = \text{【impurity scattering】}$$

- Golden rule for electron-magnon scattering

$$\propto \sum_{p'} \underbrace{\sum_q \delta(\xi_p - \xi_{p'} - \omega_{p-p',q})}_{\text{Magnon weight function } W_{p,p'}} \underbrace{P_{p,p'}(1-f_p)f_{p'}n(\xi_p - \xi_{p'})}_{\text{Scattering probability × statistical factor } A_{p,p'}} + \cdots$$

$$\boldsymbol{p} = (p_F, 0)$$




### Future work

- Considering the magnon Boltzmann eqn.
- Considering the proper Boundary condition.