基研研究会「熱場の量子論 とその応用」2011-08-23

加速系におけるスピン軌道相互作用と スピン流生成

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References:

[1] Phys. Rev. Lett. 106, 076601(2011)

[2] Appl. Phys. Lett. 98, 242501(2011)

[3] arXiv:1106.0366 (to appear in PRB)

Outline

Spin current

Spin Hall Effect

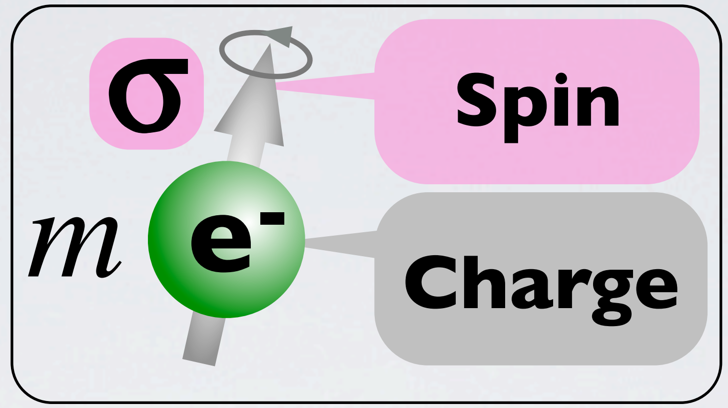
Spin current generation from mechanical rotation (Talk)

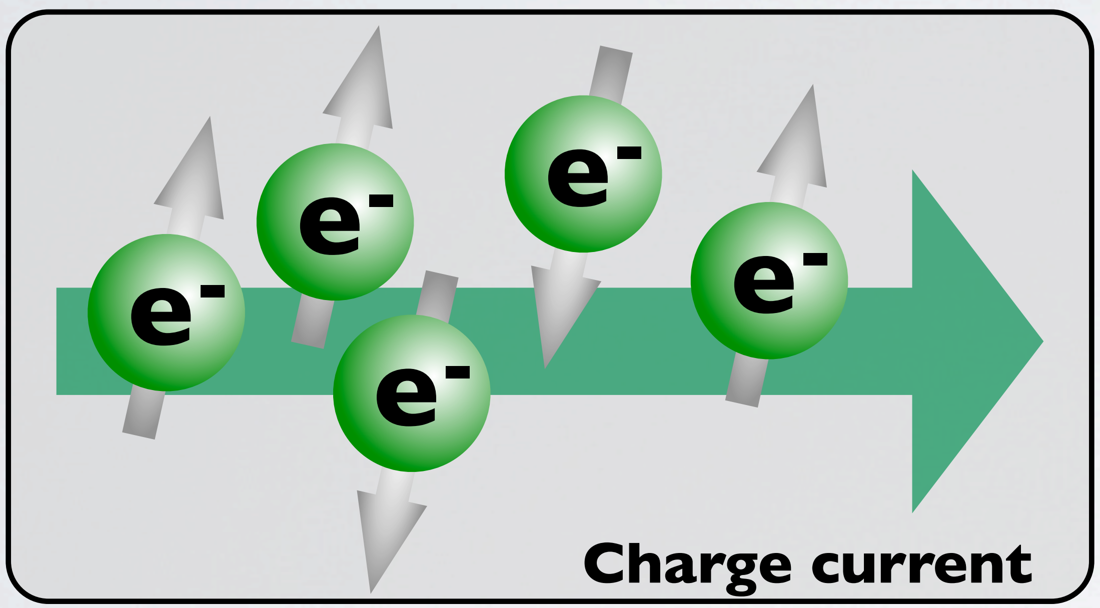
Spin current generation from linear acceleration(Poster)

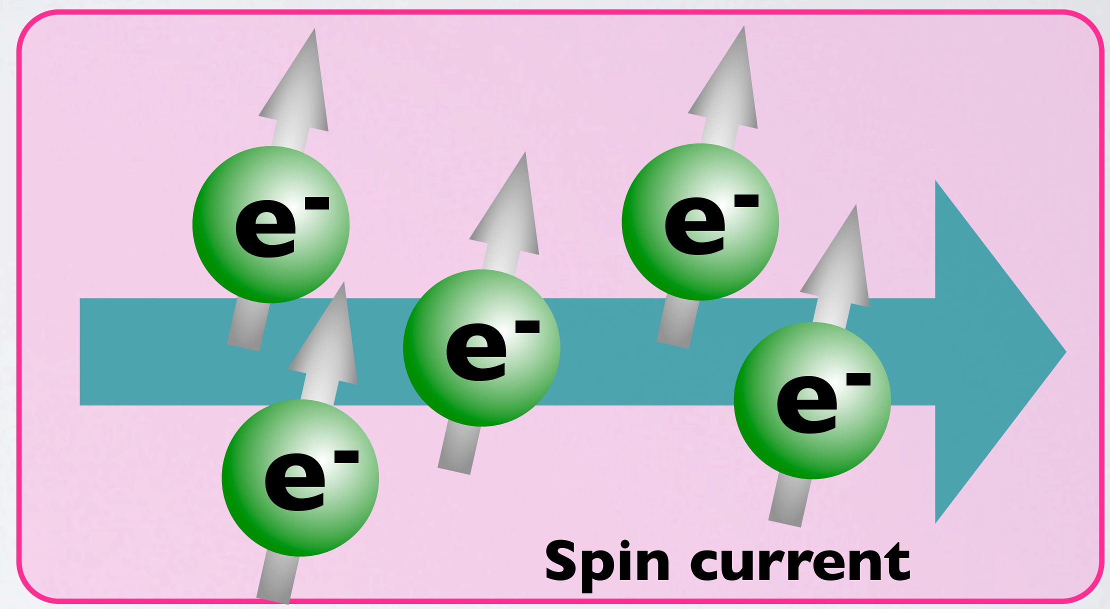
Summary

Spin current

Spin current & spintronics







Spintronics (Spin electronics)

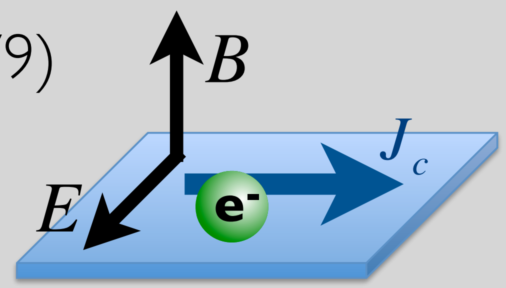
Generation/Manipulation/Detection of ***Spin current***

From charge to spin current

19th century

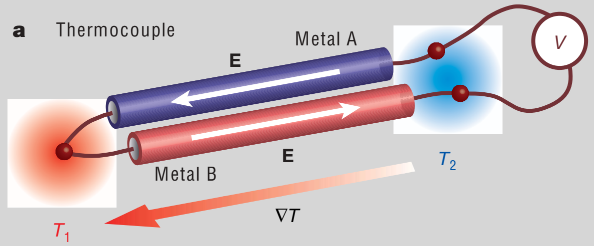
Hall effect

Hall (1879)



Seebeck effect

Seebeck (1821)



Electromotive force

Faraday
(1831)

21st century

Spin Hall effect

Dyakonov-Perel PLA (1971)
Hirsh, PRL (1999)

Kato et al., Science (2004)

Inverse Spin Hall effect

Saitoh et al., APL (2006)

Spin Seebeck effect

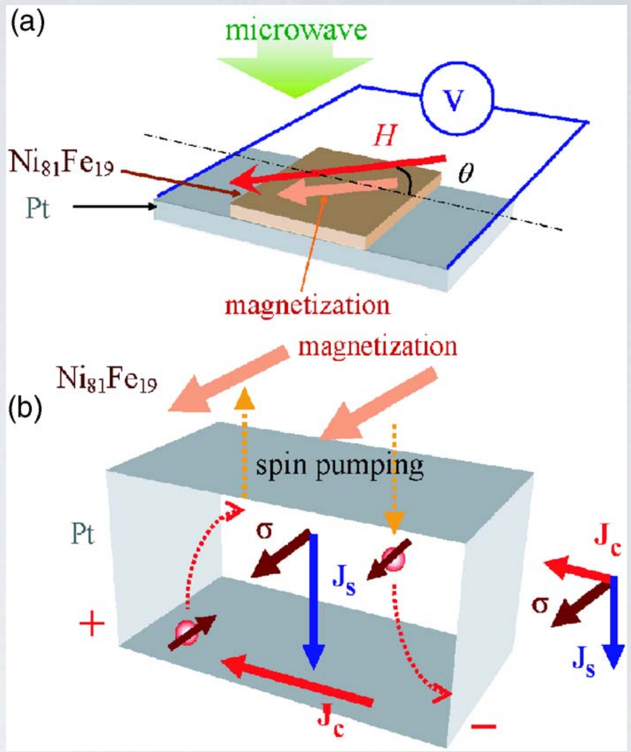
Uchida et al., Nature (2008)

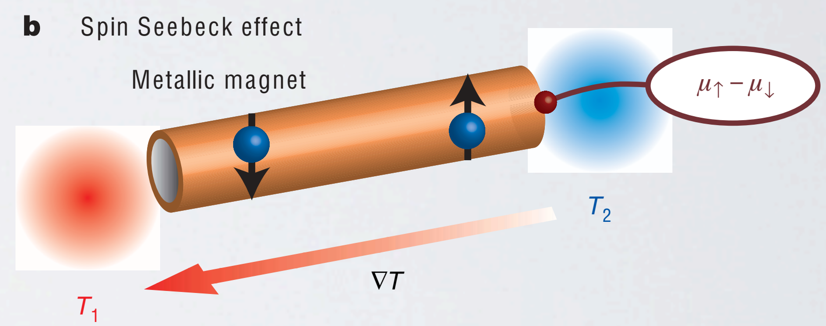
Xiao et al., PRB (2010)
Adachi et al., PRB (2011)

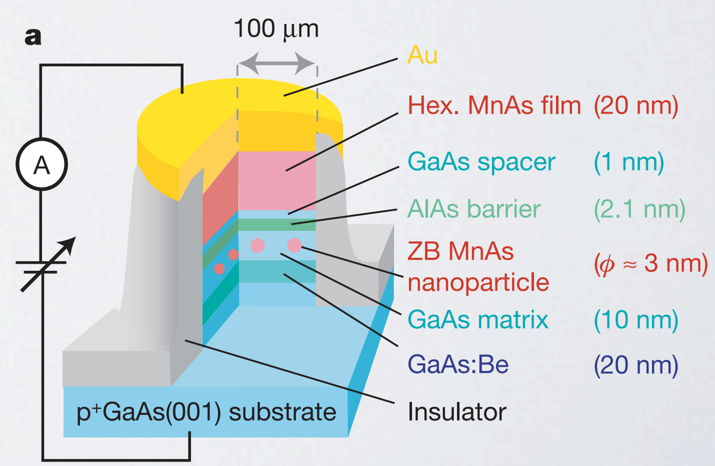
Spinmotive force

Barnes-Maekawa PRL(2007)

Hai et al., Nature (2009)

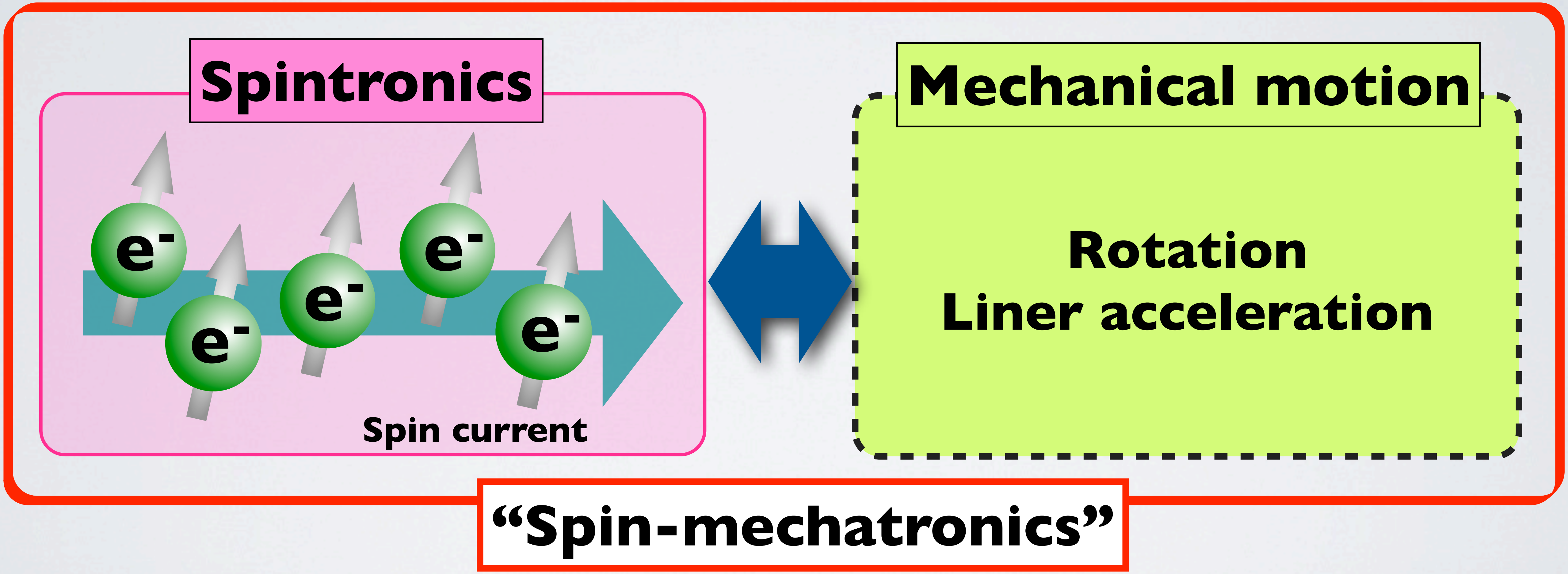






"Spin-mechatronics"

"Spin-mechatronics"
strongly coupling of mechanical motion
with spin/charge transport in nanostructures



Spintronics in non-inertial frames!

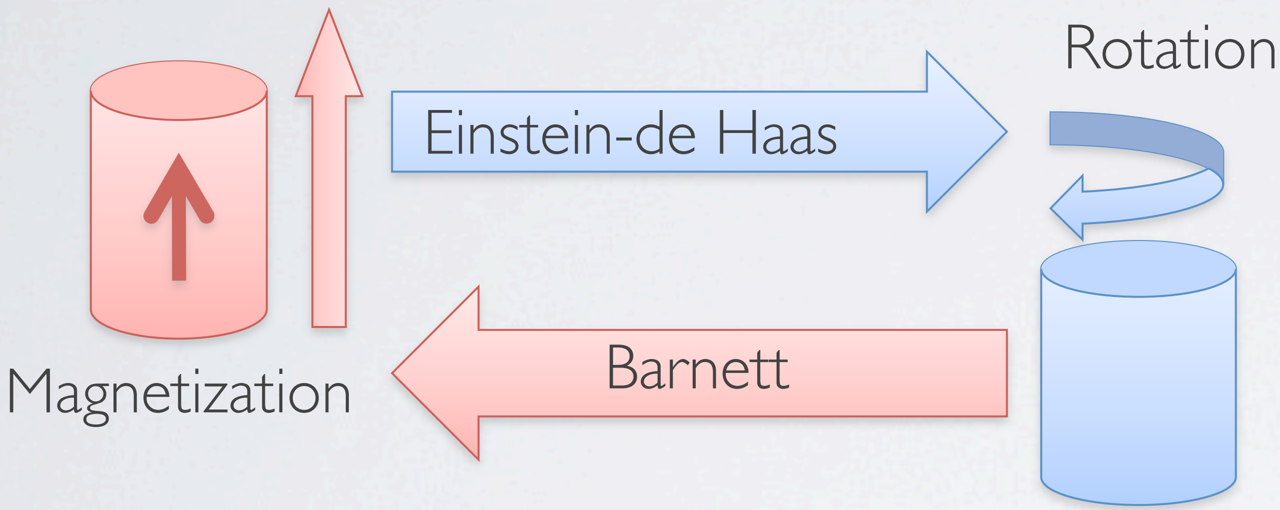
Mechanical rotation, Magnetization, & Spin current

Magnetization & Rotation

In 1915

Einstein-de Haas effect

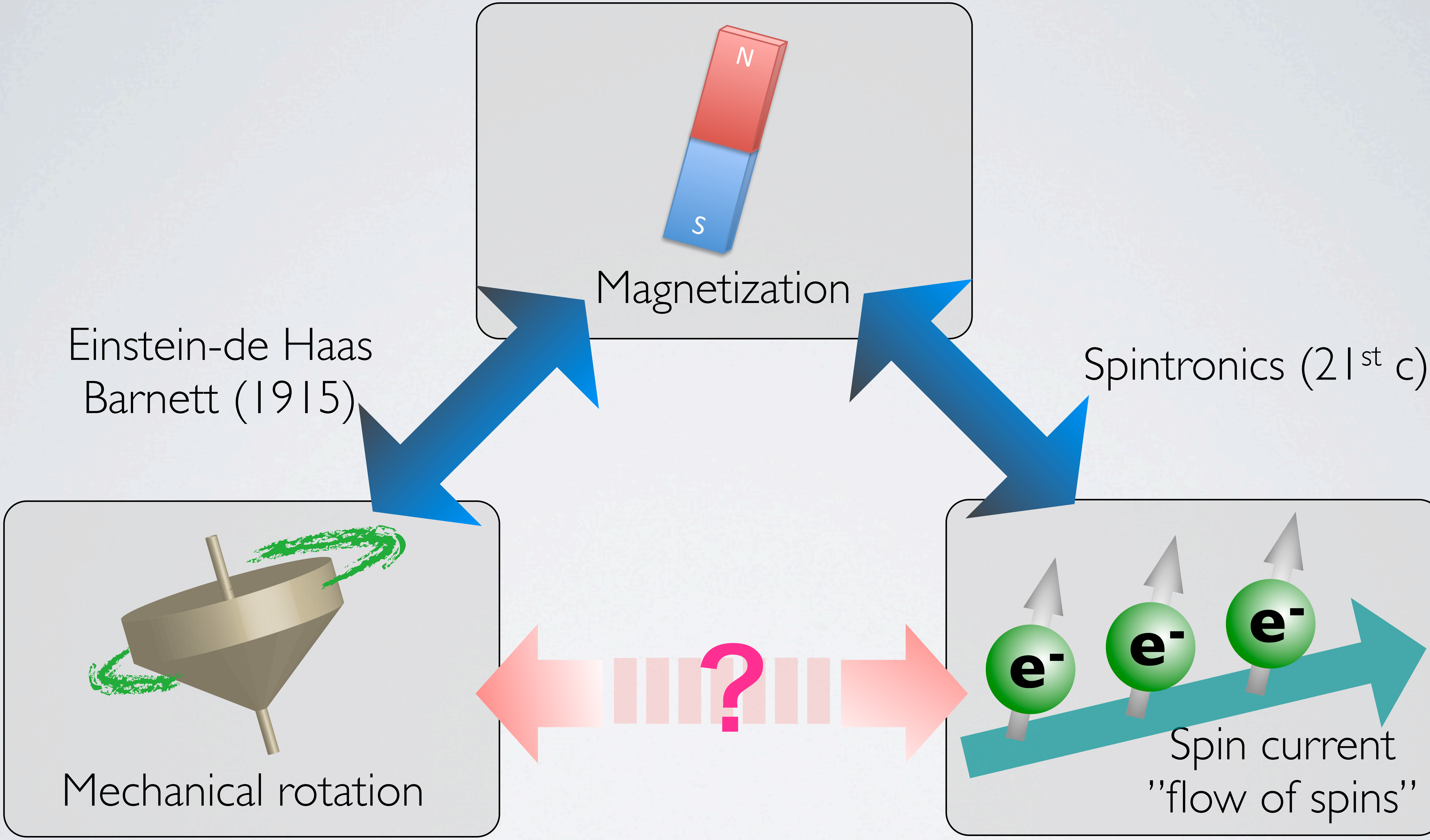
Barnett effect



→ Gyromagnetic ratio of electron

"Einstein's Only Experiment"

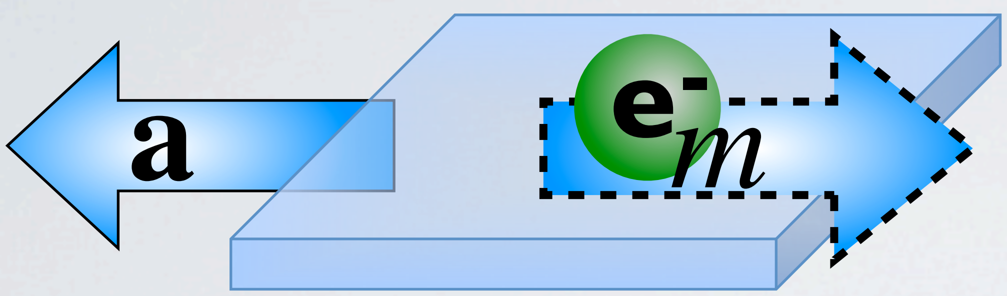
Motivation



Fundamental theory of the direct coupling
between mechanical rotation & spin current?

Inertial forces on charge/spin

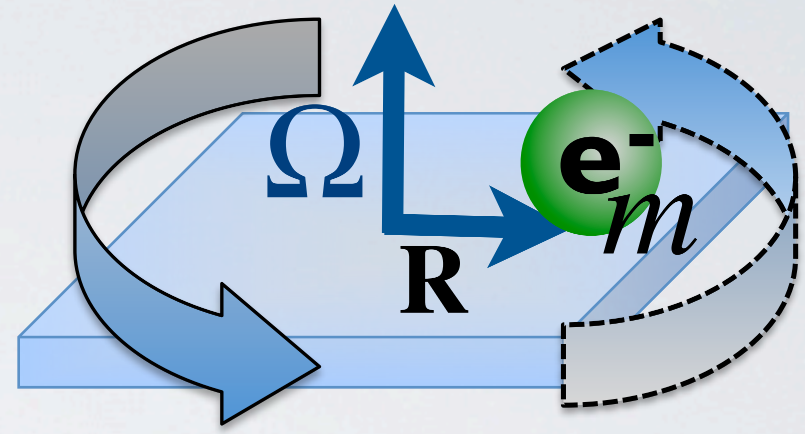
Linear acceleration



$$-m\mathbf{a} = -e\boxed{(m/e)\mathbf{a}}$$

$\mathbf{E}_{\text{eff}}$

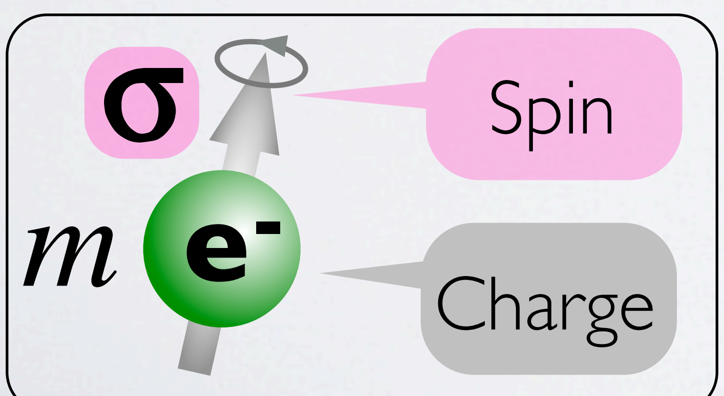
Rotational acceleration



$$-2m\mathbf{v}\times\mathbf{\Omega} = -e\mathbf{v}\times\boxed{2(m/e)\mathbf{\Omega}}$$

Coriolis

$\mathbf{B}_{\text{eff}}$

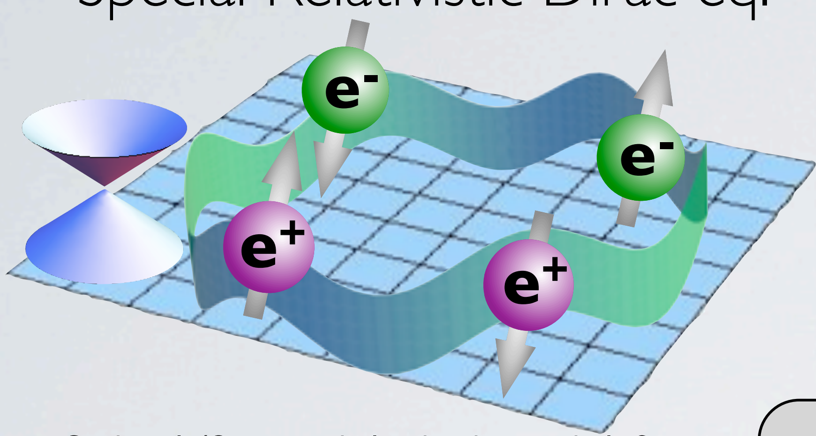


Inertial effects on spins?

Consult **general relativity** about **inertial effects on spins!**

Quantum mechanics in inertial/noninertial frame

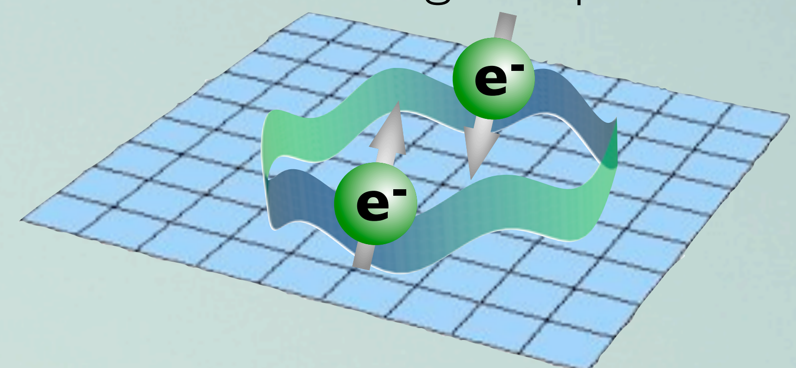
Special Relativistic Dirac eq.



Spin-1/2 particle in inertial frame

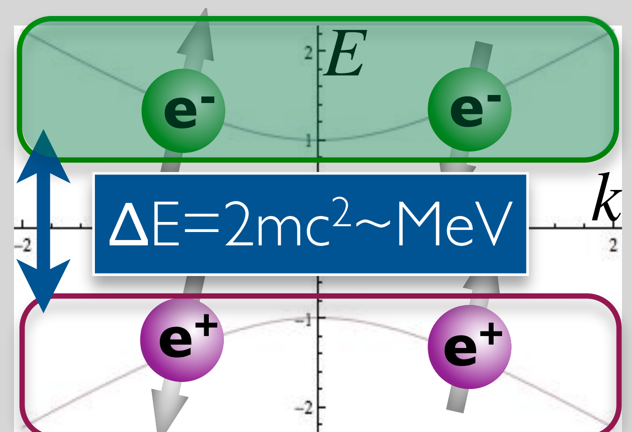
Low energy limit

Pauli-Schrödinger equation

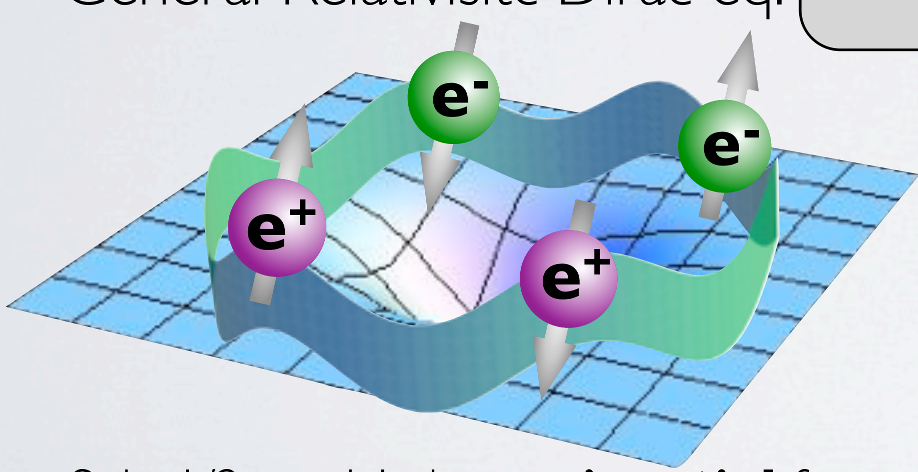


- Coulomb/Lorentz
- Zeeman
- Spin-Orbit Int.

$$\psi = \begin{pmatrix} \psi_{e,\uparrow} \\ \psi_{e,\downarrow} \\ \psi_{\bar{e},\downarrow} \\ \psi_{\bar{e},\uparrow} \end{pmatrix}$$



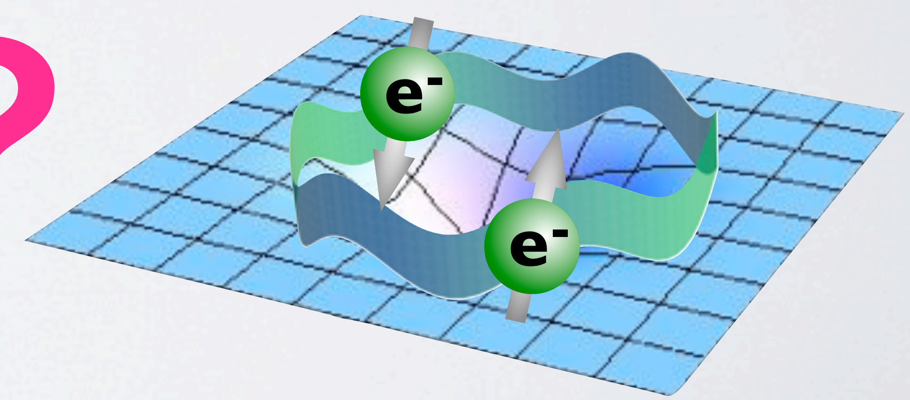
General Relativisitc Dirac eq.



Spin-1/2 particle in **noninertial** frame

?

Pauli-Schrödinger equation
in **noninertial** frame



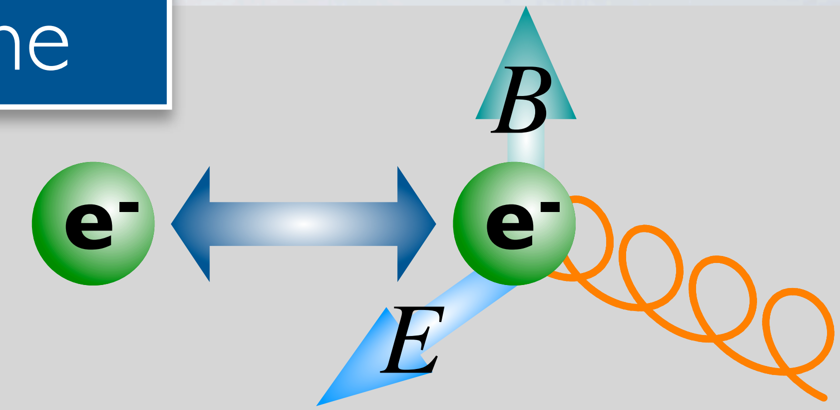
Spin Hall Effect in inertial frame

Pauli-Schrödinger eq. in inertial frame

Low energy limit of Dirac eq. in inertial frame

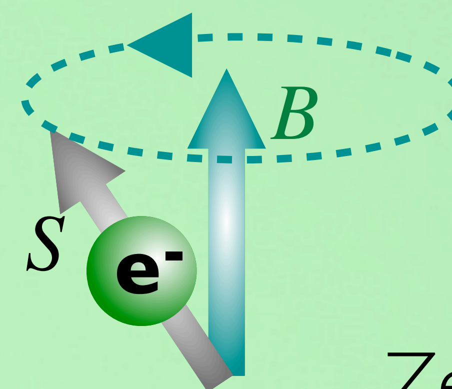
$$H = \frac{1}{2m}(\mathbf{p} + e\mathbf{A})^2 + e\phi$$

Coulomb
& Lorentz



$$-\mu_B \boldsymbol{\sigma} \cdot \mathbf{B}$$

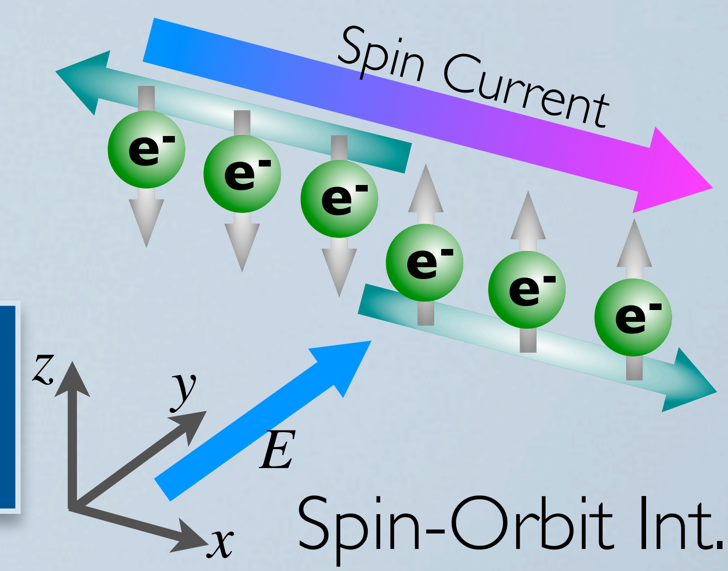
Zeeman



$$+\frac{\lambda}{\hbar}\boldsymbol{\sigma} \cdot \left[(\mathbf{p} + e\mathbf{A}) \times (-e)\mathbf{E}\right]$$

Spin-Orbit Int.

"Special relativistic effect"
originating from Dirac eq.



Enhancement of SOI in condensed matter

Spin-Orbit Interaction $\boxed{\frac{\lambda}{\hbar}}\boldsymbol{\sigma}\cdot\left[(\mathbf{p}+e\mathbf{A})\times(-e)\mathbf{E}\right]$

In Vacuum $\frac{\lambda(mv)^2}{\hbar^2}=\left(\frac{v_e}{c}\right)^2\sim 10^{-4}$

Enhancement of SOI in matter

In Pt $\frac{\lambda(mv)^2}{\hbar^2}\Rightarrow\boxed{\bar{\lambda}k_F^2\sim 0.6}$

Discoveries of large SOI systems

- Pt, ...
- GaAs, InAs, ...

[Exp] Vila et al, Phys. Rev. Lett. ('07)
[Theo] Guo et al, Phys. Rev. Lett. ('08)

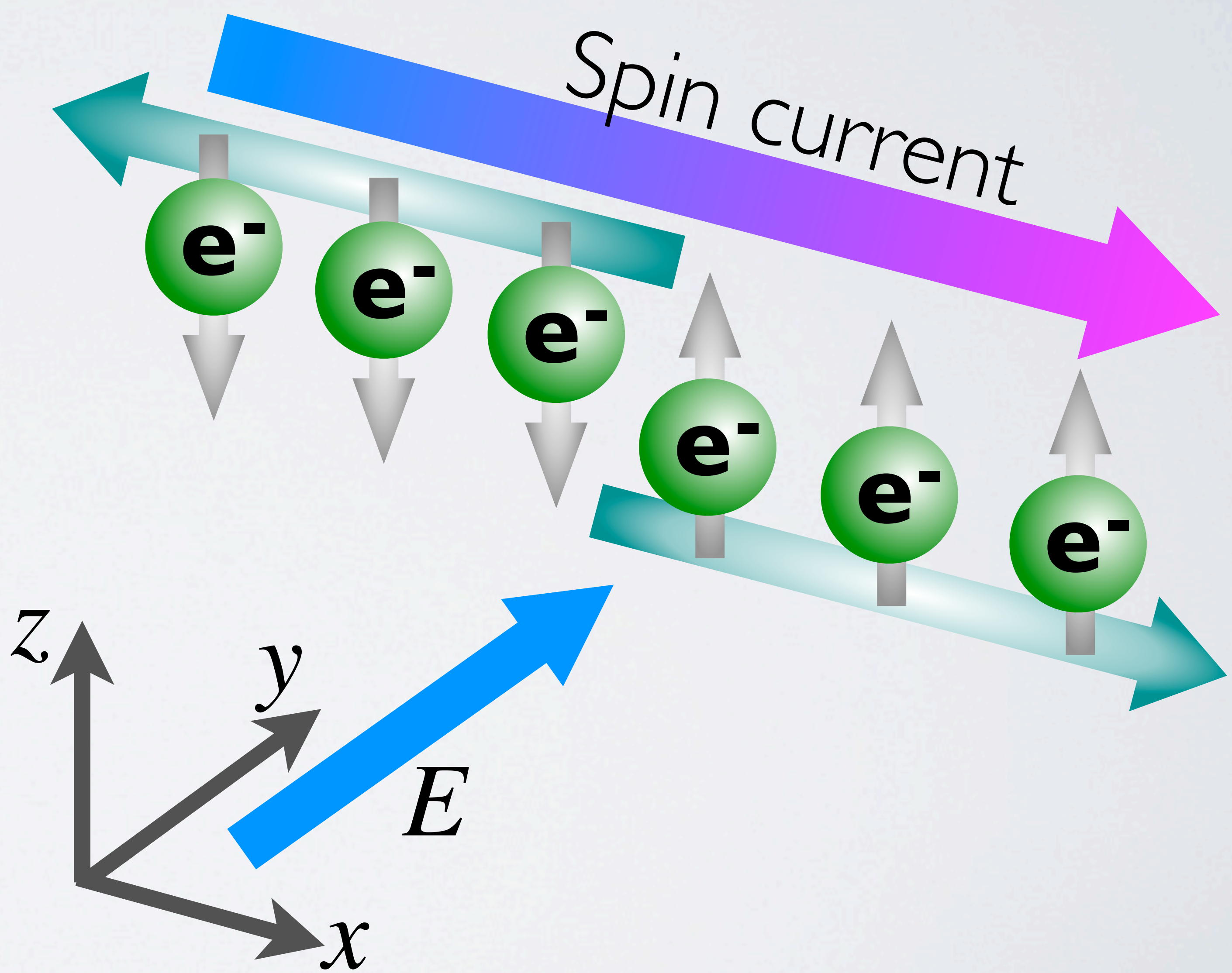
Spin Hall effect in inertial frame

$$H = \frac{1}{2m}(\mathbf{p}+e\mathbf{A})^2 + e\phi - \bar{\mu}\boldsymbol{\sigma}\cdot\mathbf{B} + \boxed{\frac{\bar{\lambda}}{\hbar}\boldsymbol{\sigma}\cdot\left[(\mathbf{p}+e\mathbf{A})\times(-e)\mathbf{E}\right]}$$

Spin-Orbit Interaction

$$\underset{\boxed{\pm x}}{\frac{d}{dt}\mathbf{r}} = \mathbf{v}\,\boxed{-\frac{e\bar{\lambda}}{\hbar}\underset{\boxed{\pm z}}{\boldsymbol{\sigma}}\times \underset{\boxed{y}}{\mathbf{E}}}$$

Spin-dependent velocity

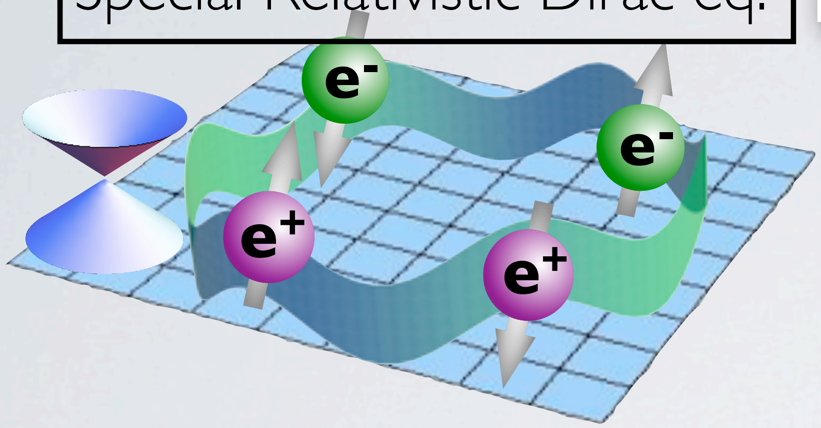


Spin current generated perpendicular to E-field

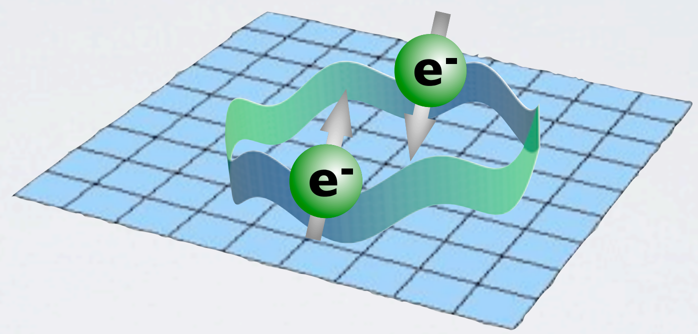
Spin Hall Effect in non-inertial frame

Inertial effects on spin-orbit interaction?

Special Relativistic Dirac eq.

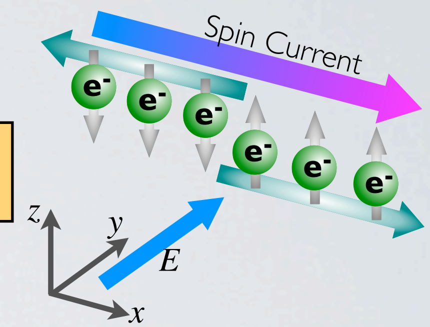


Pauli-Schrödinger equation
in **inertial** frame

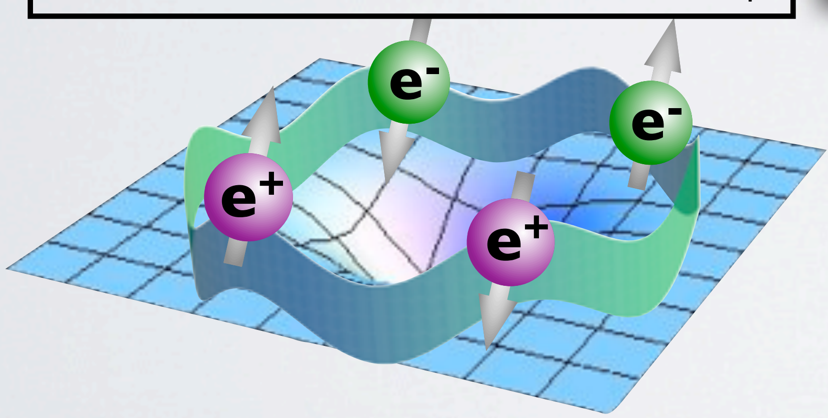


Spin-Orbit Int.

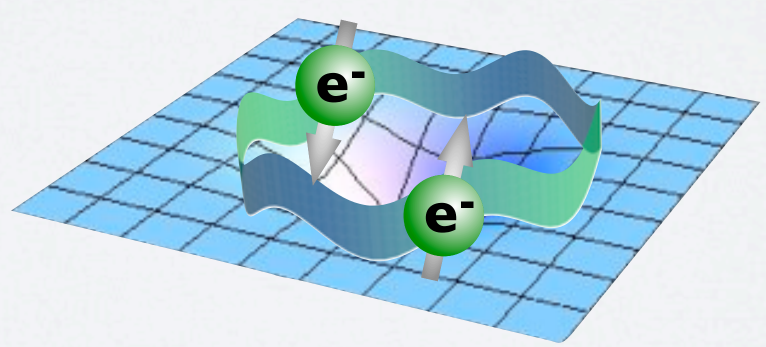
Spin Hall effect



General Relativisitc Dirac eq.



Pauli-Schrödinger equation
in **non-inertial** frame



Spin-Orbit Int.
in **non-inertial** frame

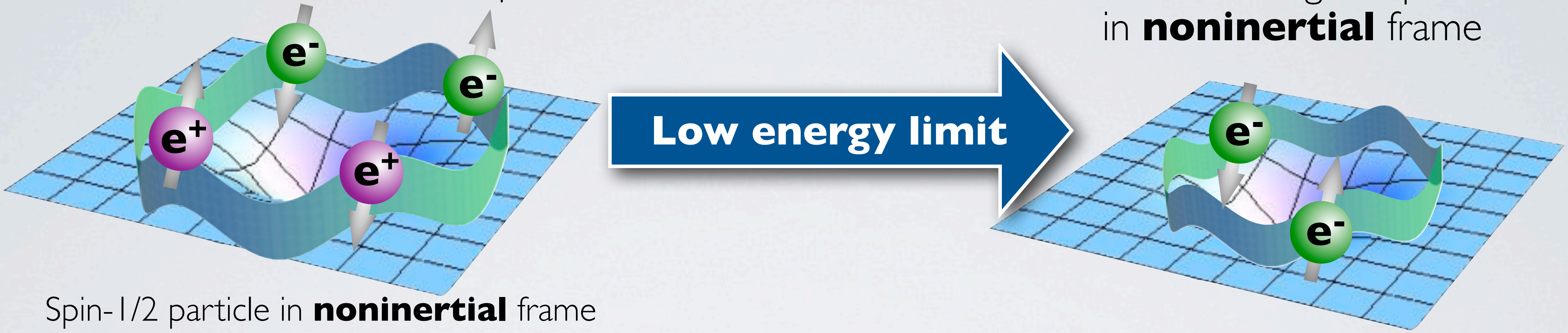
Spin Hall effect
in **non-inertial** frame

?

Rigorous derivation of inertial spin-orbit interaction

General Relativisitc Dirac eq.

Pauli-Schrödinger equation
in **noninertial** frame



Spin-1/2 particle in **noninertial** frame

Gravitational field due to massive point particle with electromagnetic field:

de Oliveira - Tiomno, Nuovo Cimento (1962)

Gravitational field in Schwarzschild spacetime without electromagnetic field:
e.g. Obukhov, Phys. Rev. Lett. (2000), Silenko-Teryaev, Phys. Rev. D (2007)

Rigid rotation & Liner acceleration **without** electromagnetic field:

Hehl - Ni, Phys. Rev. D (1990)

Rigid rotation **with** electromagnetic field:

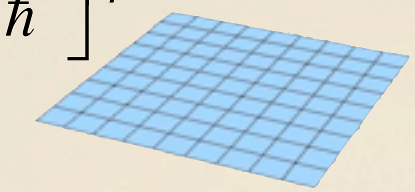
MM, Ieda, Saitoh, & Maekawa, Phys. Rev. Lett. (2011)

How to derive SOI?

E-M and gravitational fields can be included by introducing "covariant derivatives."

Dirac eq. with E-M fields

$$\left[\gamma^{\mu}\left(\partial_{\mu}-i\frac{q}{\hbar}A_{\mu}\right)+\frac{mc}{\hbar}\right]\psi=0$$



$$\left\{\gamma^{\mu},\gamma^{\nu}\right\}=2g^{\mu\nu}$$

$$H=\beta mc^{2}+c\boldsymbol{\alpha}\cdot\left(\mathbf{p}+e\mathbf{A}\right)+eA_{0}$$

Foldy-Wouthuysen 1950
Tani 1951

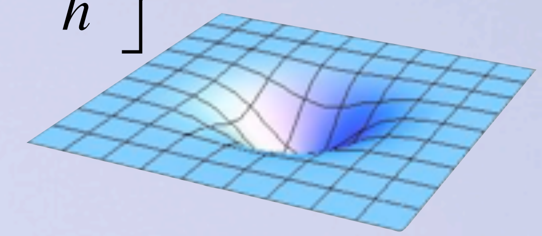
$$H_{Z}^{O(1/m)}=\mu_{B}\boldsymbol{\sigma}\cdot\mathbf{B}$$

$$H_{SOI}^{O\left(1/m^{2}\right)}=\frac{-e\lambda}{\hbar}\boldsymbol{\sigma}\cdot\left[\left(\mathbf{p}+\mathbf{A}\right)\times\mathbf{E}\right]$$

Flat space-time (inertial frame)

Dirac eq. with E-M & gravitational fields

$$\left[\gamma^{\mu}\left(x\right)\left(\partial_{\mu}-\Gamma_{\mu}\left[g\left(x\right)\right]-i\frac{q}{\hbar}A_{\mu}\right)+\frac{mc}{\hbar}\right]\psi=0$$



$$\left\{\gamma^{\mu}\left(x\right),\gamma^{\nu}\left(x\right)\right\}=2g^{\mu\nu}\left(x\right)$$

$$g_{00}=-1+\Omega^{2}r^{2}/c^{2},\ g_{ij}=\delta_{ij},\ g_{0i}=g_{i0}=\left(\boldsymbol{\Omega}\times r/c\right)_{i}$$

Curved space-time (non-inertial frame)

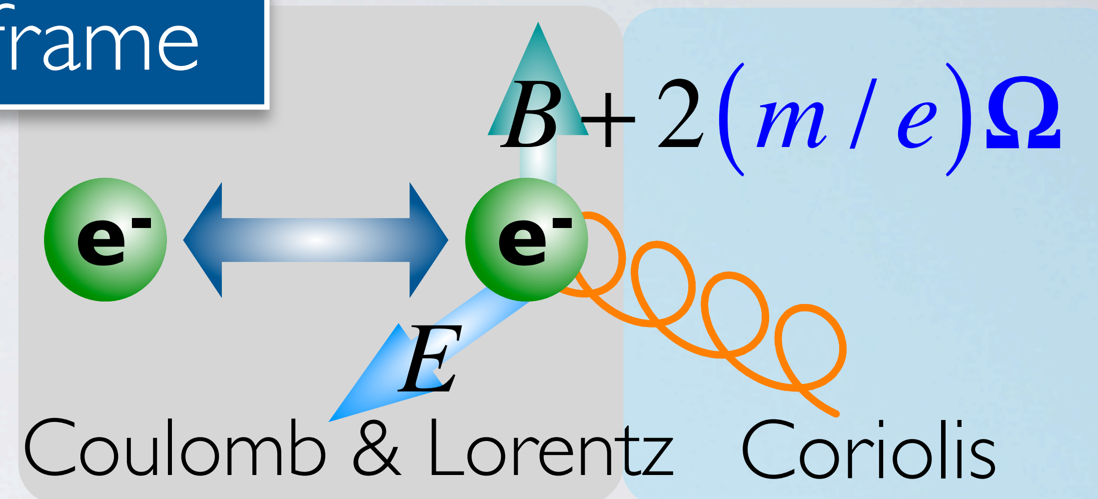
Pauli-Schrödinger eq. in rotating frame

Low energy limit of Dirac eq. in rotating frame

$$H = \frac{1}{2m}(\mathbf{p}+e\mathbf{A})^2 + e\phi \quad -\mathbf{L}\cdot\boldsymbol{\Omega}$$

Coulomb & Lorentz

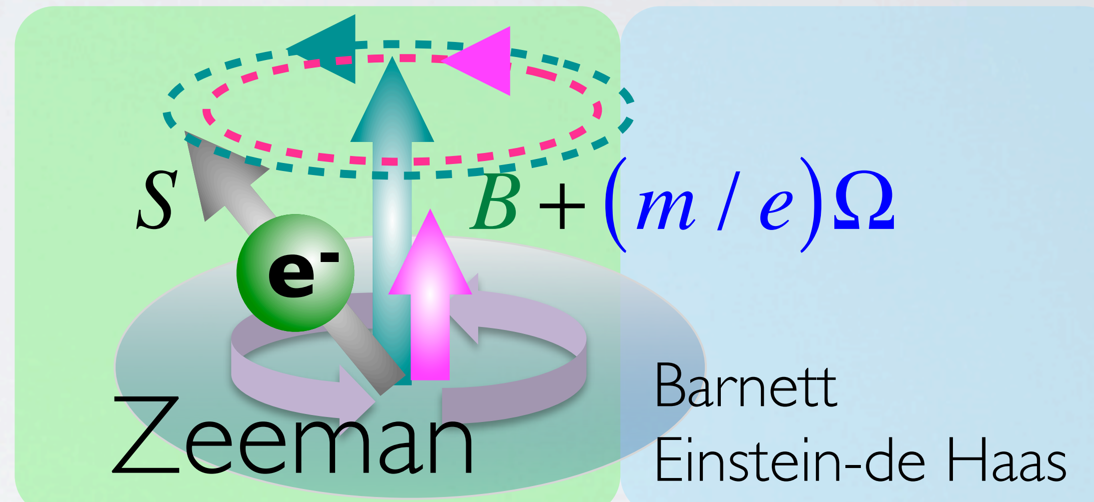
Coriolis



$$-\mu_B \boldsymbol{\sigma}\cdot\left(\mathbf{B}+(m/e)\boldsymbol{\Omega}\right)$$

Zeeman

Barnett
Einstein-de Haas



$$+\frac{\lambda}{\hbar}\boldsymbol{\sigma}\cdot\left[(\mathbf{p}+e\mathbf{A})\times(-e)\left(\mathbf{E}+(\boldsymbol{\Omega}\times\mathbf{r})\times\mathbf{B}\right)\right]$$

NEW!

Inertial Spin Orbit Int.

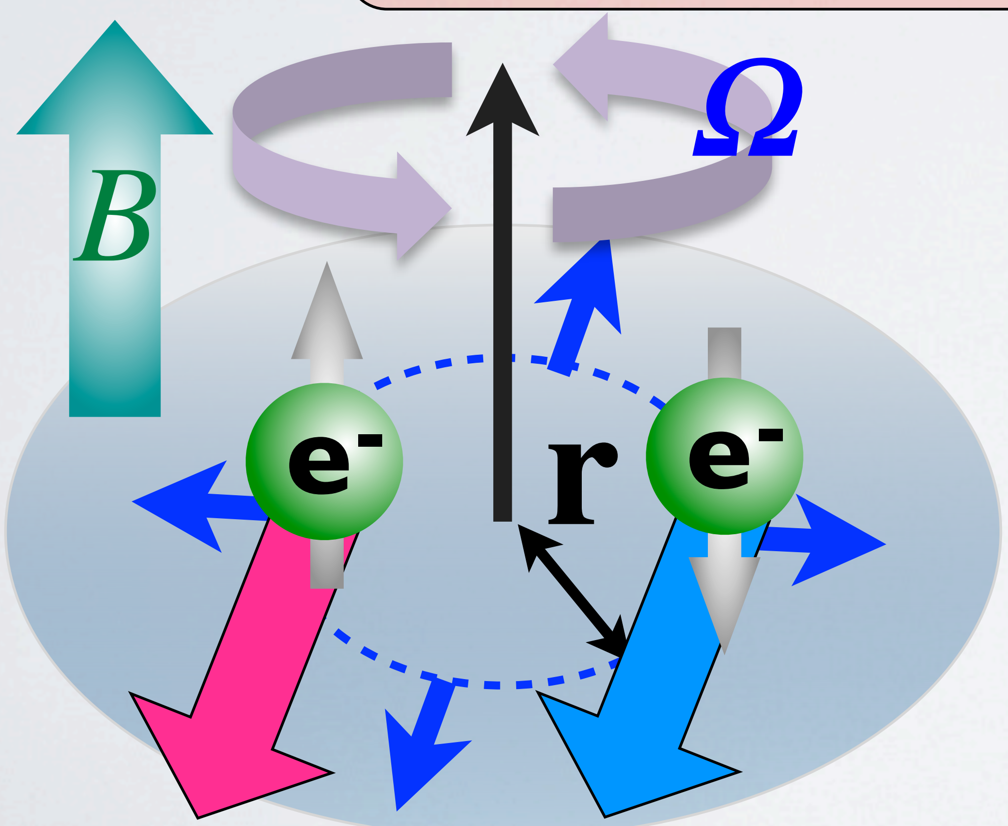
?

Spin Hall Effect in rotating frame

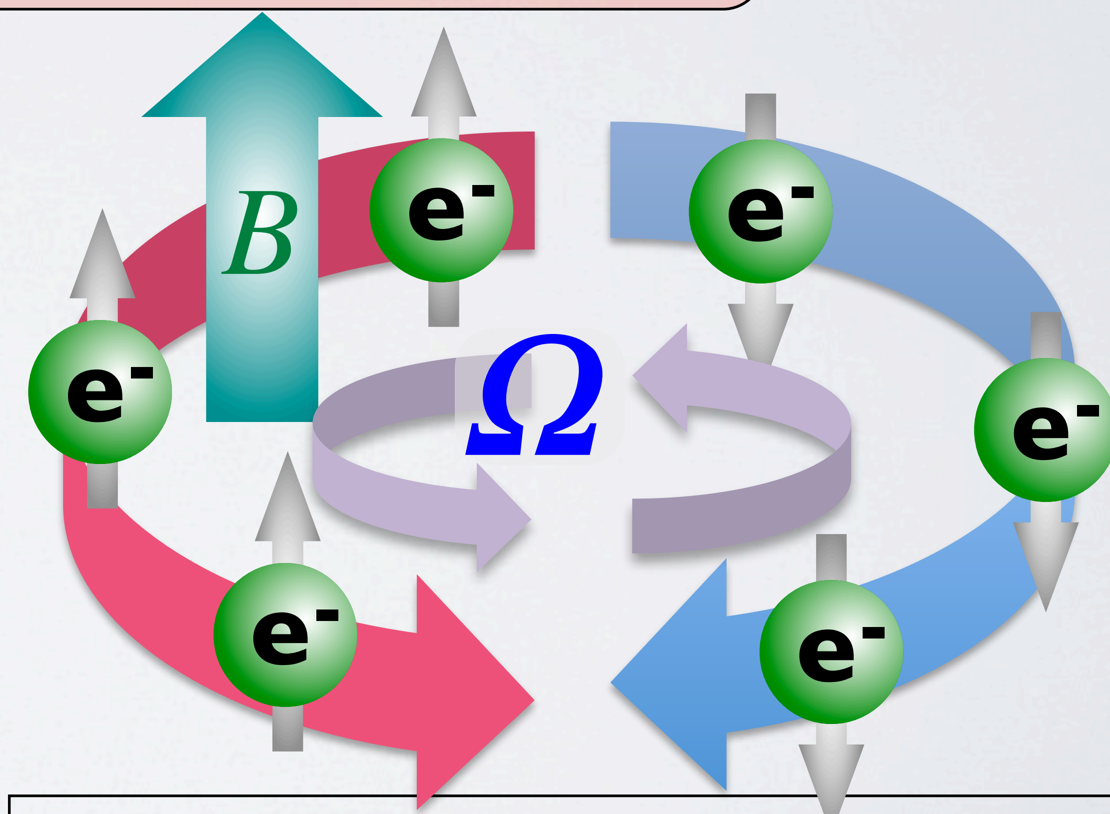
$$+\frac{\bar{\lambda}}{\hbar}\boldsymbol{\sigma}\cdot\left[(\mathbf{p}+e\mathbf{A})\times(-e)\left(\mathbf{E}+(\boldsymbol{\Omega}\times\mathbf{r})\times\mathbf{B}\right)\right]$$

$$\frac{d}{dt}\mathbf{r}=\mathbf{v}-\frac{e\bar{\lambda}}{\hbar}\boldsymbol{\sigma}\times\left(\mathbf{E}+(\boldsymbol{\Omega}\times\mathbf{r})\times\mathbf{B}\right)$$

±Azimuthal | ±z | $\mathbf{E}_{rot}$ | **Radial**



$$\mathbf{E}_{rot}=(\Omega\cdot B)\mathbf{r}$$

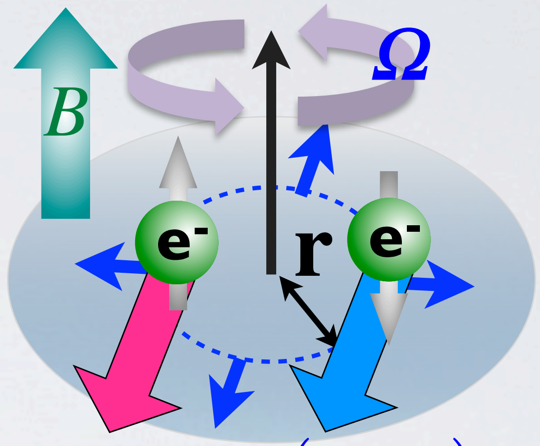


Spin current generated in azimuthal direction

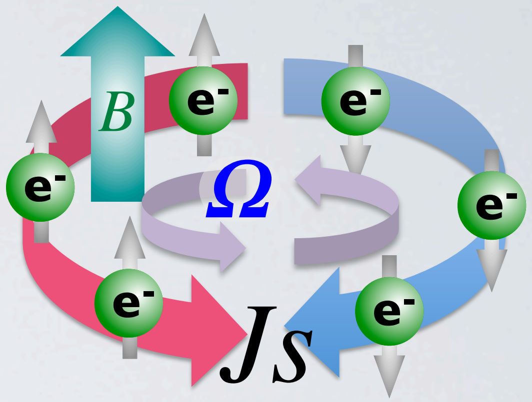
Spin current from mechanical rotation

Inertial spin Hall effect - "general relativistic effect in matter"

$$J_s^{\Omega \cdot B}(r) = 2ne\bar{\lambda}k_F^2 \frac{\hbar\Omega}{\varepsilon_F} \times \frac{eB}{m^*} \times r$$



$\mathbf{E}_{rot} = (\Omega \cdot B)\mathbf{r}$



Pt (Ballistic case)
r = 0.1m
B = 1T, Omega = 1kHz

$\rightarrow J_s = 10^8 A/m^2$

Ref.
(Ballistic regime) MM, J. Ieda, E. Saitoh, and S. Maekawa, Phys. Rev. Lett. 106, 076601(2011)
(Diffusive regime) MM, J. Ieda, E. Saitoh, and S. Maekawa, Appl. Phys. Lett. 98, 242501(2011)

Summary

Spin current generation from mechanical rotation

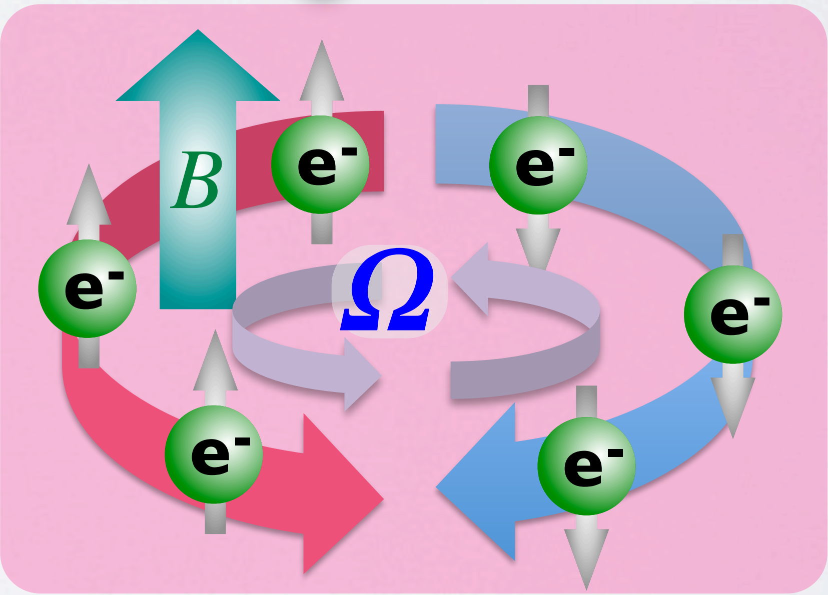
$$+\frac{\lambda}{\hbar}\boldsymbol{\sigma}\cdot\left[(\mathbf{p}+e\mathbf{A})\times(-e)\left(\mathbf{E}+\mathbf{E}_a+\mathbf{E}_{\Omega,B}\right)\right]$$

$$\mathbf{E}_a=(m/e)\mathbf{a} \qquad \mathbf{E}_{\Omega,B}=(\boldsymbol{\Omega}\times\mathbf{r})\times\mathbf{B}$$

Hehl-Ni PRD1990 MM, Ieda, Saitoh, Maekawa PRL2011

Enhancement of SOI in matter

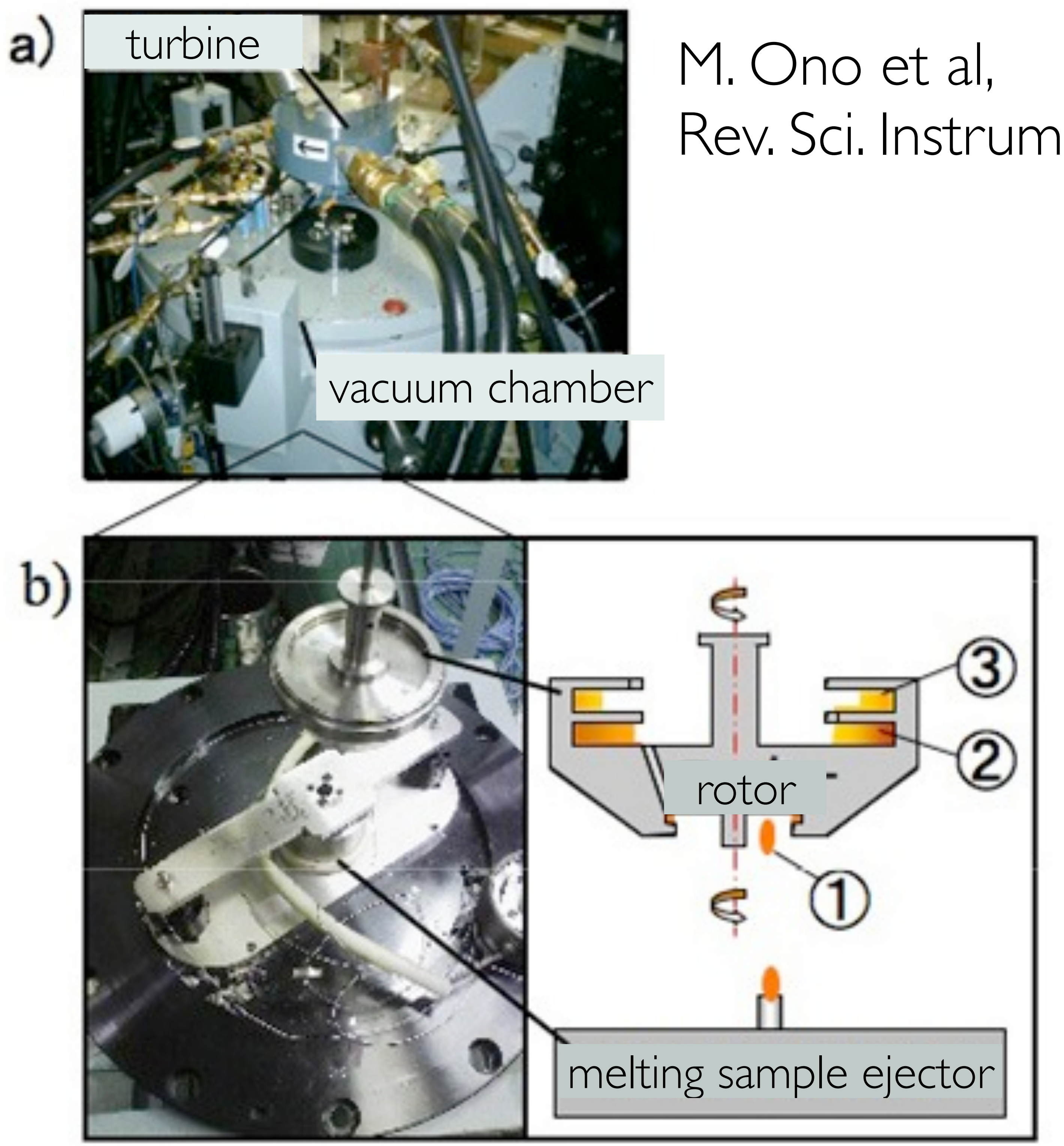
?



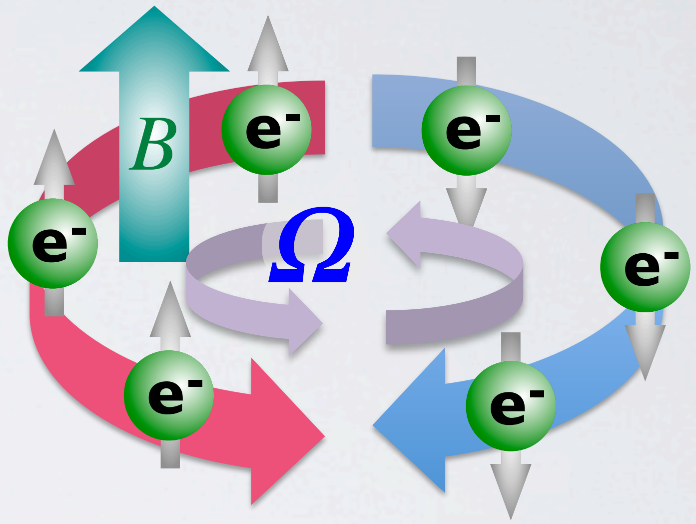
“Spin-mechatronics”

MM, Ieda, Saitoh, Maekawa, arXiv:1106.0366 (to appear in PRB)

Ultra high speed rotor in JAEA



M. Ono et al,
Rev. Sci. Instrum. 80, 082908 (2009)

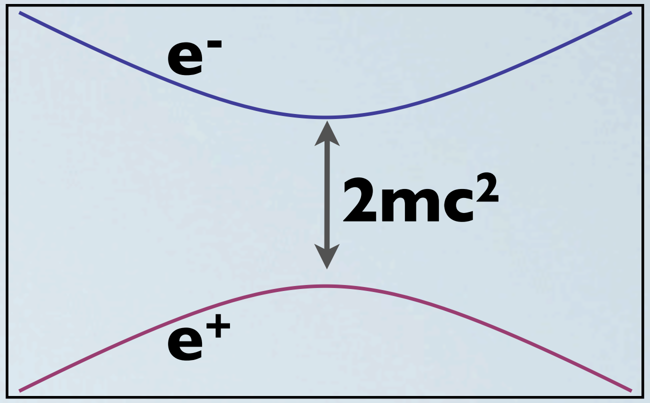


On going experiment for generation/detection of spin current due to mechanical rotation!

Backup Slides

from Dirac to Effective theory

Dirac eq. $H_{\text{Dirac}} = \beta mc^2 + c\left(\mathbf{p} + e\mathbf{A}\right)\cdot\boldsymbol{\alpha} + e\phi$



Low energy limit + Projection

Pauli-Schrödinger eq. $H_{\text{Pauli}} = \frac{1}{2m}\left(\mathbf{p} + e\mathbf{A}\right)^2 + e\phi + \mu_B \boldsymbol{\sigma}\cdot\mathbf{B} + \frac{e\lambda}{\hbar}\boldsymbol{\sigma}\cdot\left(\mathbf{p} + e\mathbf{A}\right)\times\mathbf{E}$

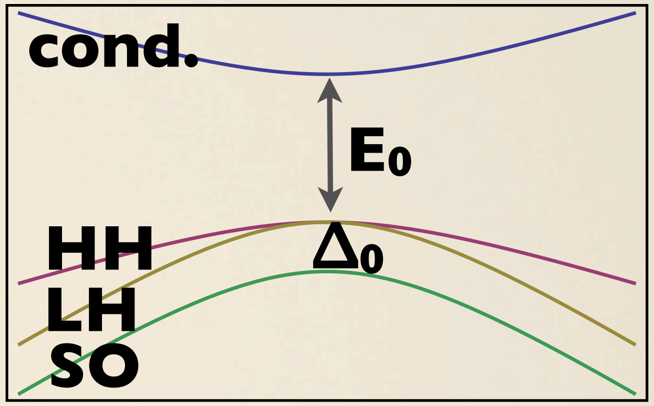
vacuum

matter

K.p perturbation

R. Winkler, "Spin-orbit coupling effects in two-dimensional electron and hole systems", Springer, 2006

e.g. 8x8 Kane model $H_{\text{Kane}} = \ldots$



Projection to cond. band

Effective theory for conduction electron

$$H_{\text{eff}} = \frac{1}{2m}\left(\mathbf{p} + e\mathbf{A}\right)^2 + e\phi + \bar{\mu}_B \boldsymbol{\sigma}\cdot\mathbf{B} + \frac{e\bar{\lambda}}{\hbar}\boldsymbol{\sigma}\cdot\left(\mathbf{p} + e\mathbf{A}\right)\times\mathbf{E}$$

$$\bar{\lambda}/\lambda = \frac{P^2}{3}\left[\frac{1}{E_0^2} - \frac{1}{\left(E_0 + \Delta_0\right)^2}\right] / \left(\hbar / 4m^2c^2\right)$$

E-M field in rotating frame

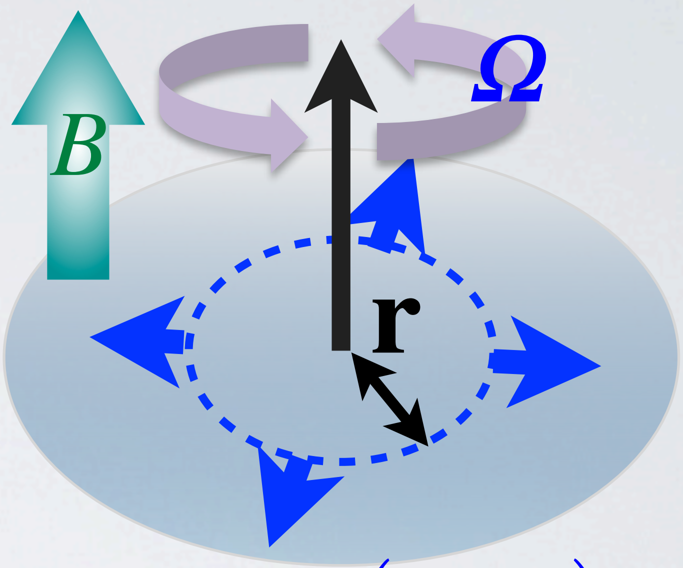
Rotation (non-inertial frame) asymmetry of E/c & B

$$\tilde{H}_{SOI} = \frac{\lambda}{\hbar}\boldsymbol{\sigma}\cdot\left[(\mathbf{p}-q\mathbf{A})\times q\left(\mathbf{E}+(\boldsymbol{\Omega}\times\mathbf{r})\times\mathbf{B}\right)\right]$$

$$\begin{cases}\mathbf{E}_{\mathrm{rot}} \approx \mathbf{E}_{\mathrm{rest}} + (\boldsymbol{\Omega}\times\mathbf{r})\times\mathbf{B}_{\mathrm{rest}} \\ \mathbf{B}_{\mathrm{rot}} \approx \mathbf{B}_{\mathrm{rest}}\end{cases} \quad (\text{rotating frame})$$

$\Uparrow$ general coordinate tr. by velocity $\boldsymbol{\Omega}\times\mathbf{r}$

$$\begin{cases}\mathbf{E}_{\mathrm{rest}} \\ \mathbf{B}_{\mathrm{rest}}\end{cases} \quad (\text{rest frame})$$



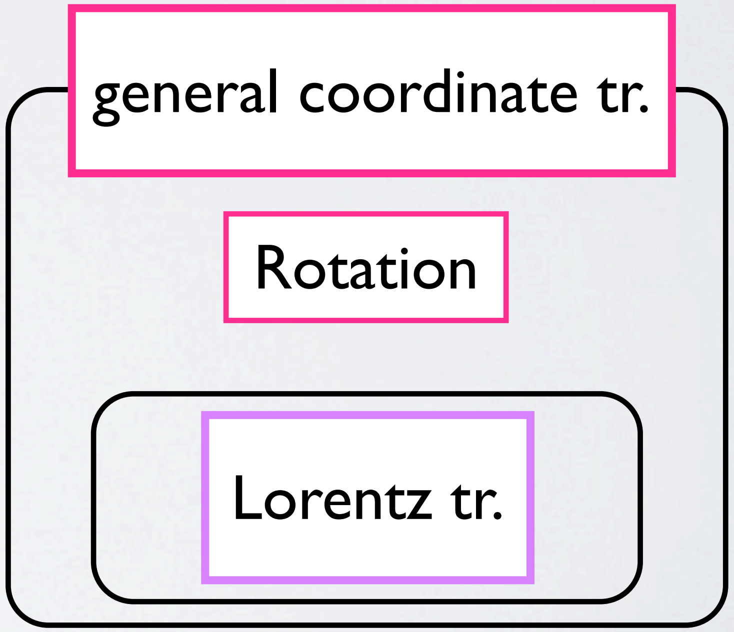
$$\mathbf{E}_{rot} = (\Omega\cdot B)\mathbf{r}$$

Lorentz tr. (inertial frame) symmetry of E/c & B

$$\begin{cases}\mathbf{E}'/c = \gamma(\mathbf{E}/c + \boldsymbol{\beta}\times\mathbf{B}) - \dfrac{\gamma^2}{\gamma+1}(\boldsymbol{\beta}\cdot\mathbf{E}/c)\boldsymbol{\beta} \\ \mathbf{B}' = \gamma(\mathbf{B} - \boldsymbol{\beta}\times\mathbf{E}/c) - \dfrac{\gamma^2}{\gamma+1}(\boldsymbol{\beta}\cdot\mathbf{B})\boldsymbol{\beta}\end{cases}$$

$\Uparrow$ Lorentz tr. by $\boldsymbol{\beta} = \mathbf{v}/c \left(\gamma = 1/\sqrt{1-\beta^2}\right)$

$$\begin{cases}\mathbf{E} \\ \mathbf{B}\end{cases} \quad (\text{rest frame})$$



e.g. MM, Ieda, Saitoh, Maekawa, arXiv:1106.0366, **Appendix C**

GENERAL COORDINATE TRANSFORMATION

$$\begin{pmatrix} dt' \\ dx' \\ dy' \\ dz' \end{pmatrix} = \begin{pmatrix} \partial t'/\partial t & \partial t'/\partial x & \partial t'/\partial y & \partial t'/\partial z \\ \partial x'/\partial t & \partial x'/\partial x & \partial x'/\partial y & \partial x'/\partial z \\ \partial y'/\partial t & \partial y'/\partial x & \partial y'/\partial y & \partial y'/\partial z \\ \partial z'/\partial t & \partial z'/\partial x & \partial z'/\partial y & \partial z'/\partial z \end{pmatrix} \begin{pmatrix} dt \\ dx \\ dy \\ dz \end{pmatrix}$$

$$\begin{pmatrix} t' \\ x' \\ y' \\ z' \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\Omega t & -\sin\Omega t & 0 \\ 0 & \sin\Omega t & \cos\Omega t & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} t \\ x \\ y \\ z \end{pmatrix}$$

$$\begin{pmatrix} dt' \\ dx' \\ dy' \\ dz' \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ -\Omega y & \cos\Omega t & -\sin\Omega t & 0 \\ \Omega x & \sin\Omega t & \cos\Omega t & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} dt \\ dx \\ dy \\ dz \end{pmatrix}$$

$$R = \begin{pmatrix} 1 & 0 & 0 & 0 \\ -\Omega y & \cos\Omega t & -\sin\Omega t & 0 \\ \Omega x & \sin\Omega t & \cos\Omega t & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

GENERAL COORDINATE TRANSFORMATION

$$F_{\mu\nu} = \begin{pmatrix} 0 & E_x & E_y & E_z \\ -E_x & 0 & -B_z & B_y \\ -E_y & B_z & 0 & -B_x \\ -E_z & -B_y & B_x & 0 \end{pmatrix}$$

$$R = \begin{pmatrix} 1 & 0 & 0 & 0 \\ -\Omega y & \cos\Omega t & -\sin\Omega t & 0 \\ \Omega x & \sin\Omega t & \cos\Omega t & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$F' = R^T F R$$

$$\Rightarrow \begin{cases} E' \approx E + (\Omega \times r) \times B \\ B' \approx B \end{cases}$$

SOI & ELECTROMAGNETIC FIELD IN ROTATING FRAME

$$\boxed{\tilde{H}_{SOI} = \frac{\lambda}{\hbar}\boldsymbol{\sigma}\cdot\left[(\mathbf{p}-q\mathbf{A})\times q\left(\mathbf{E}+(\boldsymbol{\Omega}\times\mathbf{r})\times\mathbf{B}\right)\right]}$$

$$\begin{cases} E_{\text{rot}} \approx E_{\text{rest}} + (\Omega\times r)\times B_{\text{rest}} \\ B_{\text{rot}} \approx B_{\text{rest}} \end{cases}$$

(rotating frame)

$\Uparrow$ general coordinate transformation

by velocity $\Omega\times r$

$$\begin{cases} E_{\text{rest}} \\ B_{\text{rest}} \end{cases} \text{(rest frame)}$$

$\boldsymbol{\Omega} \parallel \mathbf{B},\ \mathbf{E}=0$ (rest frame)

$$\mathbf{E}_{\text{rot}} = (\boldsymbol{\Omega}\times\mathbf{r})\times\mathbf{B}_{\text{rest}}$$

(rotating frame)