The spin Hall effect in a quantum gas

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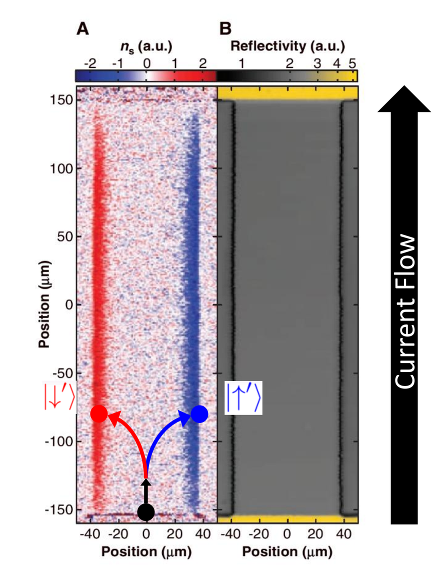
Introduction to spin Hall effect



Color indicates predominant spin composition.[1]

- Spin Hall effect is separation of electron spins perpendicular to current flow
- No external magnetic field needed – spin-orbit coupling drives effect
- Effect is integral for spintronic devices and topological insulators

This is the first observation of the spin Hall effect in a cold atom system.

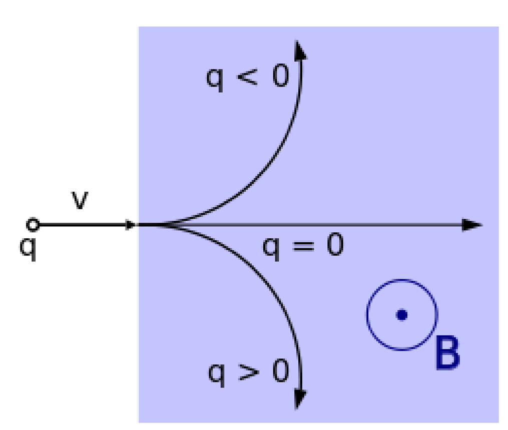
Spin-Dependent Lorentz Force

Lorentz Force

$$\vec{F} = q(\vec{v} \times \vec{B})$$

$\vec{F}$ = force
q = charge
$\vec{v}$ = velocity
$\vec{B}$ = magnetic field

- Cross product means that particles always move perpendicular to velocity and $\vec{B}$ field.
- Force proportional to charge of the particle
- Particles execute curved trajectories



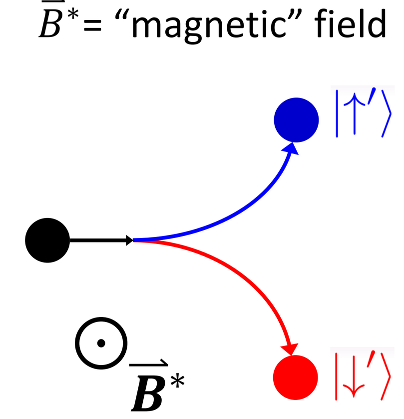
*Wikipedia

Spin-Dependent Lorentz Force

$$\vec{F} = \vec{s} \cdot (\vec{v} \times \vec{B}^*)$$

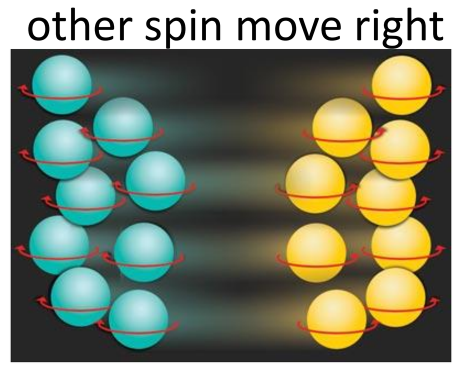
$\vec{F}$ = force
$\vec{s}$ = spin
$\vec{v}$ = velocity
$\vec{B}^*$= "magnetic" field

- Elementary particles have intrinsic spin (electrons either "up" or "down")
- Each spin acts as if it has opposite charge response to $\vec{B}^*$
- Lorentz-type force, but normal magnetic field does not act on spin



Spin-orbit coupling

Atoms with spin pointing one direction move left, atoms with other spin move right

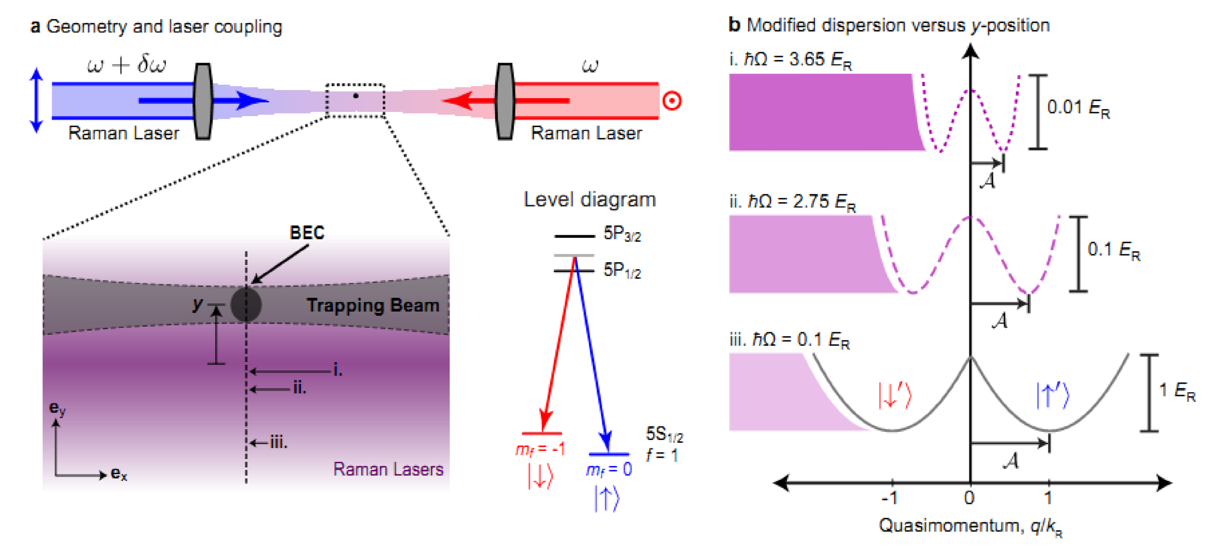


*physicsworld.com

This effect is usually set by a material's properties (crystal structure, doping, etc.)

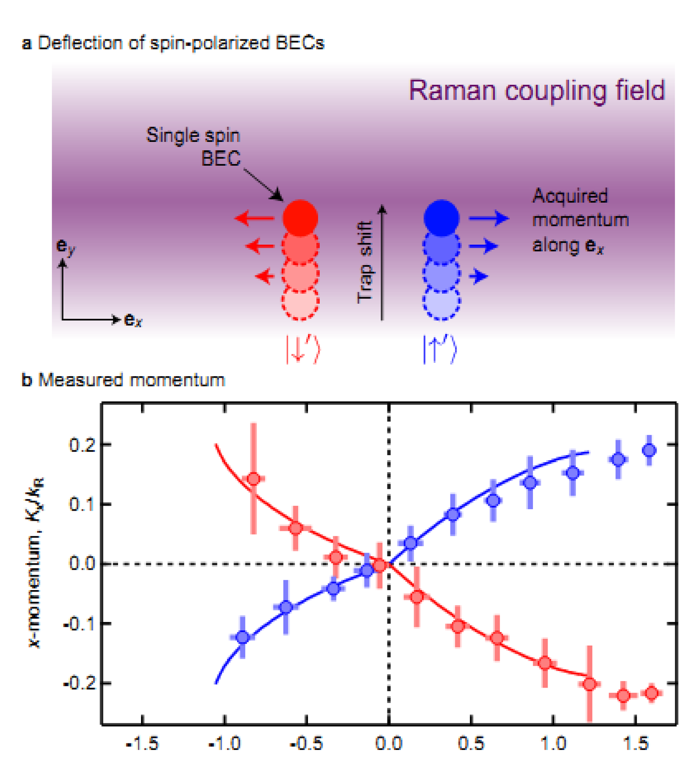
Certain materials can have the strength of SOC tuned by an external voltage

Our system



- ^{87}Rb atoms in F = 1 ground state, confined in 90° cross-beam optical dipole trap (ODT)
- λ =790.21 nm Raman beams (Δω/2π = 15 MHz) couple $m_F = 0$ and $m_F = -1$ spin states, with large bias magnetic field along $\mathbf{e}_z$
- Adjustment of acousto-optic modulator frequency allows dynamic control of BEC *y*-position by displacing one ODT beam
- No crystal structure, but system has **spin-orbit coupling**[2]
- Atoms play the role of electrons, with spin coupling to linear momentum along $\mathbf{e}_x$

Realization of SDLF



Abruptly change position of optical trapping beam

Wait ¼ of trapping period so that atoms travel to center of displaced trap, turn off all potentials

Vary initial position of atoms over small range in intensity gradient, effectively varying $\mathbf{e}_y$ velocity

Kick into and out of beams (one spin state at a time), measure momentum – atoms acquire perpendicular momentum

Spin Current Definition

Define average current density:

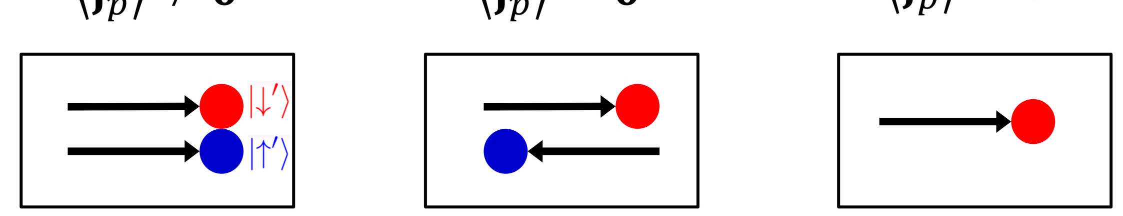
$$\langle \mathbf{j}_i \rangle = \int_V n_i(\mathbf{r})\mathbf{v}_i(\mathbf{r})dr\,/V$$

i = spin (|↓'⟩ or |↑'⟩)
n = density $\mathbf{v}$= velocity
$\mathbf{r}$ = position V = volume

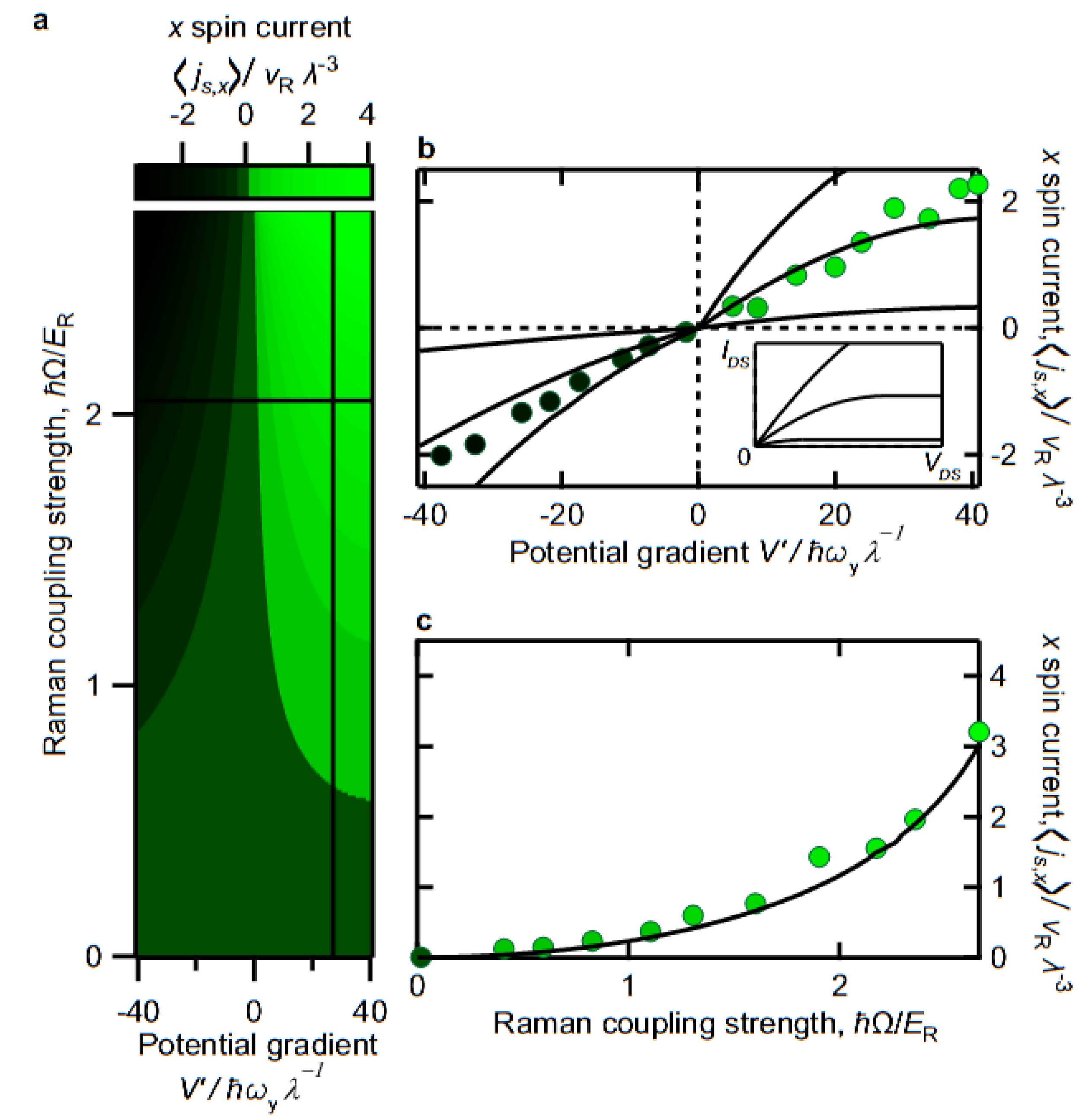
Average spin current
$$\langle \mathbf{j}_s \rangle = \langle \mathbf{j}_{\uparrow'} \rangle - \langle \mathbf{j}_{\downarrow'} \rangle$$

Average particle current
$$\langle \mathbf{j}_p \rangle = \langle \mathbf{j}_{\uparrow'} \rangle + \langle \mathbf{j}_{\downarrow'} \rangle$$

$\langle \mathbf{j}_s \rangle = 0$, $\langle \mathbf{j}_p \rangle \neq 0$	$\langle \mathbf{j}_s \rangle \neq 0$, $\langle \mathbf{j}_p \rangle = 0$	$\langle \mathbf{j}_s \rangle \neq 0$, $\langle \mathbf{j}_p \rangle \neq 0$



Spin currents



Start with equal mixture of both spins

Measure spin current as a function of both laser coupling strength and drive force V′ along $\mathbf{e}_y$ (beam displacement)

Non-linear turn on with coupling, smoother control via gradient

Spin Transistor

System forms an analogue to Datta Das spin transistor[3]

Drain current => spin current
Drain-source voltage => V′ (potential gradient)
Gate-source voltage => laser coupling strength

Strong similarity between black curves in top right (our system) and inset (characteristic transistor)

Behind the SDLF

In Hamiltonian mechanics, electric fields (**E**) and magnetic fields (**B**) enter through vector (**A**) and scalar (**ϕ**) potentials:

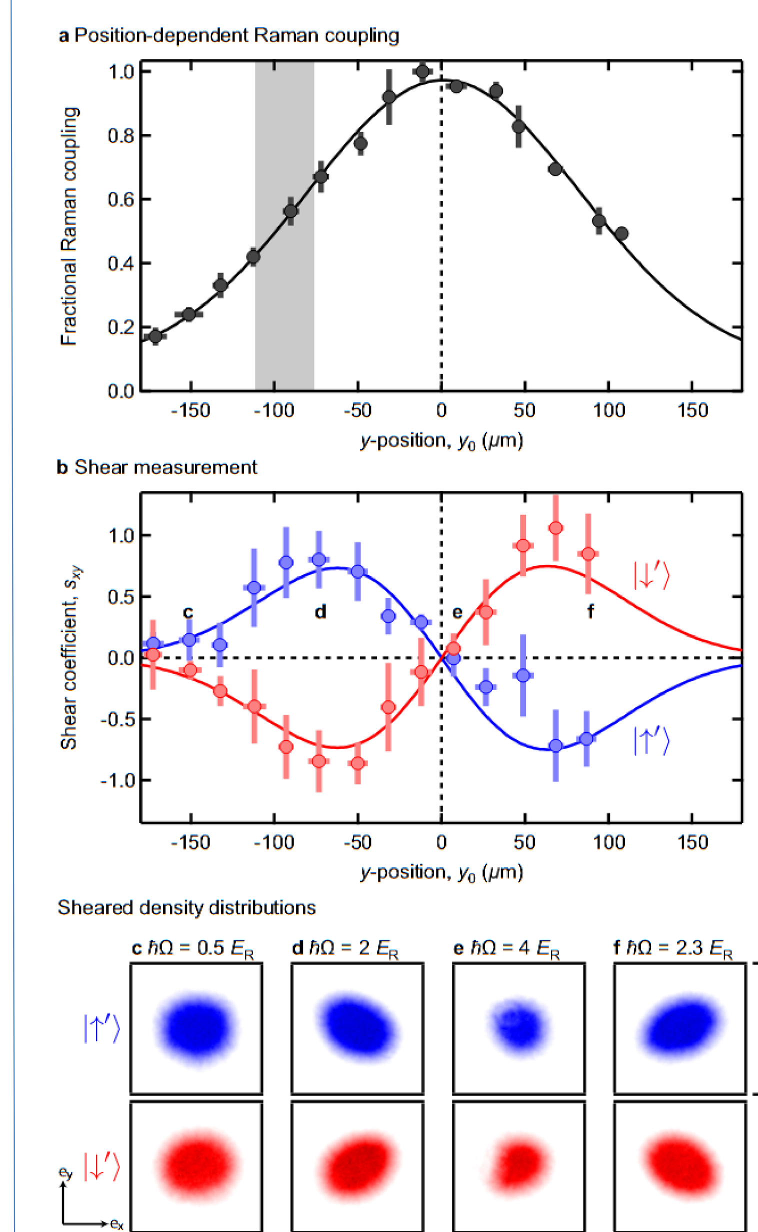
$$\vec{B} = \vec{\nabla} \times \vec{A} \qquad \vec{E} = -\vec{\nabla}\phi - \frac{\partial \vec{A}}{\partial t}$$

So that the Hamiltonian (for particle of charge *e*) becomes:

$$H = \frac{1}{2m}\left(\vec{p} - e\vec{A}\right)^2 - e\phi$$

Our system effectively creates a vector potential $\vec{A}^*$ acting on the *spin* of the particle, so that each spin acts as one type of charge

Vector potential gradient



Vector potential is proportional to coupling strength (intensity)

Adjust equilibrium position of BEC along Gaussian intensity gradient of Raman beams

Snapping off Raman beams gives electric field kick

In intensity gradient, kick is spatially dependent, shearing the cloud after expansion

Shear is opposite for two pseudo-spins

Summary/Outlook

- We have realized the spin Hall effect for the first time in an ultracold quantum gas
- The spin Hall effect is a tool in the development of a new generation of "spintronic" devices
- This system forms a prototype spintronics device – an analogue to a transistor
- Extensions of this technique could realize the quantum spin Hall effect, leading to exotic topological insulators in ultracold gases

References

[1]Kato *et. al.*, Science **306**, 1910 (2004).
[2]Lin *et. al.*, Nature **471**, 83 (2011).
[3]Vaishnav, J. Y., *et al.*, PRL **101** 265302 (2008).
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