Is a Stern-Gerlach splitter possible with an ion beam?

C. Henkel[1], G. Jacob[2], F. Stopp[2], F. Schmidt-Kaler[2],
Y. Japha[3], M. Keil[3], and R. Folman[3]

[1] *Universität Potsdam* – [2] *JGU Mainz* – [3] *BGU Beer Sheva*

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merci à :

DFG (IANV project/DIP programme)

talks on web

Institute of Physics and Astronomy, Universität Potsdam, Germany
`www.quantum.physik.uni-potsdam.de`

Motivation – Quantum Histories

Historic Landmark Experiment

– spin splitting a beam of Ag atoms

Gerlach & Stern [*Z Phys* 1922]

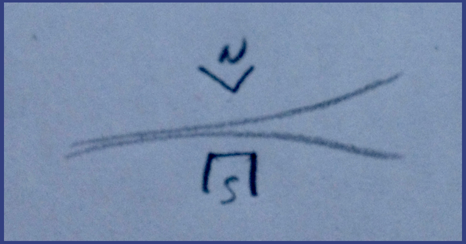

Figure 2 The result of the Stern-Gerlach experiment communicated in a postcard to Niels Bohr. (© Niels Bohr Archive, Copenhagen, DK)

– spins align by M1 radiation? . . . too slow

Einstein & Ehrenfest [*Z Phys* 1922]

“Einstein, Ehrenfest, and the quantum measurement problem”,
Unna & Sauer [*Ann Phys* (*Berlin*) 2013]

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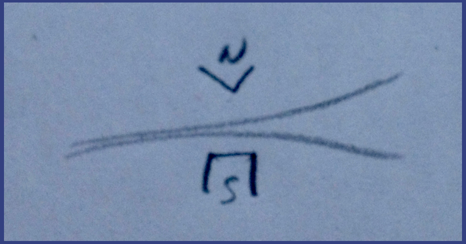

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. . . and the spinning electron?

- “no go”

Bohr & Mott (Como 1927) Pauli (Solvay 1930)

Brillouin (Acad Sci USA 1928)

Stern-Gerlach split vs. Lorentz blur $\delta x \dfrac{\partial B}{\partial x}$

Garraway & Stenholm [*Phys Rev A* 1999]

“Electrons, Stern–Gerlach magnets, and quantum mechanical propagation”, Batelaan [*Am J Phys* 2002]

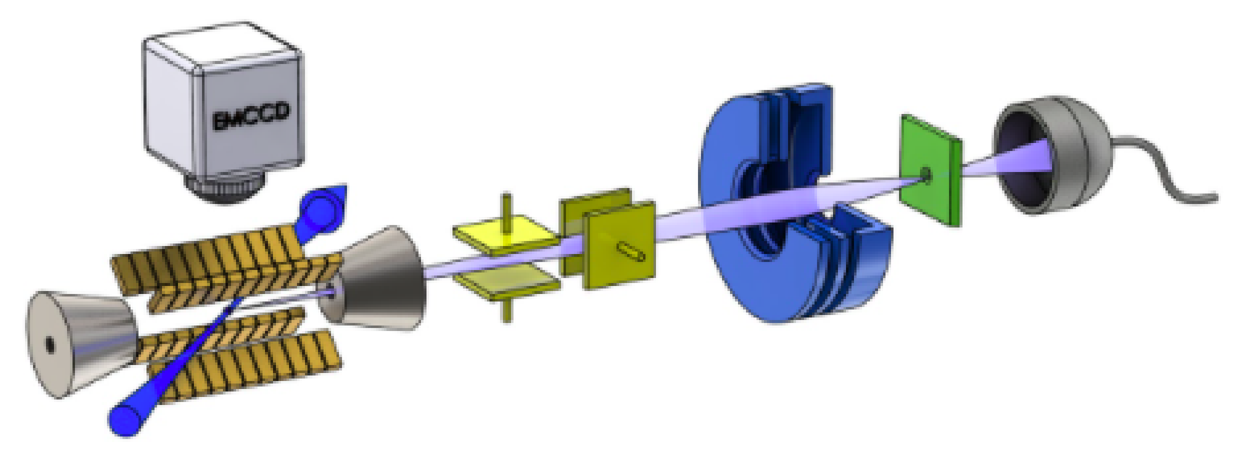
Our Proposal

Split an ion beam

mag. moment $\boldsymbol{\mu} = -g_s \frac{e\hbar}{2\,m_e}\mathbf{S}$ vs. $\frac{e}{M}\mathbf{p} \times$ Lorentz force

Single ion beam machine $^{40}\mathrm{Ca}^{+}$ isotope

– segmented Paul trap – ion optics



Jacob & Schmidt-Kaler group [*Phys Rev Lett* 2016]

ion energy $10\,\mathrm{keV} \ldots 0.1\,\mathrm{eV}$

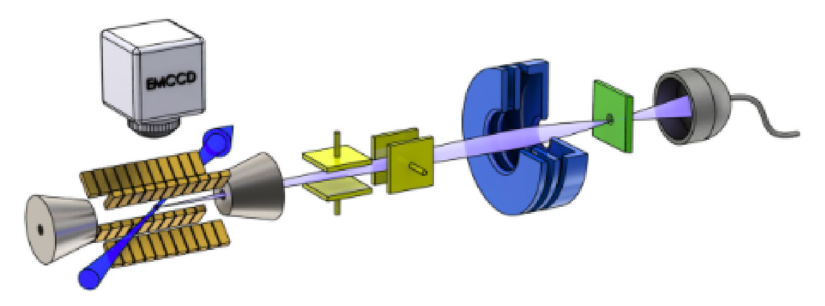
dispersions $v_z/\delta v_z \gtrsim 500$, $\delta\theta_\perp \sim 25\,\mu\mathrm{rad}$

- implant single ions with $\sim 10\,\mathrm{nm}$ precision in surface

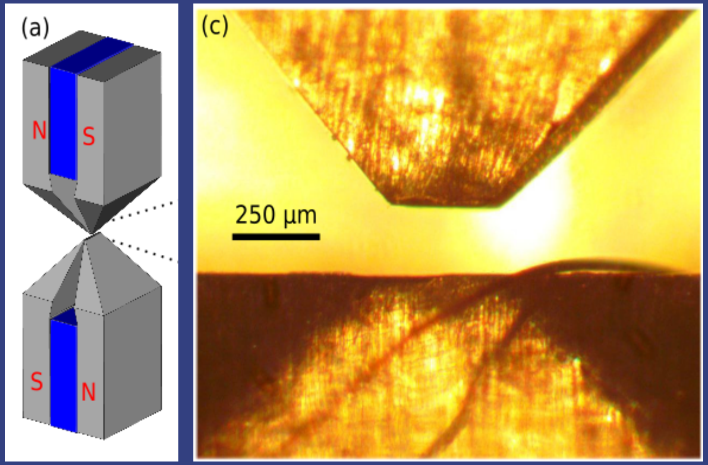
Our Proposal

Split an ion beam

$$\boldsymbol{\mu} = -g_s \frac{e\hbar}{2\,m_e}\mathbf{S} \quad \text{vs.} \quad \frac{e}{M}\mathbf{p} \times$$

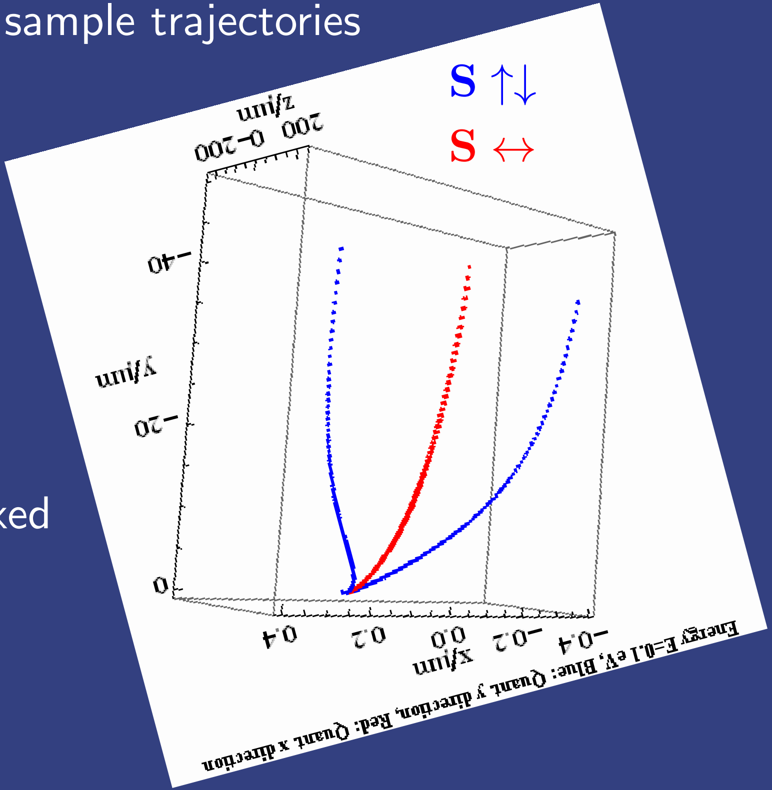


Tight magnetic quadrupole



Hsu & al [*Sci Rep* 2016]

sample trajectories



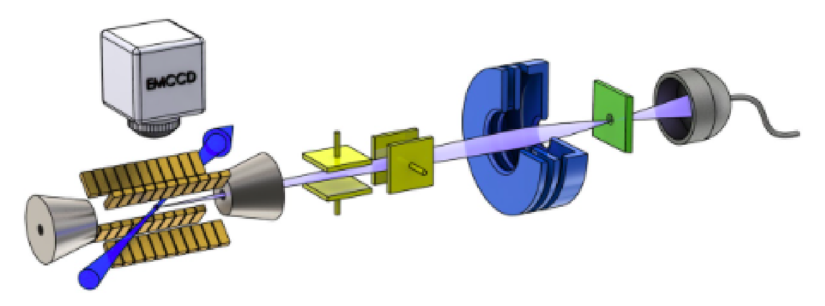
simulation with spin direction fixed

but . . . fast precession

Our Proposal

Split an ion beam

$$\boldsymbol{\mu} = -g_s \frac{e\hbar}{2\,m_e}\mathbf{S} \quad \text{vs.} \quad \frac{e}{M}\mathbf{p}\times$$



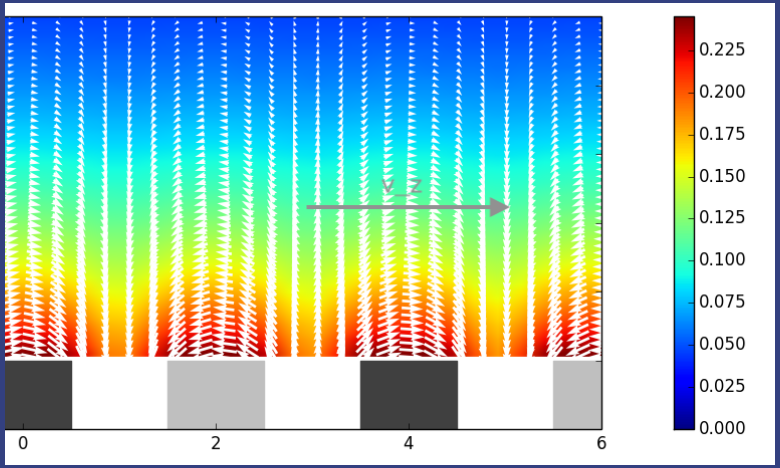
simulation with dynamic spin

$\sim$ follows rotating field

Enga, Bloom, Lew (& Erdman):

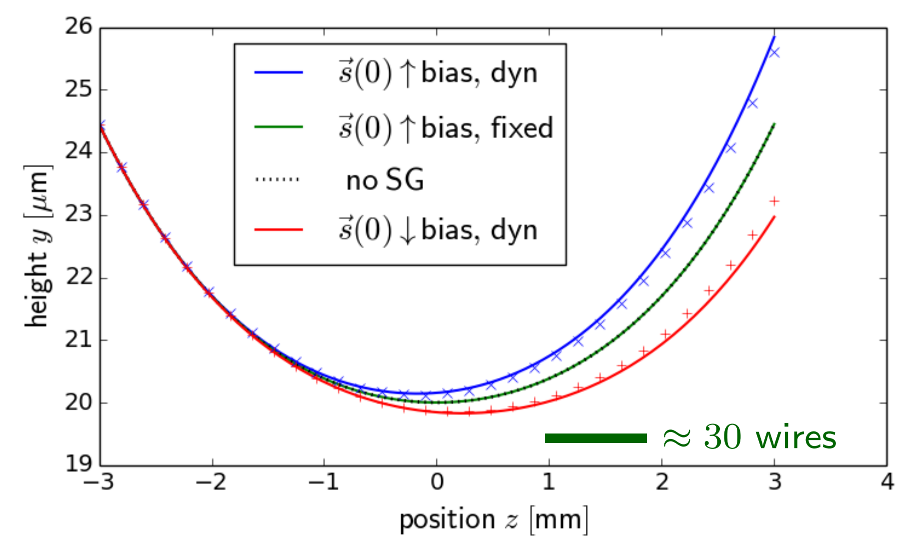
“transverse Stern–Gerlach” ($\geq$ 1962)

Array of wires on chip



CH & al [*in prep* 2018]

sample trajectories



Semiclassical trajectories

Spin & c.m. dynamics

$$\begin{aligned} \text{spin} \quad \frac{\mathrm{d}\mathbf{S}}{\mathrm{d}t} &= \frac{g_s e}{2m_e}\mathbf{B} \times \mathbf{S}\,, \qquad \mathbf{S} = \frac{1}{2}\langle \hat{\boldsymbol{\sigma}} \rangle \\ \frac{\mathrm{d}\mathbf{p}}{\mathrm{d}t} &= -\frac{g_s e}{2m_e}(\mathbf{S}\cdot\nabla)\mathbf{B} + \frac{e}{M}\mathbf{p}\times\mathbf{B} - \nabla V_{\mathrm{im}} \end{aligned}$$

Stern-Gerlach Lorentz Coulomb (image)

average spin, deterministic motion (no splitting)

→ debate "quantum vs classical"

[Ranada & Ranada 1979;
França 2009; Arantes Ribeiro 2010 . . .]

→ spin-polarised proton beams?

relativistic dynamics
much weaker nuclear magneton [Barber 2008]

Semiclassical trajectories

$$
\begin{aligned}
\text{spin}\quad \frac{\mathrm{d}\mathbf{S}}{\mathrm{d}t} &= \boxed{\frac{g_s e}{2m_e}\mathbf{B}\times\mathbf{S}}, \qquad \mathbf{S} = \frac{1}{2}\langle\hat{\boldsymbol{\sigma}}\rangle \\
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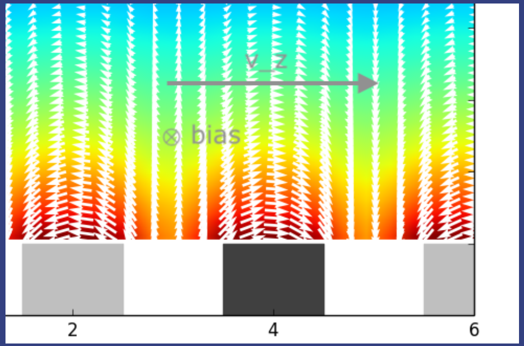
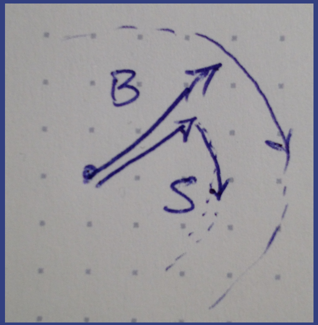
\end{aligned}
$$

Spin precession





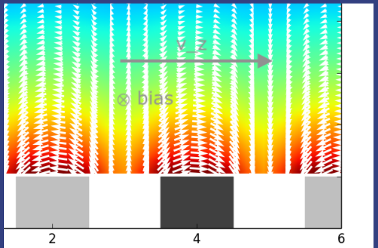
magnetic field rotates, spin rotates (in sync)

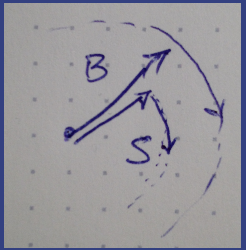
Semiclassical trajectories

$$\text{spin}\quad \frac{\mathrm{d}\mathbf{S}}{\mathrm{d}t} = \frac{g_s e}{2m_e}\mathbf{B}\times\mathbf{S}\,, \qquad \mathbf{S} = \frac{1}{2}\langle\hat{\boldsymbol{\sigma}}\rangle$$

$$\frac{\mathrm{d}\mathbf{p}}{\mathrm{d}t} = \boxed{-\frac{g_s e}{2m_e}(\mathbf{S}\cdot\nabla)\mathbf{B} + \frac{e}{M}\mathbf{p}\times\mathbf{B}} - \nabla V_{\mathrm{im}}$$

Spin precession





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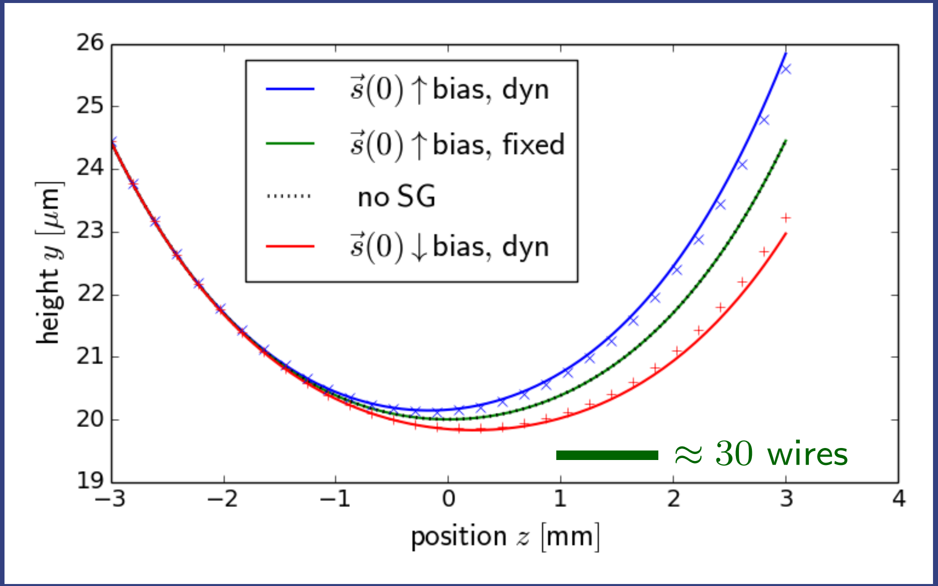


‘Adiabatic’ (precession-averaged) force

$$\overline{F_y} \approx M u \omega_1\, \mathrm{e}^{-2\kappa y}\frac{\Omega_1(\Omega_0 - \kappa v_{z0})}{\tilde{\Omega}^2}S_{x0} + \frac{M\omega_1^2\,\mathrm{e}^{-2\kappa y}}{2\kappa} + eB_0 v_{z0} - \frac{e^2 R_{\mathrm{im}}}{16\pi\varepsilon_0 y^2}$$

symbols ×× ++ in plot ↑

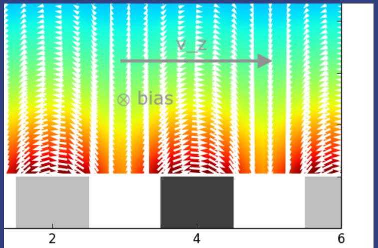
cyclotron $\omega = eB/M$, Larmor $\Omega = g_s eB/2m_e \gg \omega$, $u \sim \hbar\kappa/m_e \sim 100\,\mathrm{m/s}$

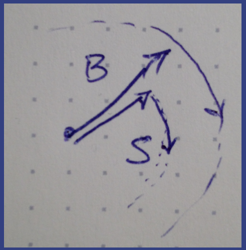
Semiclassical trajectories

$$\text{spin}\quad \frac{\mathrm{d}\mathbf{S}}{\mathrm{d}t} = \frac{g_s e}{2m_e}\mathbf{B}\times\mathbf{S}\,, \qquad \mathbf{S} = \frac{1}{2}\langle\hat{\boldsymbol{\sigma}}\rangle$$

$$\frac{\mathrm{d}\mathbf{p}}{\mathrm{d}t} = -\frac{g_s e}{2m_e}(\mathbf{S}\cdot\nabla)\mathbf{B} + \frac{e}{M}\mathbf{p}\times\mathbf{B}\ \boxed{-\nabla V_{\mathrm{im}}}$$

Spin precession





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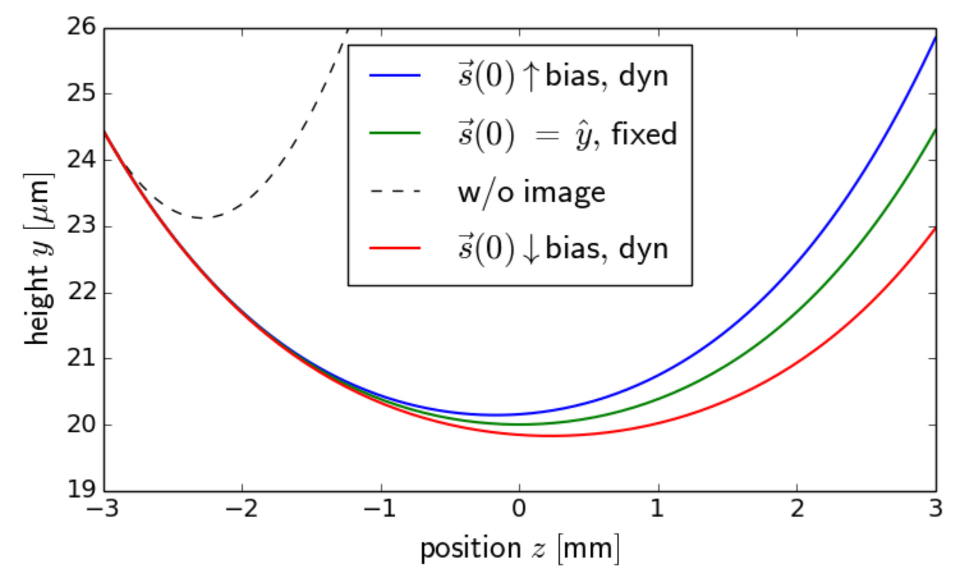
'Adiabatic' (precession-averaged) force

Compensate image force

```
bias field B_0 =  15 G
rotating field B_1(20 um) = 19.92 G
beam velocity v = 700 m/s
wire+ to wire- dist =  30 micron
splitting: 1.715 mrad
total time: 8.571 us
```

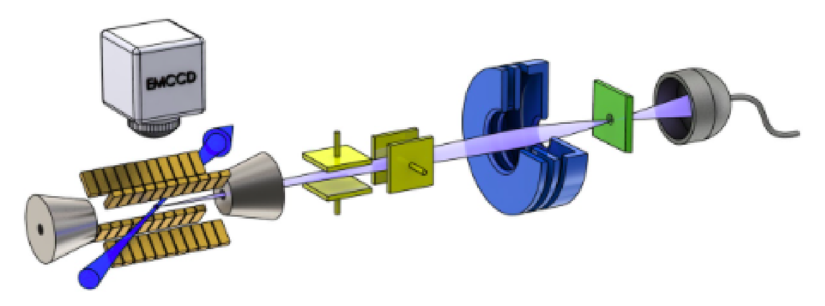


Conclusions

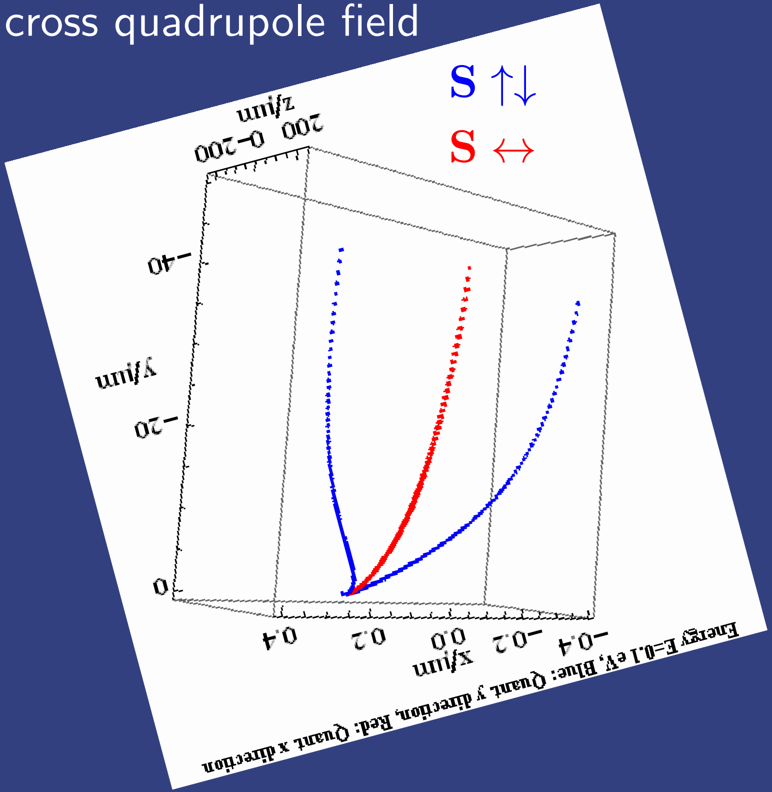
Spin splitting of an ion beam? . . . yes.

widths δx, δv_y . . . to estimate

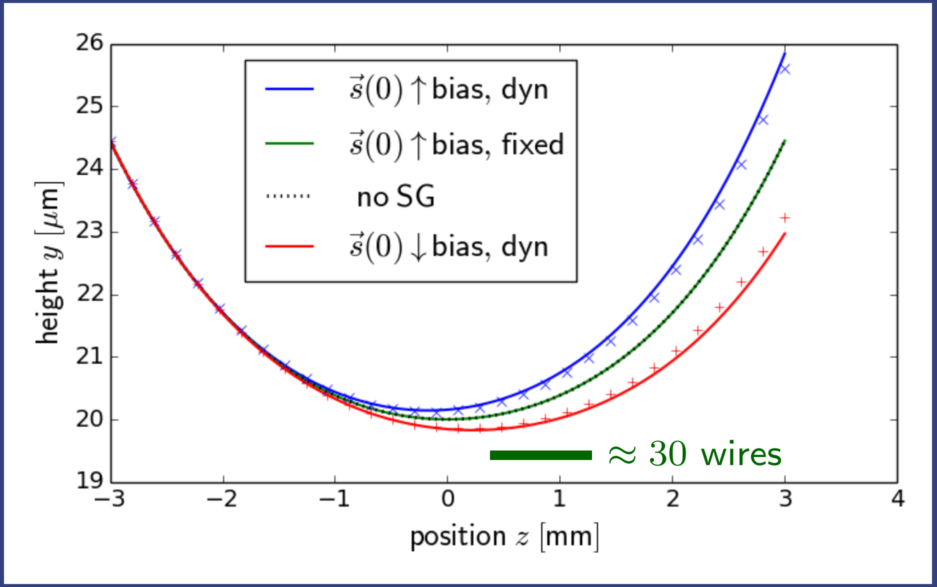
"quantum machine"



cross quadrupole field



"transverse Stern-Gerlach"



recombine atoms → Stern-Gerlach interferometer

Margalit & Folman group, arXiv:1801.02708