Аномальный магнитный момент электрона

Van Dyck, Schwinberg, Dehemelt did a good job in 1987!
Phys. Rev. Lett. **59**, 26 (1987)

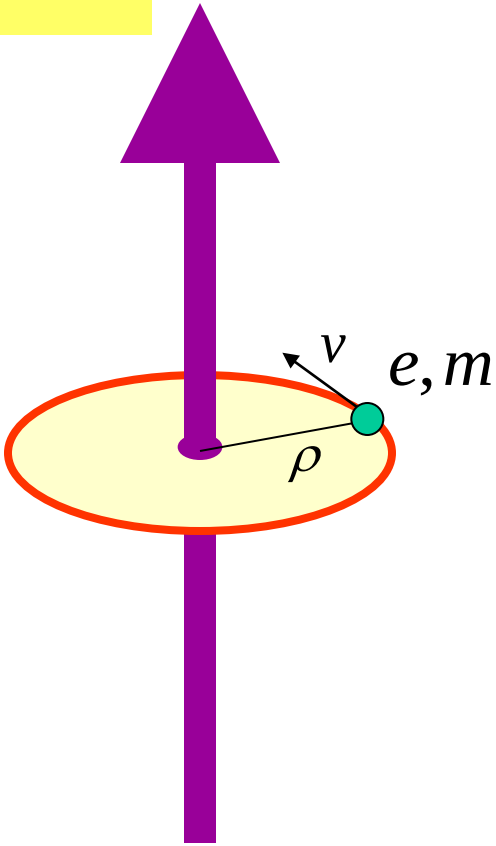
Magnetic Moments

magnetic moment

$$\vec{\mu} = g\,\mu_B \frac{\vec{L}}{\hbar}$$

angular momentum

Bohr magneton $\frac{e\hbar}{2m}$



Magnetic Moments

magnetic moment

$$\vec{\mu} = g\,\mu_B \frac{\vec{S}}{\hbar}$$

angular momentum

Bohr magneton $\frac{e\hbar}{2m}$

$g = 1$ identical charge and mass distribution

$g = 2$ spin for Dirac point particle

$g = 2.002\ 319\ 304\ ...$ simplest Dirac spin, plus QED

(if electron g is different → electron has substructure)

Dirac + QED Relates Measured g and Measured α

$$\frac{g}{2} = 1 + C_1\left(\frac{\alpha}{\pi}\right) + C_2\left(\frac{\alpha}{\pi}\right)^2 + C_3\left(\frac{\alpha}{\pi}\right)^3 + C_4\left(\frac{\alpha}{\pi}\right)^4 + \ldots\ \delta a$$

Dirac point particle

Measure

QED Calculation

Kinoshita, Nio, Remiddi, Laporta, etc.

weak/strong

Sensitivity to other physics (weak, strong, new) is low

1. **Use measured g and QED to extract fine structure constant**
2. **Wait for another accurate measurement of α → Test QED**

Why Measure the Electron Magnetic Moment?

1. **Electron g - basic property of simplest of elementary particles**
2. **Determine fine structure constant – from measured g and QED**
3. **Test QED – requires independent α**
4. **Test CPT – compare g for electron and positron → best lepton test**
5. **Look for new physics beyond the standard model**
   - **Is g given by Dirac + QED? If not → electron substructure (new physics)**
   - **Muon g search needs electron g measurement**

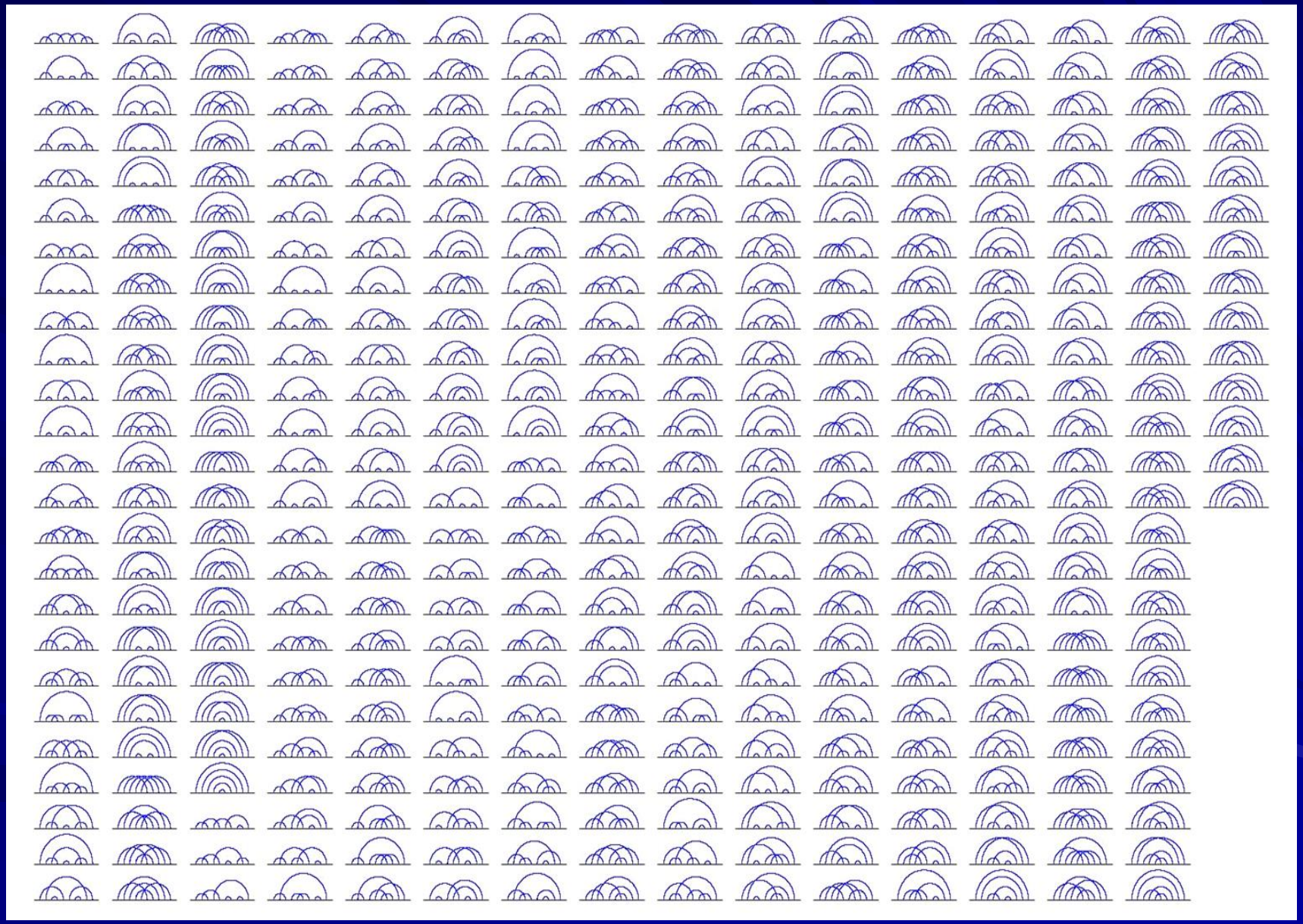
Basking in the Reflected Glow of Theorists

Gabrielse

$$\frac{g}{2} = 1 + C_1\left(\frac{\alpha}{\pi}\right) + C_2\left(\frac{\alpha}{\pi}\right)^2 + C_3\left(\frac{\alpha}{\pi}\right)^3 + C_4\left(\frac{\alpha}{\pi}\right)^4 + C_5\left(\frac{\alpha}{\pi}\right)^5 + \ldots\ \delta a$$

Remiddi Kinoshita G.G

2004



Direct Test for Physics Beyond the Standard Model

$$g = 2 + 2a_{QED}(\alpha) + \delta g_{SM:Hadronic+Weak} + \delta g_{New\,Physics}$$

Is g given by Dirac + QED? If not → electron substructure

Does the electron have internal structure? Brodsky, Drell, 1980

$$m^* > \frac{m}{\sqrt{\delta g / 2}} = 130\ GeV / c^2$$

limited by the uncertainty in independent α values

$$m^* > \frac{m}{\sqrt{\delta g / 2}} = 600\ GeV / c^2$$

if our g uncertainty was the only limit

Not bad for an experiment done at 100 mK, but LEP does better

$$m^* > 10.3\ TeV$$

LEP contact interaction limit

How Does One Measure the Electron g to 7.6 parts in 10^{13}?

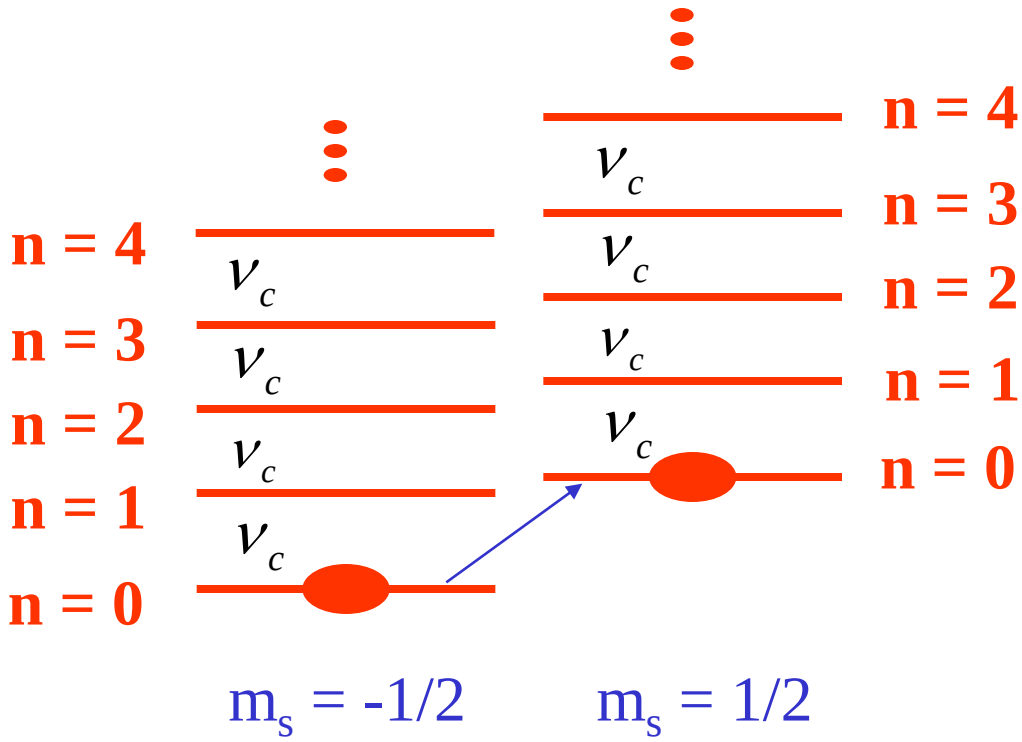
Basic Idea of the Measurement

Quantum jump spectroscopy
of lowest cyclotron and spin levels
of an electron in a magnetic field

Spin → Two Cyclotron Ladders of Energy Levels

Cyclotron frequency:

$$\nu_c = \frac{1}{2\pi}\frac{eB}{m}$$



Spin frequency:

$$\nu_s = \frac{g}{2}\nu_c$$

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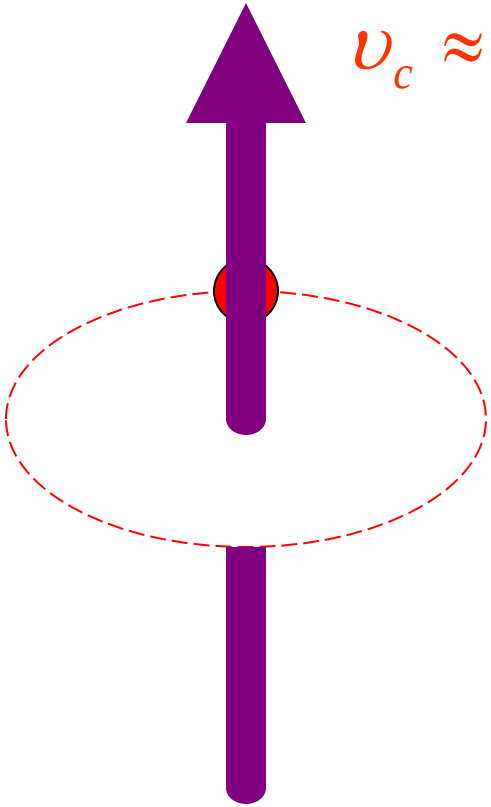
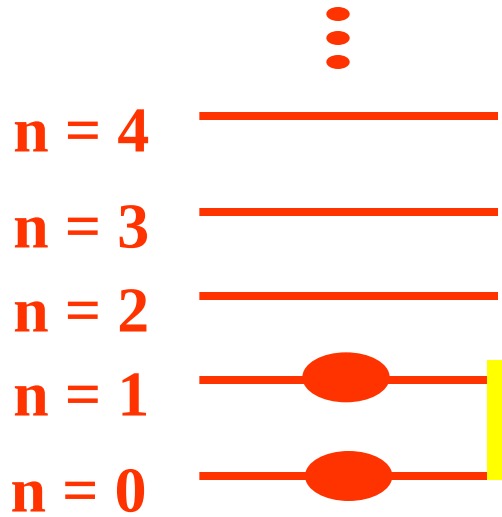
One Electron in a Magnetic Field

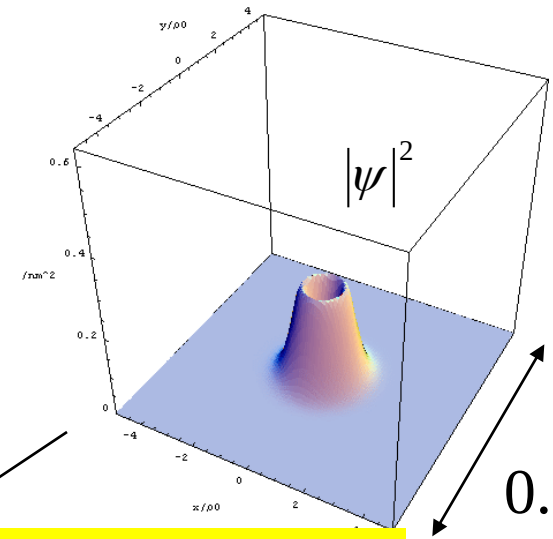


$\upsilon_c \approx 150$ GHz

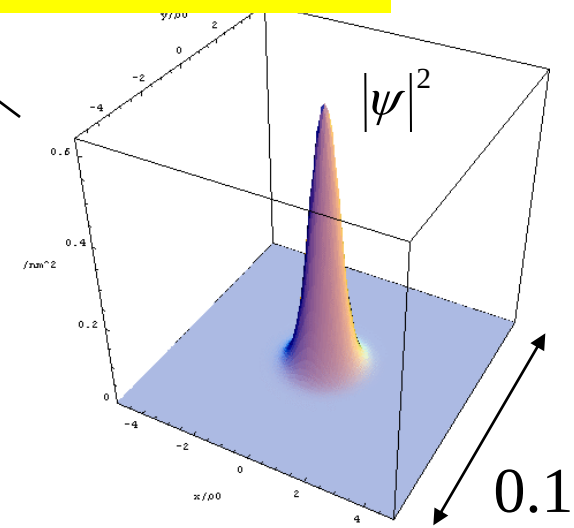
B ≈ 6 Tesla



$h\upsilon_c = 7.2$ kelvin



0.1 μm



0.1 μm

Need low temperature cyclotron motion T << 7.2 K

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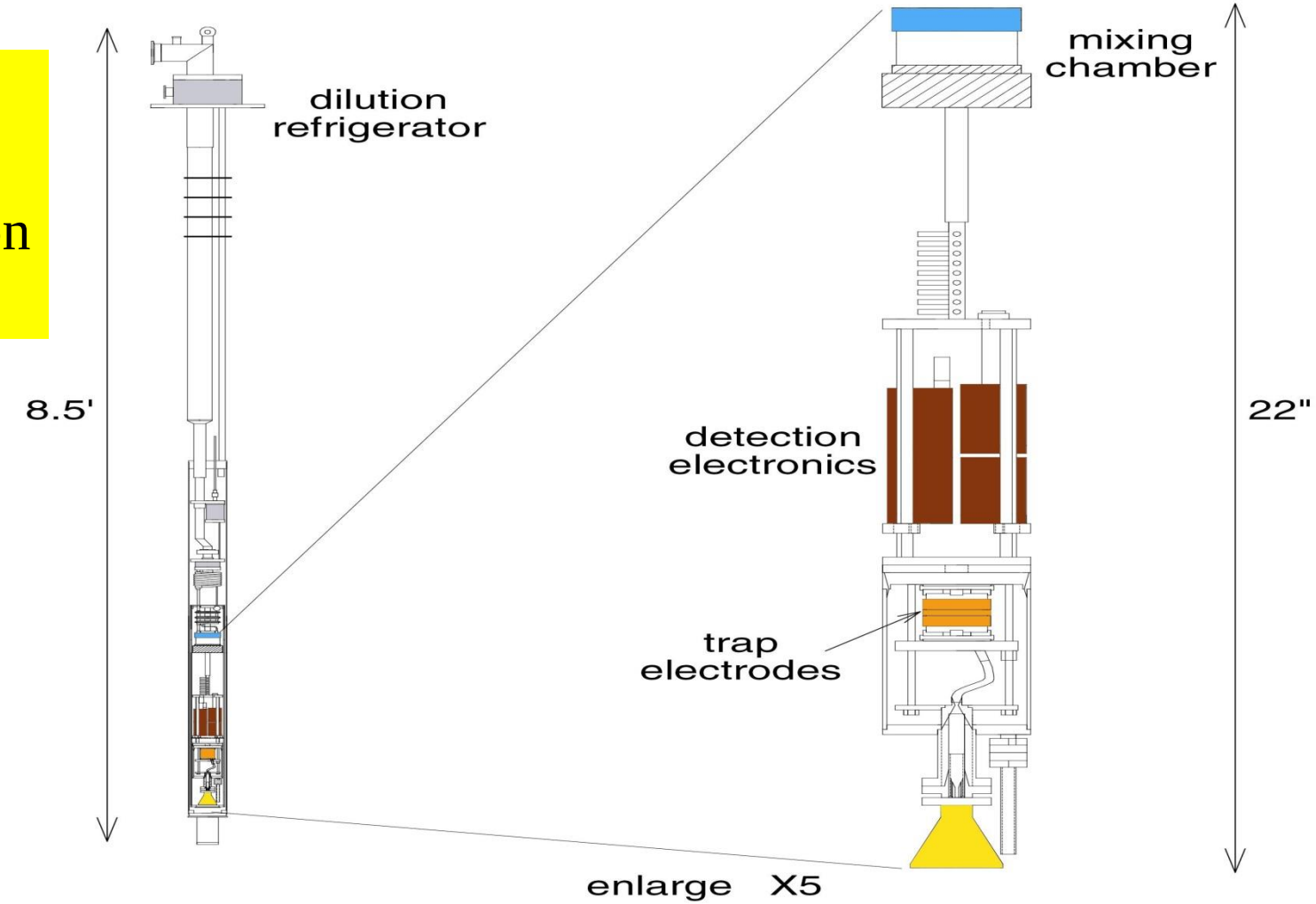
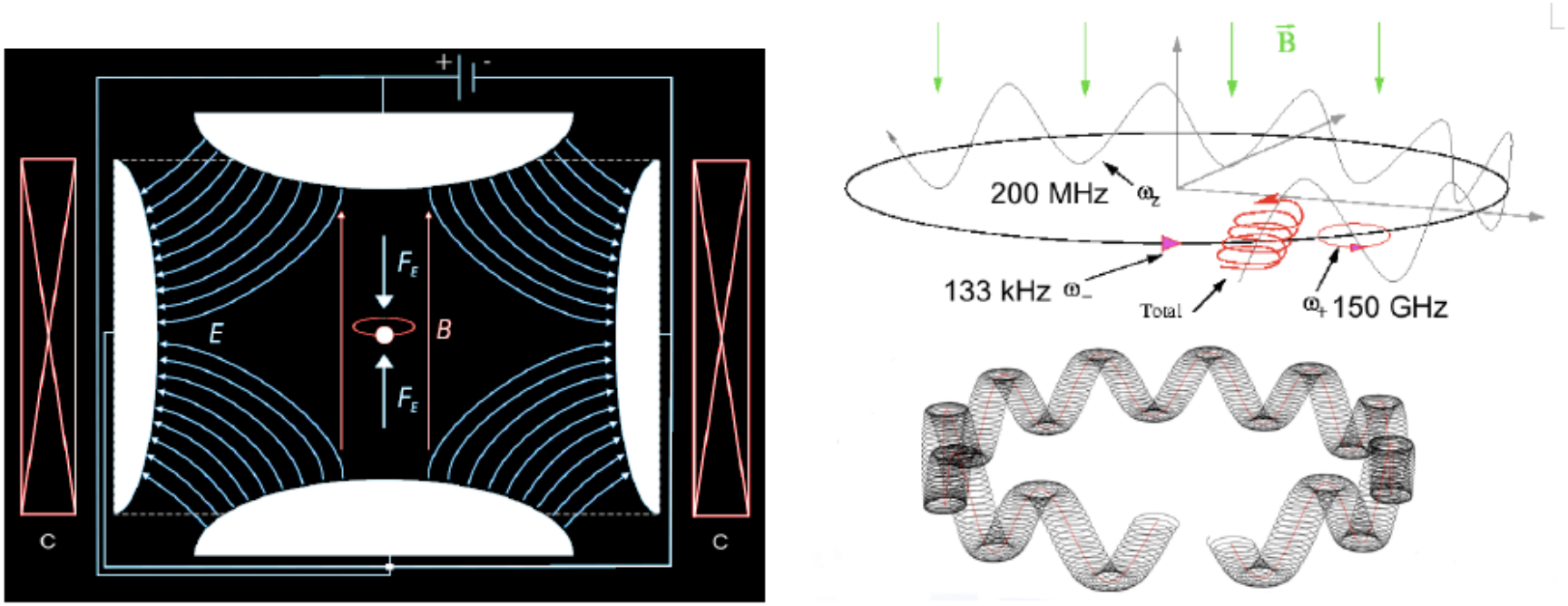
First Penning Trap Below 4 K → 70 mK

Need low temperature cyclotron motion T << 7.2 K





(a) (b)

Figure 6.2: *Sketch of the fields and the electron trajectory in a Penning trap*. Confinement is achieved by a vertical magnetic field and a quadrupole electric field. Source: [17]. (a) The magneton frequency ω_- and the modified cyclotron frequency ω_+ contribute to the electron trajectory as well as a low-frequency oscillation in z-direction. (b)

центробежная сила $m\Omega^2 R$, которая должна уравновешиваться силой Лоренца $e\Omega RB$ (так как скорость равна ΩR) минус сила eE. Таким образом, получаем уравнение для нахождения Ω:

$$m\Omega^2 R - e\Omega RB + eE = 0. \tag{4.3}$$

Решим это уравнение, и если окажется, что есть положительная частота Ω, то тем самым мы докажем, что предположение о движении электрона по кругу отвечает всем требованиям, а так как решение физической задачи должно быть единственным, то именно так электрон и должен двигаться. Решение, очевидно, таково:

$$\Omega = \frac{\omega_B}{2}\left(1 \pm \sqrt{1 - \frac{4eE}{mR\omega_B^2}}\right). \tag{4.4}$$

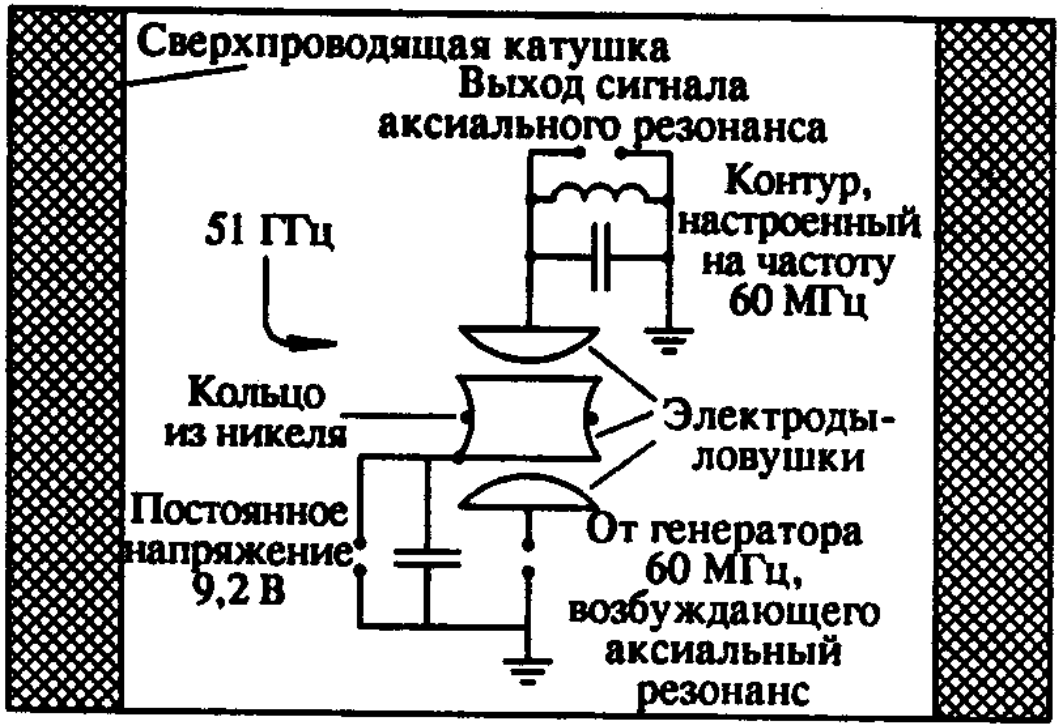
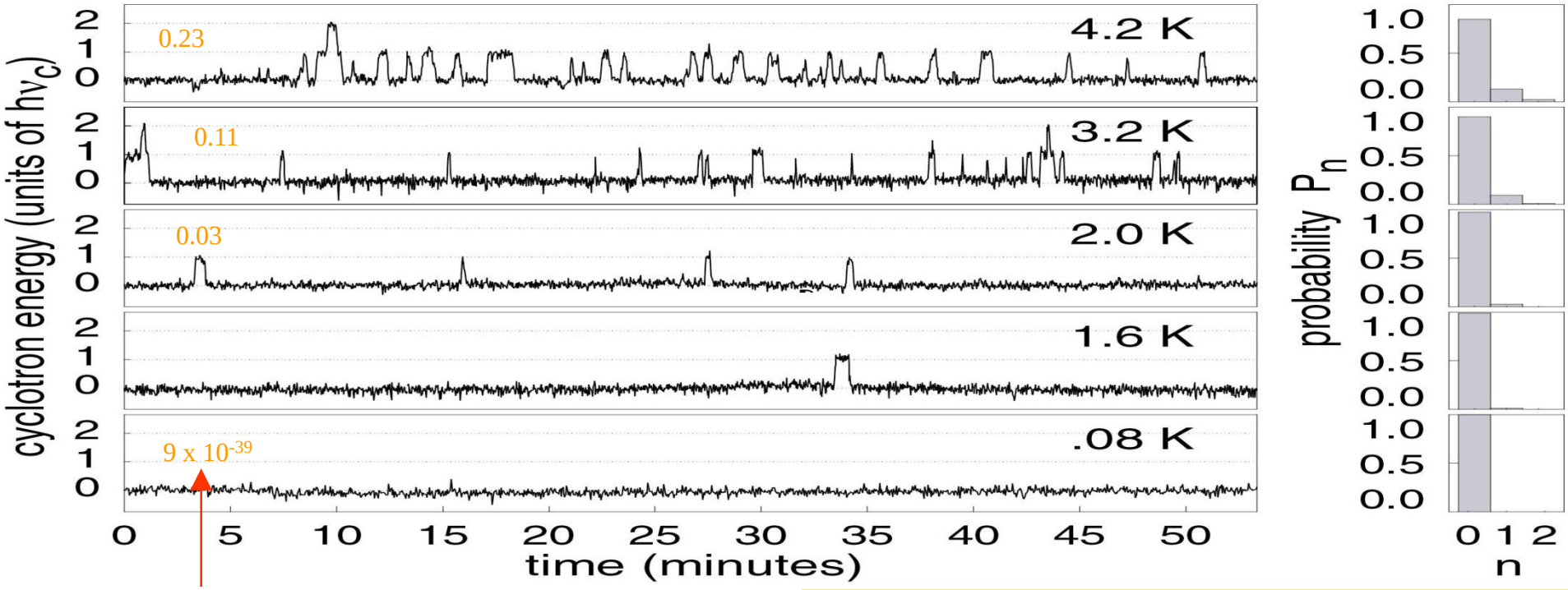


Рис. 4.1. Схема эксперимента по измерению отношения спинового и циклотронного расщепления уровней свободного электрона в магнитном поле

Electron in Cyclotron Ground State

QND Measurement of Cyclotron Energy vs. Time



average number of blackbody photons in the cavity

On a short time scale

→ in one Fock state or another

Averaged over hours

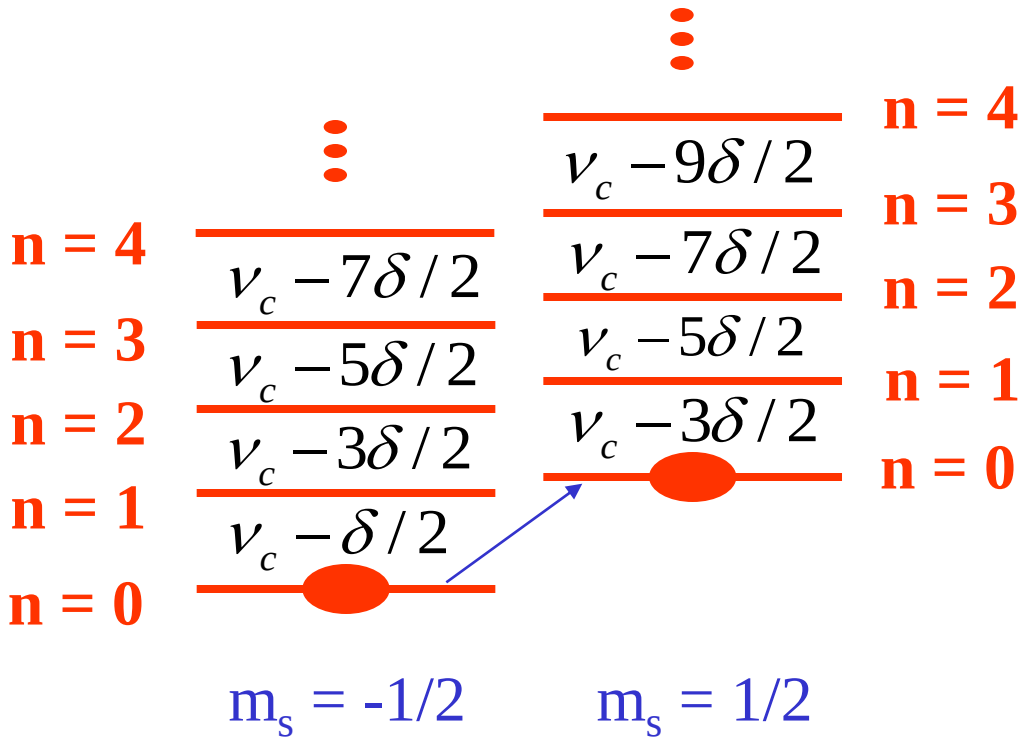
→ in a thermal state

S. Peil and G. Gabrielse, Phys. Rev. Lett. **83**, 1287 (1999).

Special Relativity Shift the Energy Levels δ

Cyclotron frequency:

$$2\pi\nu_c = \frac{eB}{m}$$



Spin frequency:

$$\nu_s = \frac{g}{2}\nu_c$$

Not a huge relativistic shift, but important at our accuracy

$$\frac{\delta}{\nu_c} = \frac{h\nu_c}{mc^2} \approx 10^{-9}$$

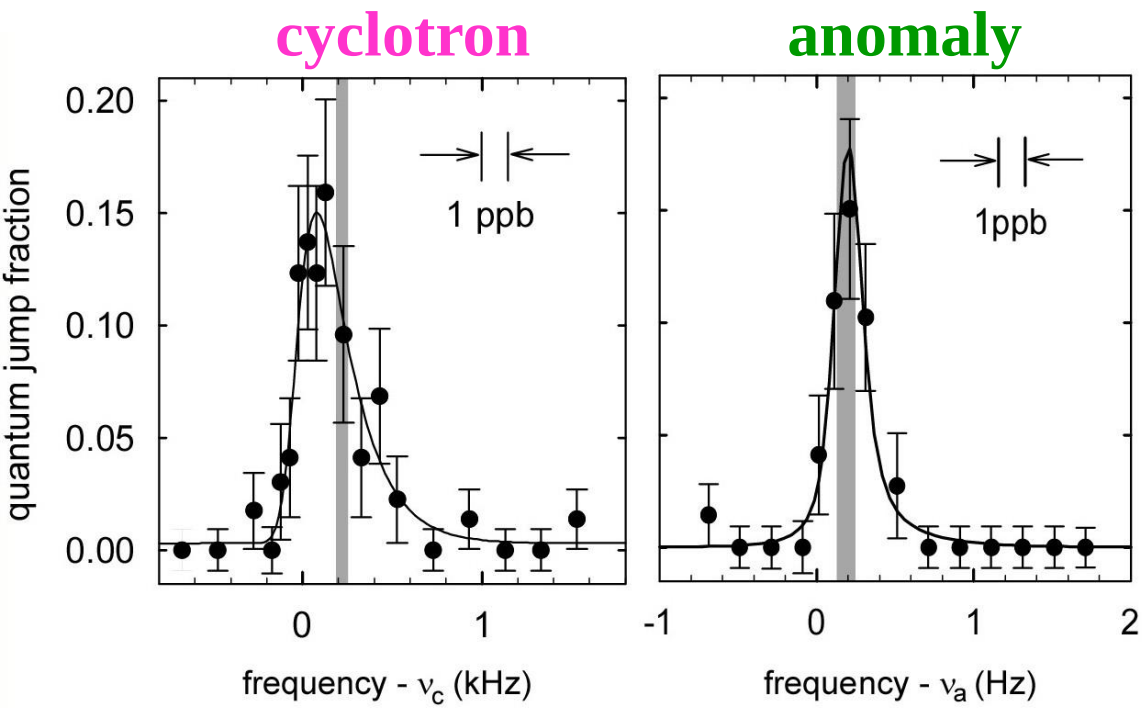
Solution: Simply correct for δ if we fully resolve the levels

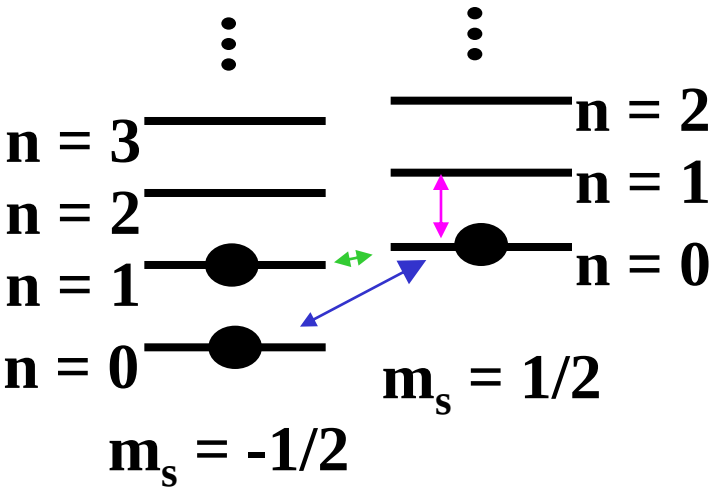
(superposition of cyclotron levels would be a big problem)

Measured Line Shapes for g-value Measurement

It all comes together:

- Low temperature, and high frequency make narrow line shapes
- A highly stable field allows us to map these lines

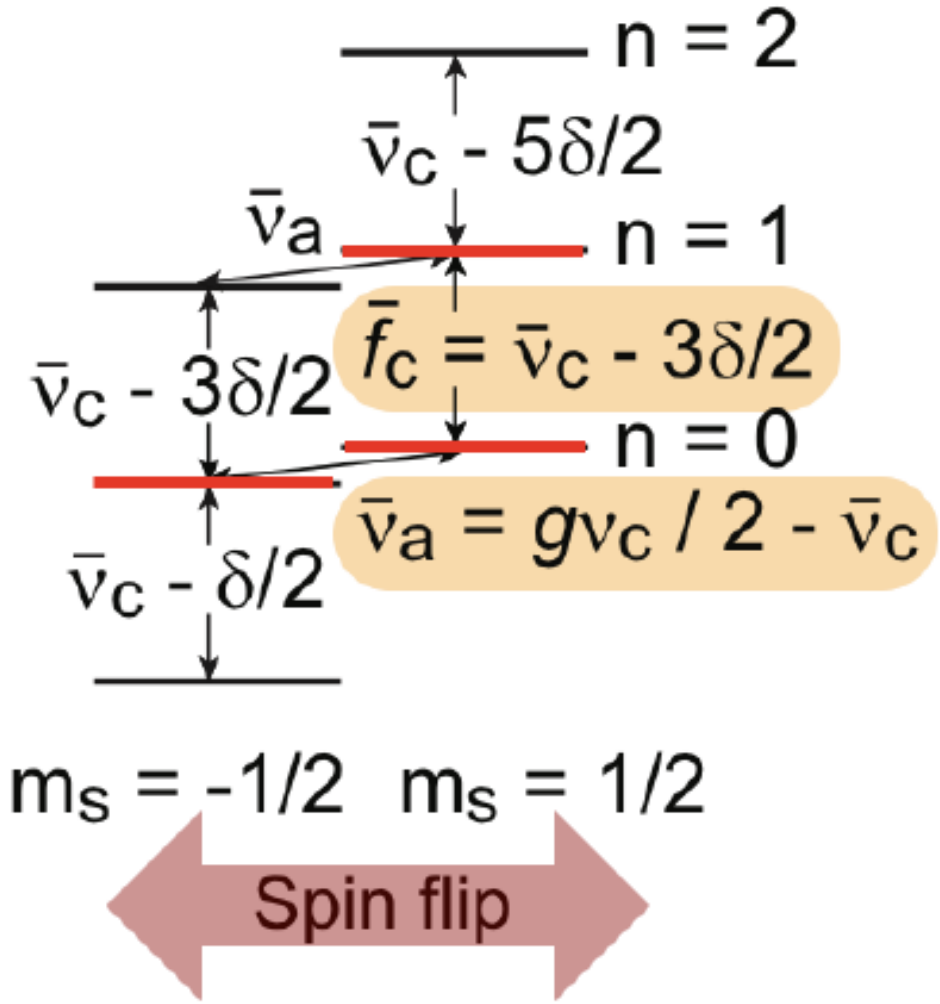




Precision:

Sub-ppb line splitting (i.e. sub-ppb precision of a *g*-2 measurement) is now "easy" after years of work

FIG. 3. Lowest cyclotron and spin levels of an electron in a Penning trap.



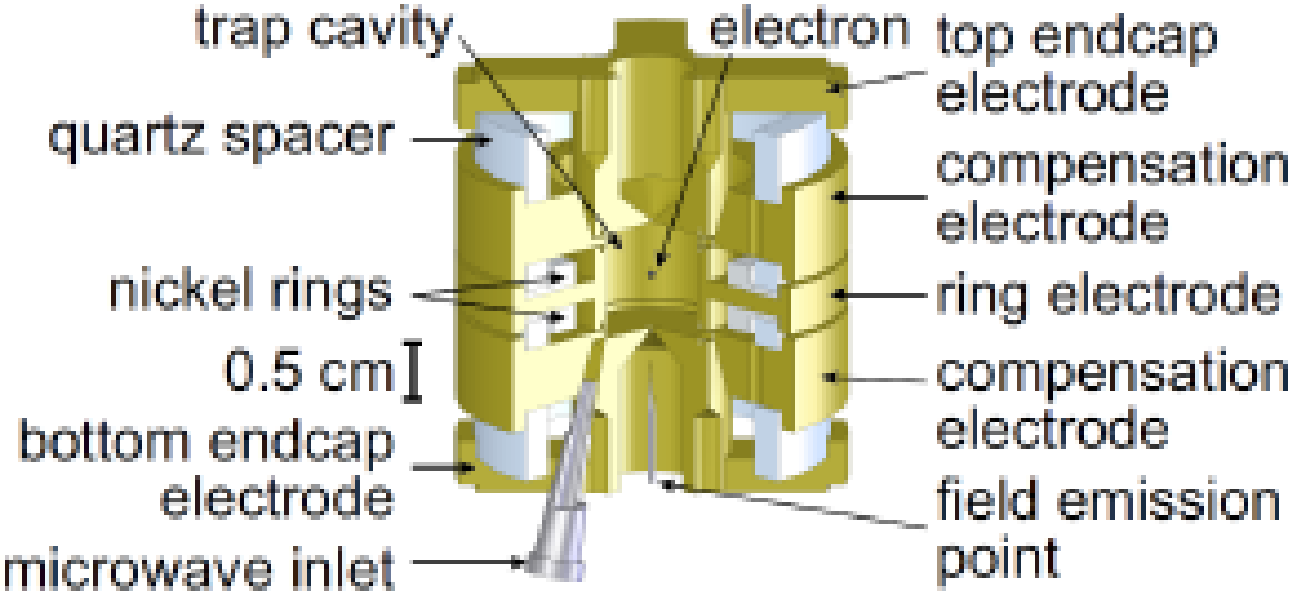


FIG. 4. Cylindrical Penning trap cavity used to confine a single electron and inhibit spontaneous emission.

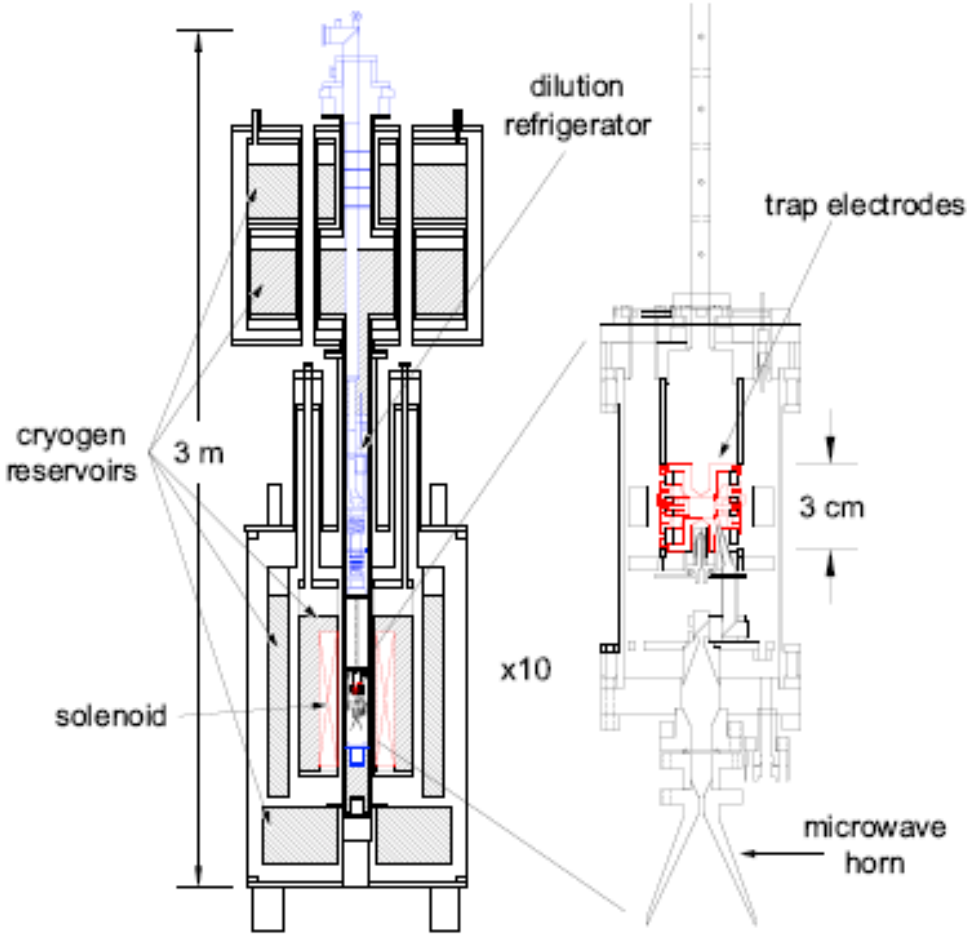
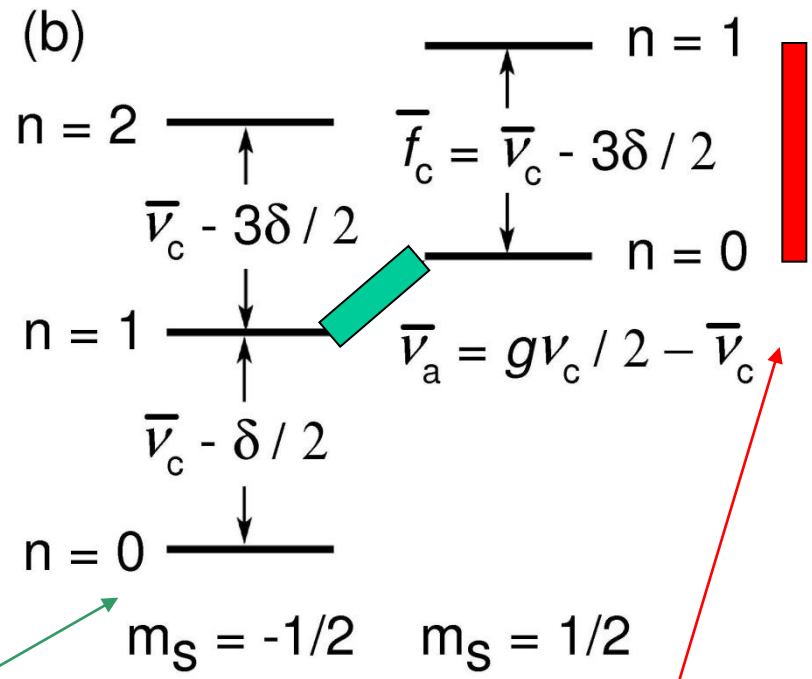
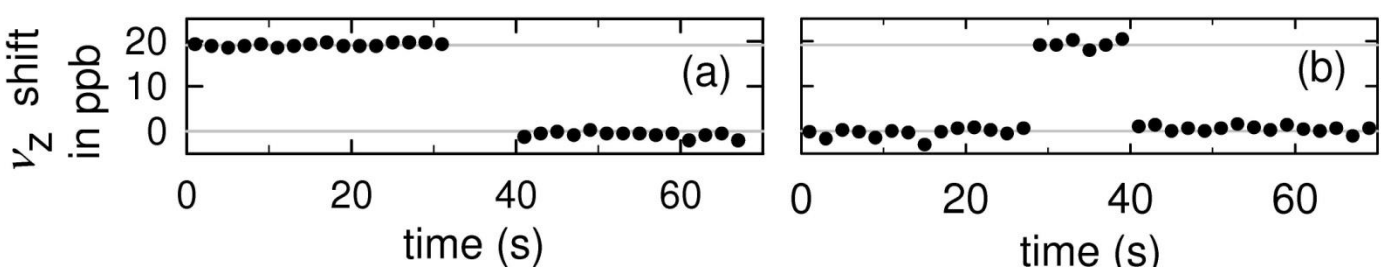


FIG. 5. The apparatus. The solenoid and electrodes that form the Penning trap are in red. The dilution refrigerator is in blue. Cryogen spaces are hatched.

Quantum Jump Spectroscopy

- one electron in a Penning trap
- lowest cyclotron and spin states





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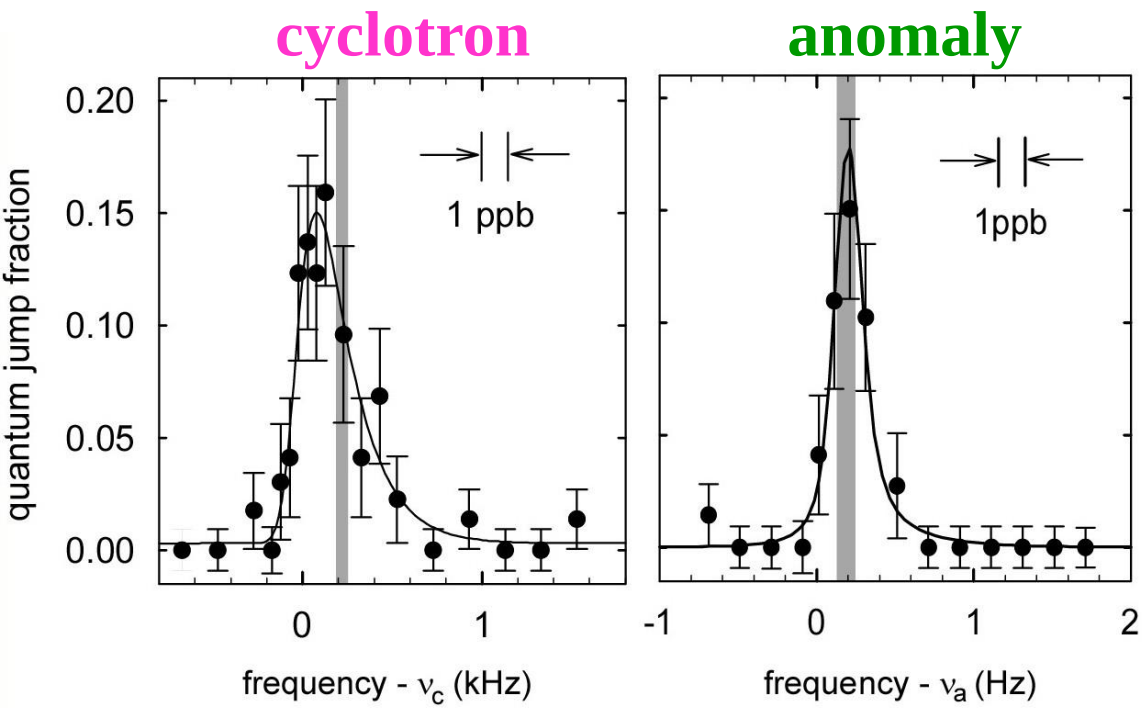
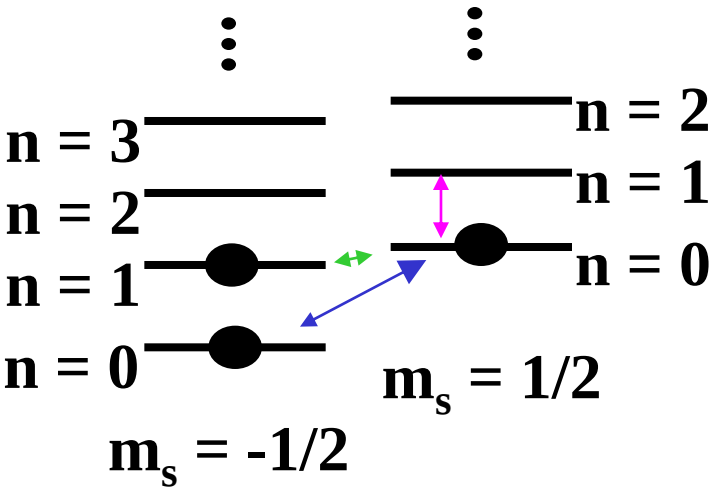




Precision:

Sub-ppb line splitting (i.e. sub-ppb precision of a *g*-2 measurement) is now "easy" after years of work

New Measurement of Electron Magnetic Moment

magnetic moment

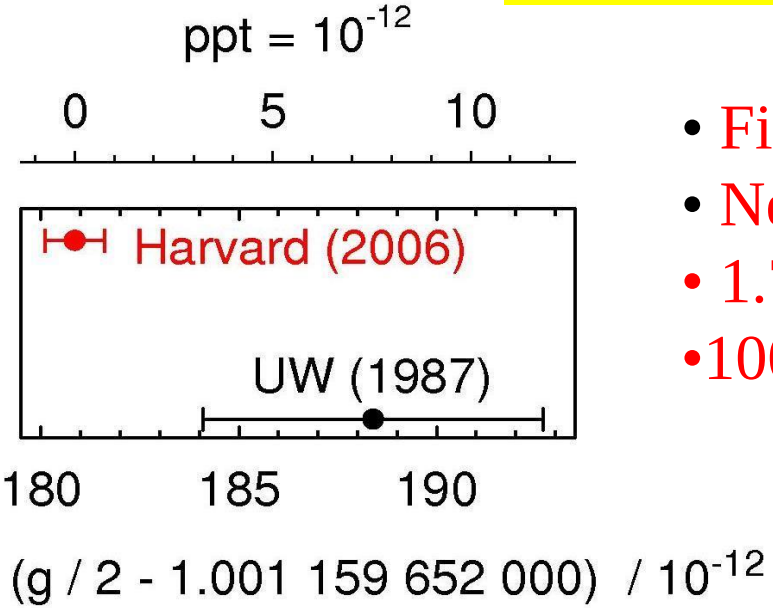
$$\vec{\mu} = g\,\mu_B \frac{\vec{S}}{\hbar}$$

spin

Bohr magneton $\frac{e\hbar}{2m}$

$$g/2 = 1.001\,159\,652\,180\,85$$

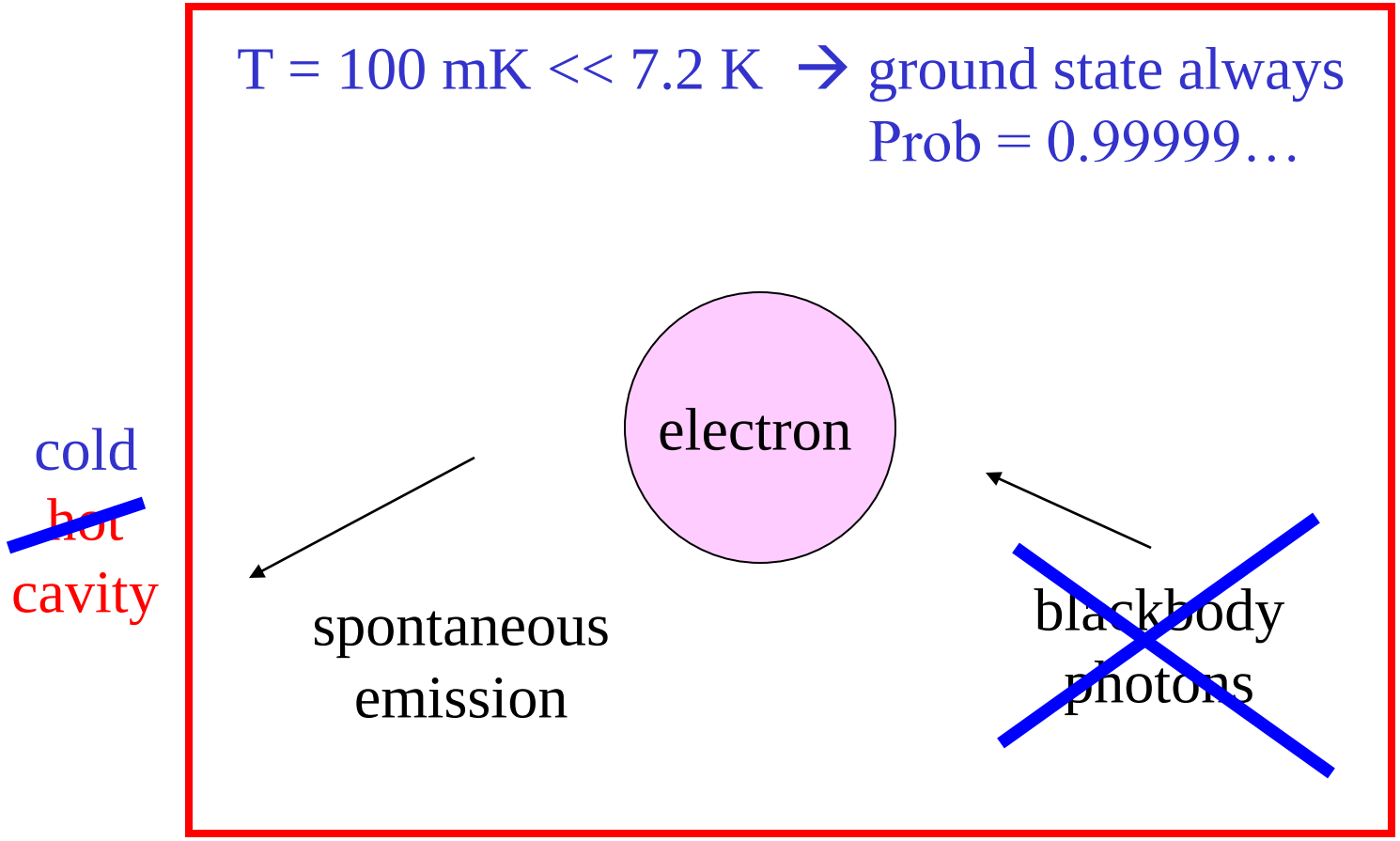
$$\pm 0.000\,000\,000\,000\,76 \qquad 7.6\times10^{-13}$$



- First improved measurement since 1987
- Nearly six times smaller uncertainty
- 1.7 standard deviation shift
- 1000 times smaller uncertainty than muon g

B. Odom, D. Hanneke, B. D'Urso and G. Gabrielse, Phys. Rev. Lett. **97**, 030801 (2006).

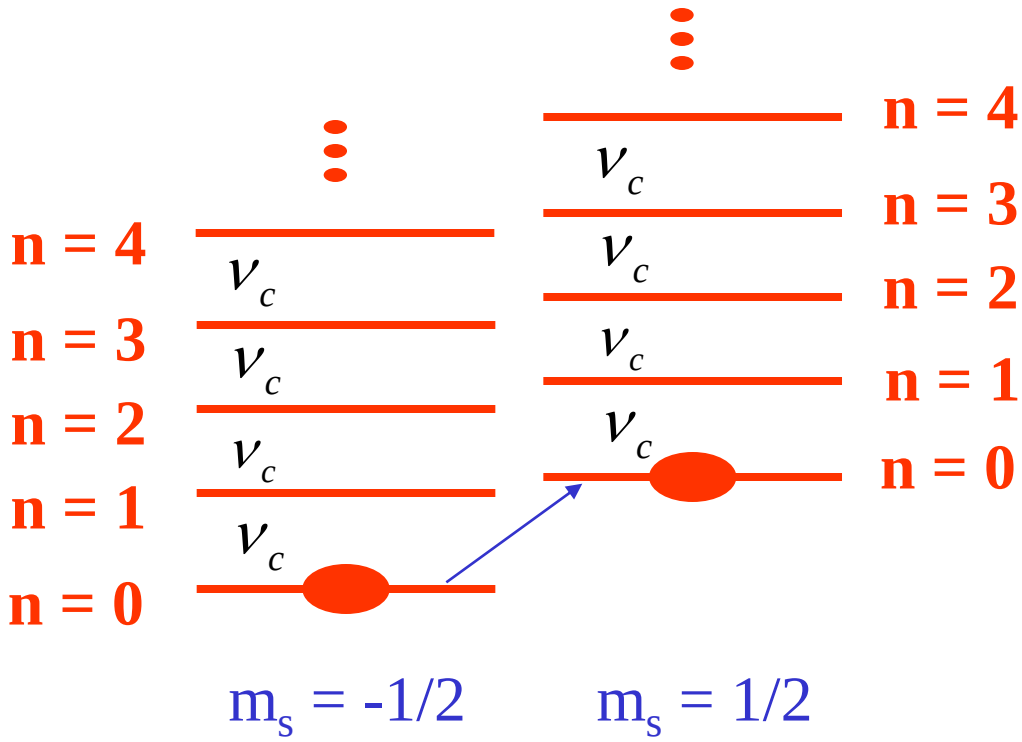
Electron Cyclotron Motion Comes Into Thermal Equilibrium



Basic Idea of the Fully-Quantum Measurement

Cyclotron frequency:

$$\nu_c = \frac{1}{2\pi}\frac{eB}{m}$$



Spin frequency:

$$\nu_s = \frac{g}{2}\nu_c$$

Measure a ratio of frequencies: $\frac{g}{2} = \frac{\nu_s}{\nu_c} = 1 + \frac{\nu_s - \nu_c}{\nu_c}$

$\square\ 10^{-3}$

B in free space

- almost nothing can be measured better than a frequency
- the magnetic field cancels out (self-magnetometer)