Antiproton and Antihydrogen Studies at ATRAP
antihydrogen studies

antiproton’s magnetic moment

first direct measurement
- 680 fold improvement
- CPT test

\[
\frac{\mu_p}{\mu_p} = -1.000\,000\,(5)\,[5.0\,\text{ppm}]
\]

positron accumulator
antiproton’s magnetic moment

\[ \vec{\mu} = g \frac{q\hbar}{2m} \frac{\vec{S}}{\hbar} \]

Proposal:
direct measurement in Penning trap

ASACUSA: anti-protonic He


Proposal:
direct measurement in Penning trap

C C Rodegheri et al., New Journal of Physics 14, 063011 (2012)

BASE


ATRAP

\[ \vec{\mu} = g \frac{q\hbar}{2m} \frac{\vec{S}}{\hbar} \]

**cyclootron frequency**

\[ \nu_c = \frac{e \cdot B}{2\pi m} \]

\[
\begin{align*}
g &= \frac{2\nu_L}{\nu_c} \\
\nu_L &= g \frac{e \cdot B}{4\pi m}
\end{align*}
\]
measurement in a Penning trap

**cyclootron frequency**

$$\nu_c = \frac{e \cdot B}{2\pi m}$$

**Larmor frequency**

$$\nu_L = g \frac{e \cdot B}{4\pi m}$$

**Brown-Gabielse Invariance Theorem**

$$\nu_c^2 = \nu_+^2 + \nu_-^2 + \nu_z^2$$

- magnetron motion $$\nu_-$$
- axial motion $$\nu_z$$
- reduced cyclotron motion $$\nu_+$$

- axial motion sensitive to spin state

- $${\Delta \nu}_z \propto \left[ \frac{g m}{2} + \left( n + \frac{1}{2} \right) + \nu_- \left( \ell + \frac{1}{2} \right) \right]$$

For a detection cycle that flips the spin state with probability 0.00, 0.05, 0.2, 0.4, 0.6, 0.8, 1.0, the increase from an ideal electric- and magnetic-field configuration applied between the endcaps is the closeness to resonance. In an ideal electric- and magnetic-field configuration, the latter is thus an inefficiency with respect to detecting a spin flip. The inefficiency is much higher, with a detection cycle producing an above-threshold shift for a spin that is down before the cycle begins, and with an efficiency equal to 1% from Fig. 5(b). Our interpretation is supported by the high fidelity resonant drive that saturates the spin transition (i.e., that saturates the spin transition). The increase from 0.00 to 10 $$/C_1$$ 9 $$/C_1$$ to 110 $$/C_1$$ for positive $$/C_1$$ 140406-3 $$/C_1$$ to 30 $$/C_1$$ is shown in Fig. 3z13 shows the linear behaviour in the reduced cyclotron frequency in Fig. 3z13 shows the linear behaviour in the reduced cyclotron frequency.
**electron:** 3 parts in $10^{13}$


**spin-flip drive**

![Graph showing time vs. $\nu_z$ shift (ppb)]

$\nu_z$ shift (ppb) vs. time (s)

4 Hz

**electricality:**

$\Delta E = h\nu_L$

3 mm

end cap

compensation

iron ring

compensation

end cap

**(anti-)proton:**

$\mu_N / \mu_B = m_e / m_p \approx 1/2000$

$\Rightarrow$ challenge to detect $\Delta \nu_z$ after spin-flip drive

$\Delta \nu_z, sf = 130$ mHz (Harvard trap)

$\Delta \nu_z, sf = 130$ mHz (Harvard trap)
Self Excited Oscillator

single proton

$\Gamma = 2.8 \text{ Hz}$

noise dip

frequency - $\nu_Z$ (Hz)

noise resonance

power (a.u.)

frequency (kHz)

$\Gamma = 0.27 \text{ Hz}$

power

frequency - $\nu_Z$ (Hz)


Sept. 11, 2013
for our detection of one-quantum transitions in the cyclotron frequency. To adjust the beam energy and 50 ms current pulses sent to the capacitor through a 100 MΩ potential as possible) has little effect upon the axial frequency.

As a small change in the measured axial frequency is the detected precession frequency, which we do not measure directly, the atomically sharp tungsten field-emission tip. A hole in the capacitor (10 µm in its capacitance, and in the mechanical strain across the 4T magnetic field, and the electrostatic

The axial frequency, for the B150 GHz. The axial frequency, for the B\text{150 GHz}.

The formal requirement for a QND measurement is that the strong field from the superconducting solenoid. To lowest order

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)

\[ \Delta \nu, sf = 130 \text{ mHz} \] (Harvard trap)
statistical detection of spin flips

\[ \nu_L \]

Proton work

\[ f - 919,000 \text{ Hz} \]

Time (hours)

\[ \Delta \text{(Hz)} \]

Time (hours)

\[ \Delta_0 \text{(Hz)} \]

Time (hours)

\[ \sigma^2 \text{ mHz}^2 \]

Frequency shifts

Small measured shifts in the axial frequency

Tum numbers the saturated iron ring, that arises when amplified signal from the proton's axial spin involves a magnetic field perpendicular to causes no spin flips has ensured frequency shifts resonant spin drive has

\[ \frac{8\pi}{C_1} \]

\[ \frac{8\pi}{C_2} \]

\[ \frac{8\pi}{C_3} \]

\[ \frac{8\pi}{C_4} \]

\[ f \]

\[ f_0 \]

BASE:

antiproton apparatus

trap with magnetic bottle

degraded

catching region

3 mm

6 mm

July 2012
first one-particle measurements

\[ \mu_p = \frac{g_p}{2} = 2.792\,846\,5\,\text{[2.5 ppm]} \]

\[ \mu_N = \frac{g_N}{2} = -2.792\,845\,5\,\text{[4.4 ppm]} \]
Resolving One-Quantum Spin Transitions

**analysis trap**
- with magnetic bottle
- spin state determination

**precision trap**
- homogenous B-field
- drive spin transition
- measure cyclotron frequency

**requires resolving of individual one-proton spin flip**

**threshold analysis**

---

**BASE collaboration**

**Bayesian analysis**

---

**proof-of-principle double Penning trap method**

---


antihydrogen studies

Adiabatic cooling

Axial potential

Temperature $T$ (K)

$U_i, f_i$

$U_f, f_f$

$f_i/f_f$

$T$ vs $f_i$ (kHz)

$T$ vs $\omega_0/\omega$

$p_i/p_f$

$\ln N$ vs $p_i$

$\pi \varepsilon_i$

$\omega_0/\omega$

$\nu$

$\nu$

$\pi$

$3.5 \pm 0.7 \text{ K}$

Ideal gas

$T$ vs $\omega_0/\omega$

$\omega_0/2\pi$ [kHz]

$2000 \text{ kHz}$

$470 \text{ kHz}$

$\text{Exp.}$

$\text{Sim.}$


trapped antihydrogen

results:
• 20 trials
• \(5 \pm 1\) trapped antihydrogen per trial
• storage times between 15 and 1000 s


• study regarding mirror trapped antiprotons at ATRAP

new apparatus for Hbar studies

**design features of Ioffe trap**
- octupole & quadrupole radial traps ➔ smaller pbar losses
- deeper traps (510 mK and 790 mK)
- wider trap radius ➔ more trapped antihydrogen
- shorter turn off (ca. 10 ms for octupole) ➔ higher sensitivity for trapped atoms ➔ better optimization of trapping

currently under construction & commissioning
commissioning of Ioffe magnet

fast turn-off time for
- higher sensitivity for trapped atoms
- quench protection

pinch coil: 390 A

previous generation trap

trap depth (mK) vs. time after quench (s)

93%

0.0 0.5 1.0 1.5

0 50 100 150 200 250 300 350

magnetic field [T] vs. time [ms]

-0.1 0 0.1 0.2 0.3 0.4 0.5 0.6

new magnet for Ioffe trap

Sept. 11, 2013

PSI 2013
q/m-comparisons p - pbar: 1 part in $10^{10}$

- pbar and p cyclotron clocks
- gravitational redshifts

$g_{\overline{p}} < (1 + 10^{-6}) \cdot g_p$

Future:
- AEGIS & GBAR collaborations:
  - “free fall” Hbar beam experiments
  - Alpha


axial loffe trap depth

$g_{\overline{H}} = 200 \cdot g_H$

? $g_{\overline{H}} < 110 \cdot g_H$

- limit of gravitational mass of $\overline{H}$
- simulation challenge
- ATRAP conclusions

C. Amole et al., Nature Communications 4, 1785 (2013)

• work at ATRAP on two experimental programs

• Antihydrogen studies:
  - trapped anti-hydrogen: 5 ± 1 per trial (more than before but need more)
  - new apparatus with improved loffe trap

• magnetic moment of (anti-)proton
  - first direct measurement of magnetic moment for proton and antiproton (680 fold improvement)
  - CPT test:
    \[ \frac{\mu_{\bar{p}}}{\mu_p} = -1.000\,000\,000\, (5) \, [5.0\,\text{ppm}] \]
  - resolved individual one-proton spin flips
  - working towards higher precision of 10^{-9}-10^{-10}