Direct measurement of the proton magnetic moment

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Up to now the magnetic moment of the proton has never been measured directly. The present most precise value for the magnetic moment comes from measurements of the hyperfine splitting in atomic hydrogen by Winkler *et al.* [1]. Several bound-state corrections have to be included to extract the magnetic moment of the free proton with a precision of 8.2 parts in 10^9 [2]. A direct and precise measurement with just one single isolated proton stored in a cryogenic Penning trap has the potential to improve this value by one order of magnitude without a need for theoretical corrections and opens the way for a corresponding measurement on the antiproton.

An ideal Penning trap is a superposition of a homogeneous magnetic field and an electrostatic quadrupole potential. In such a trap an ion has three independent eigenmotions: two radial modes, the modified cyclotron motion with frequency ω_+ and the magnetron motion with frequency ω_-, and an axial motion with frequency ω_z. The principle of a measurement of μ_p is the determination of two frequencies of the proton: the spin-precession frequency ω_L and the free cyclotron frequency ω_c. The frequency ratio yields the magnetic moment $\omega_L/\omega_c = \mu_p/\mu_N$ in units of the nuclear magneton μ_N.

The Larmor frequency is determined by measuring the spin transition probability as a function of the frequency of an external magnetic driving field. To this end an inhomogeneous magnetic field, a so-called *magnetic bottle*, is used to couple the spin magnetic moment to the axial motion of the proton. Using this *continuous Stern-Gerlach effect* a spin transition results in a frequency jump of the axial motion. In our magnetic bottle with $B_2 = 3 \cdot 10^5\,\mathrm{T/m^2}$ a spin transition results in an axial frequency jump of 171 mHz at $742\,\mathrm{kHz}$.

However, the strong magnetic bottle also couples the magnetic moments of the radial modes to the axial mode. Thus the axial frequency is extremely sensitive to energy changes in the radial modes. This results in axial frequency fluctuations. As a measure for these fluctuations the standard deviation of the difference between two subsequent axial frequency measurements $\alpha = \nu_z(t) - \nu_z(t+\Delta t)$ can be defined, $\Xi = \left((N-1)^{-1}\sum(\alpha_i - \bar{\alpha})^2\right)^{1/2}$. The minimal fluctuation achieved is $\Xi_{opt} \approx 150\,\mathrm{mHz}$. This value is not sufficient to detect spin transitions directly. However, a series of spin transitions leads to an increase of the fluctuations $\Xi_{SF} \approx \sqrt{\Xi_{opt}^2 + P_{SF}\Delta\nu_{z,SF}^2}$. A measurement of Ξ_{SF} and Ξ_{opt} then allows a determination of the spin transition probability [3], thus the Larmor frequency.

The spin-flip resonance has been measured by tuning the

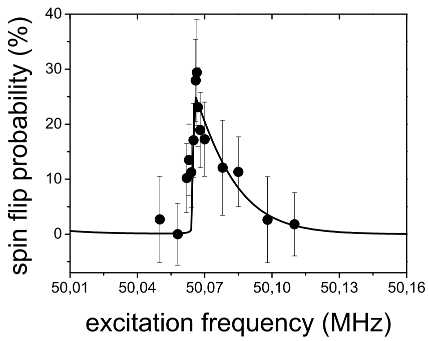

Figure 1: Larmor resonance of a single proton stored in the analysis trap. The broadening is due to the coupling of the axial motion to the thermal bath of the detection system in the inhomogeneous magnetic field.

spin transition drive over the Larmor frequency. The result is presented in Fig. 1. The line broadening is due to the coupling of the axial motion to the thermal bath of the detection system in the magnetic bottle. From this the Larmor frequency can be determined to 2 parts in 10^6, limited by the line broadening. Combined with a measurement of the free cyclotron frequency the *g*-factor was determined to $5.585696(50)$ [4].

Taking advantage of the so-called double Penning-trap setup, a narrower spin-flip resonance is expected, which allows for a measurement of the g-factor with even higher precision in the future. To this end spin transitions are driven in a Penning trap with a homogeneous magnetic field, where no additional line broadening occurs, and subsequently detected in a second Penning trap with a magnetic bottle. This will demand the direct detection of spin transitions, hence lower axial frequency fluctuations. In the future, we plan to measure the antiproton magnetic moment as a test of CPT invariance within the FLAIR Collaboration.

References

[1] P. F. Winkler *et al.*, Phys. Rev. **A 5**, 83 (1972).

[2] P. J. Mohr *et al.*, Rev. Mod. Phys. **80**, 633 (2008).

[3] S. Ulmer *et al.*, Phys. Rev. Lett. **106**, 253001 (2011) .

[4] C. C. Rodegheri *et al.*, New J. Phys. **14** 063011 (2012)