New Experiment for the Measurement of the g-Factors of $^3He^+$ and $^3He^{2+}$

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MOTIVATION

Magnetometry

Helium NMR (Nuclear Magnetic Resonance) probes offer a higher accuracy than water NMR probes due to their reduced dependence on impurities, probe shape and environmental influences such as temperature, pressure, or chemical corrections [1].

	Water	Helium
Dependence on temperature	1	1/100
Dependence on probe shape	1	1/1000
Diamagnetic shielding	1	1/10

comparable to theory

Furthermore, the diamagnetic shielding parameter σ is known more precisely for ^3He than water. This parameter quantifies how the electrons surrounding the bare nucleus change the NMR resonance frequency. However, so far ^3He NMR probes lack a calibration by a direct measurement of the nuclear magnetic moment independent of water NMR probes.

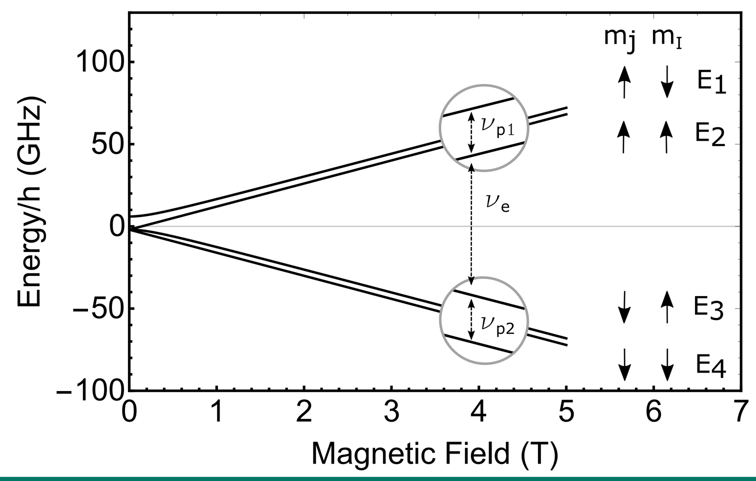
Muon g-2

Motivated by the 3σ discrepancy between experimental and theoretical values of the muon's anomalous magnetic moment a_μ as predicted by the Standard Model, two experiments located at Fermilab and J-Parc [2,3] aim at an improved measurement with a precision of 140 ppb. This requires measuring the anomaly frequency ω_a of the muon in a precisely tuned magnetic field and the spin precession frequency ω'_{NMR} of nucleons in water NMR probes used for magnetic field calibration. The successful implementation of our experiment would enable an uncorrelated magnetic field measurement using He NMR probes with very different and smaller systematic effects.

$$a_\mu = \frac{g_e}{2}\frac{\omega_a}{\omega'_{He}}\frac{m_\mu}{m_e}\frac{\mu'_{He}}{\mu_e}$$

Hyperfine splitting of $^3He^+$

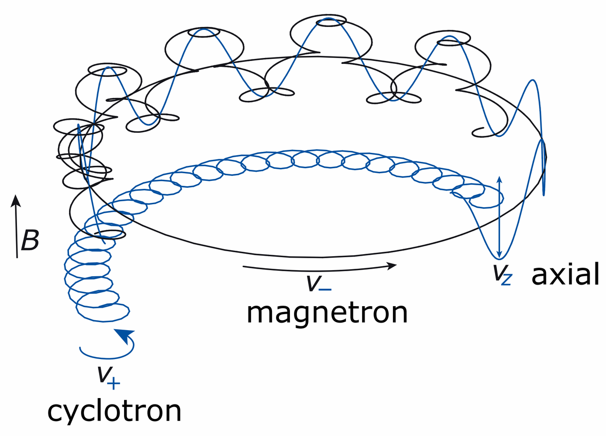
The measurement will provide a high-precision determination of electronic and nuclear magnetic moments and will also give access to the zero-field ground-state hyperfine splitting of $^3He^+$, which is strongly influenced by nuclear effects.



SINGLE ION IN A PENNING TRAP

Eigenmotions

A Penning trap confines an ion in a superposition of a homogeneous magnetic field and a quadrupolar electrostatic potential. The motion of the particle in an ideal trap is composed of three independent harmonic oscillations.



Determination of the Magnetic Moment

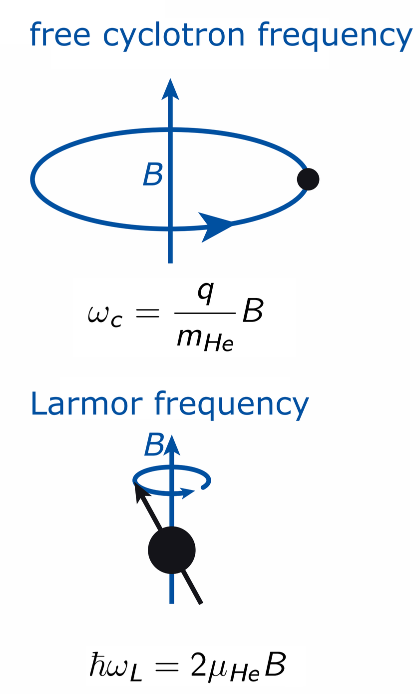
The magnetic moment is determined from two frequencies, the free cyclotron frequency and the Larmor frequency.

$$\frac{\omega_L}{\omega_c} = \mu_{He}\left(\frac{q}{2m_{He}}\right)^{-1} = g_{He}\frac{m_{He}}{4m_p}$$

Here, the free cyclotron frequency follows from the ion's eigenfrequencies via the "Invariance theorem"[4].

$$\nu_c = \sqrt{\nu_+^2 + \nu_z^2 + \nu_-^2}$$

The Larmor frequency is determined by inducing radio frequency transitions between the two spin states in the precision trap. The resulting spin state can be detected by applying the continuous Stern-Gerlach effect in the analysis trap.

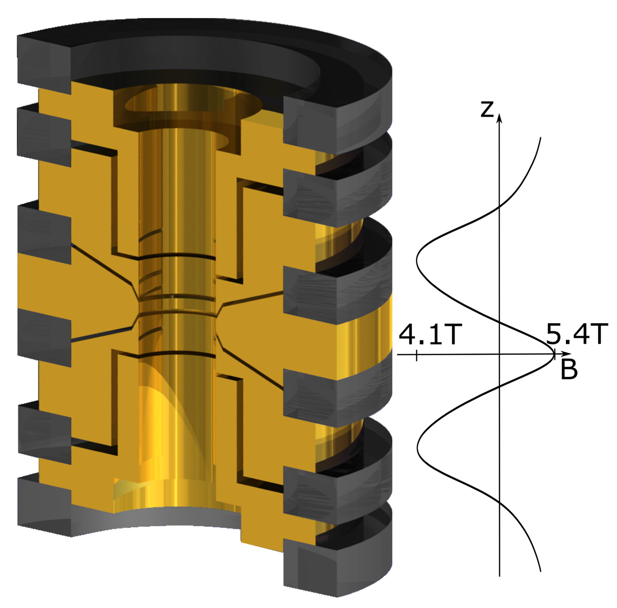


SPIN-STATE DETECTION

Magnetic Bottle

For spin-state detection the continuous Stern Gerlach effect is utilized, i.e. the coupling of the spin magnetic moment to the axial frequency. To this end a strong magnetic inhomogeneity B_2=700kT/m², called magnetic bottle, is superimposed on the homogeneous background field. This is achieved using ferromagnetic trap electrodes in the analysis trap. The result is that a spin-flip causes an axial frequency jump.

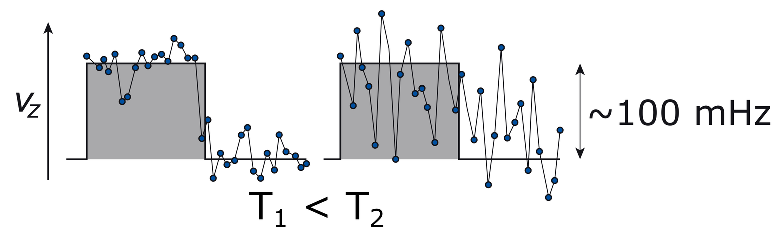
$$\nu'_z(\uparrow) - \nu'_z(\downarrow) = 2\frac{\mu_z B_2}{m\omega_z}$$



The challenge in detecting a nuclear spin-flip is due to the small nuclear magnetic moment and accordingly small frequency shift. A very strong magnetic bottle is needed to obtain a measurable frequency shift of ~100mHz out of 700kHz.

Cyclotron Noise

The strong magnetic bottle not only couples the spin magnetic moment to the axial motion but also leads to a coupling of the radial modes to the axial mode. The result is that noise driven fluctuations of the cyclotron quantum state (1 transition in 30 seconds) cause additional noise in the axial motion which prevents the detection of spin-flips. Using in the case of the proton/antiproton conventional cooling methods the noise could reduced sufficiently to allow for the detection of spin-flips. However due to the 3 times smaller spin-flip frequency jump in the case of ^3He, lower temperatures are needed, demanding the use of laser assisted cooling techniques.

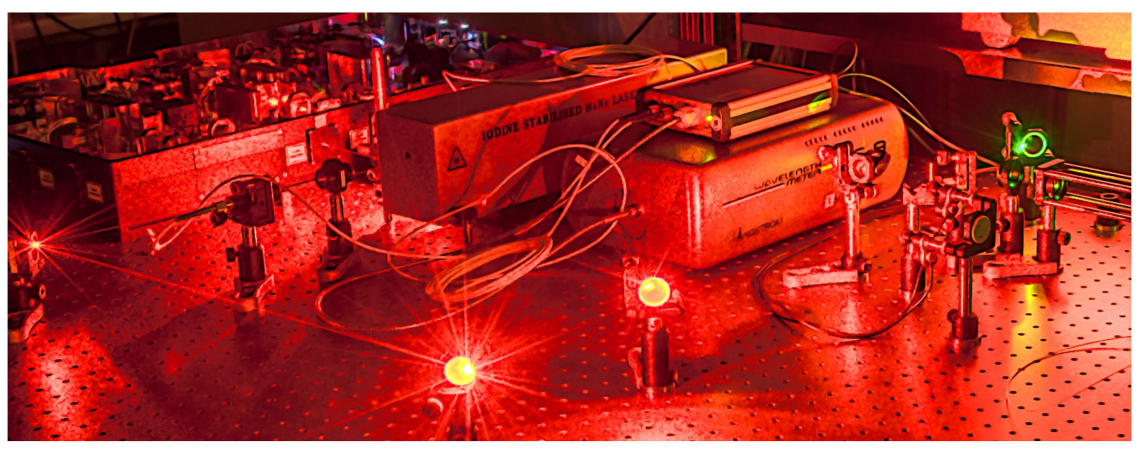


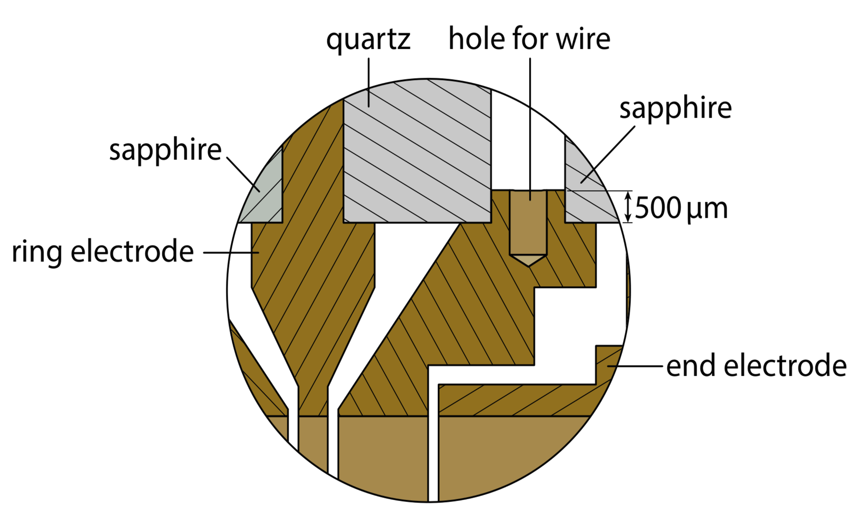
LASER-COOLING

Common Endcap Coupling

To achieve low temperatures and thus the necessary spin-flip detection fidelity, sympathetic laser-cooling will be applied. To this end the so-called common endcap method will be implemented. Here, a single ^3He ion stored in one trap is sympathetically cooled by a cloud of laser-cooled Beryllium ions in a neighbouring trap. The interaction will take place by image currents induced into a common electrode shared by both traps. The coupling strength between both species can optimized by a Penning trap design with reduced trap capacitance C_T [5].

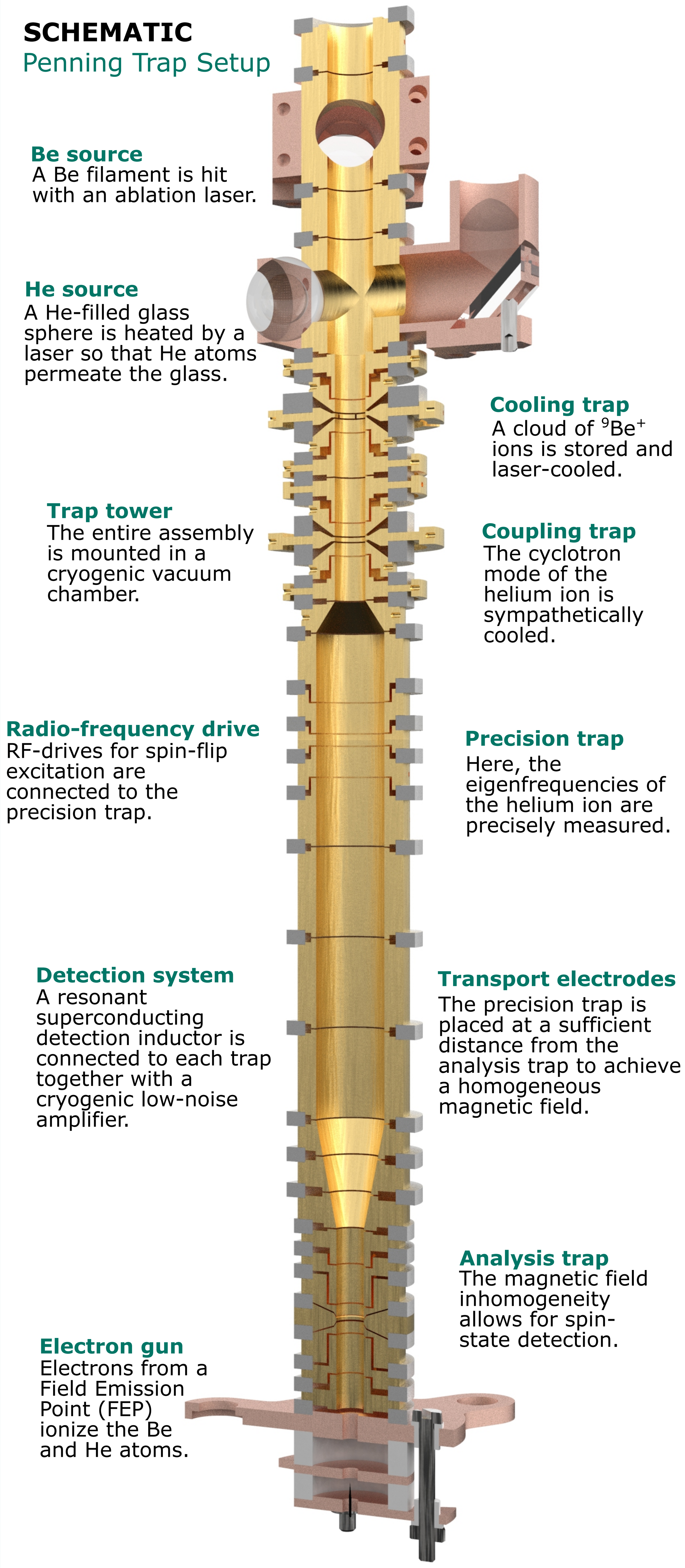
$$\tau_{exc} = 2\pi^2\nu_z C_T\frac{D^2}{q^2}\sqrt{m_{He}m_{Be}}\frac{1}{\sqrt{N_{Be}}}$$





SCHEMATIC

Penning Trap Setup



Acknowledgment

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