$g$-factor measurements of short lived states in the mass region $50 < A < 110$. 

G J Kurbartzki
Department of Physics and Astronomy, Rutgers University, New Brunswick, NJ, USA
E-mail: kum@physics.rutgers.edu

Abstract. Magnetic moments provide important nuclear structure information. This contribution will present the experimental tools and challenges of measuring magnetic properties of excited nuclear states, especially of the short lived picosecond states. Our understanding of the transient field and its applicability will be discussed using examples and results of recent measurements on medium heavy nuclei ($A \sim 100$).

Magnetic moments provide sensitive information on the individual contributions of protons and neutrons to the wave functions of nuclei and their excited states. This fact is a direct consequence of the large magnitude and opposite signs of the free proton and neutron $g$ factors. A good illustration can be found in the $g$ factors of the $2^+_1$ states in the isotopic chains of Sr and Zr around the closed neutron shell at $N = 50$. Large positive $g$ factors for $N = 50$ are followed by negative $g$ factors in $^{92}\text{Zr}$ and $^{94}\text{Zr}$.

Magnetic moments are usually measured by observing the spin precession of the nuclei in a known magnetic field. The spin of the nuclear state will precess with the Larmor frequency

$$\omega_L = \frac{d\theta}{dt} = \frac{g \mu_N}{\hbar} B \tag{1}$$

Depending on the lifetime of a state, the required field strength for a measurable $\Delta \theta$ may be in the $10^3$ Tesla range. Such fields cannot be provided in the laboratory, but they do exist as hyperfine fields in atoms. For instance, the spin of a single electron in the $1s$ orbit gives rise to a magnetic field at the site of the nucleus of

$$B_{1s} = 16.7 Z^3 \text{[Tesla]} \tag{2}$$

Fully occupied shells do not contribute. Such fields are indeed observed in highly ionized atoms under conditions which occur when atoms move through a solid medium. Outer electrons are stripped off, electrons are rapidly lost and recaptured, and deep inelastic scattering creates inner shell vacancies. If such ions traverse a polarized ferromagnetic medium, which acts as a reservoir of electrons with a preferred spin direction, this polarization is transferred into the moving ions, giving rise to a net field direction of the hyperfine fields. In this picture the field strength is a dynamic changing sum of the products of hyperfine fields, the charge state distributions of ions moving in a ferromagnetic medium, and a polarization factor, which may...
Figure 1. Compilation of transient fields, $B_{TF}$, measured for a set of calibration points. The velocity of the ions is given in terms of $v/Zv_0$, a measure of the electronic occupation of the ion in a given charge state. Three different regions can be assigned corresponding to the hyperfine field being dominated by $1s$ ($v/Zv_0 \approx 1$), $2s$ and $3s$ ($v/Zv_0 \leq 0.2$) electrons.

The fields depend on the probe ions, their velocities and the ferromagnetic host. This description is of little practical use, since none of the details are known. The fields were therefore calibrated with a set of known $g$ factors. It was found that the fields vary smoothly with the charge, $Z$, and velocity, $v$, of the ions. A compilation of fields derived from transient field measurements using gadolinium for states with independently measured $g$ factors is presented in figure 1. This presentation implies a linear dependence on $Z$. The $v$ dependence is only related to charge state distributions.

Figure 2. Setup at WNSL Yale Tandem.
Above the 1s-orbital velocity of Zv₀ (Bohr velocity v₀ = c/137), as more ions are bare, the fields decrease and vanish. The polarization transfer is the least understood part of this approach.

In practice, transient field measurements rely on parametrizations for absolute g factor values. The Rutgers parametrization [1] is applicable in the 2s and 3s regions and for ion velocities between 2 and 8v₀. The 1s region was parametrized for high velocity application of the transient field by Stuchbery [2].

The standard experimental setup is an angular correlation table (figure 2) with four γ detectors close to the vacuum chamber. The vacuum chamber contains the usual triple-layer target mounted in a magnet. The target should be coolable to liquid nitrogen temperature or lower. The chamber also contains particle detectors for particle-γ coincidence measurements.

The probe nuclei are excited and spin aligned by projectile Coulomb excitation in inverse kinematics. The target is typically a combination of carbon, where the reaction takes place, gadolinium, the ferromagnetic medium, and copper, where the probe ions come to rest and decay in an environment free of internal fields. The knock-on carbon nuclei have sufficient energy to penetrate both the target and a thin-foil beam stop to reach a particle detector. At energies near the Coulomb barrier the projectiles tend to pick up an α particle from the carbon. This α-transfer reaction makes it possible to measure g factors of some unstable nuclei in inverse kinematic conditions.

Figure 3 shows a particle spectrum obtained with a 345 MeV ⁹⁶Ru beam. The energy loss in the carbon target layer is ~30 MeV. The Coulomb barrier is at 333 MeV. At higher energies light particles (not stopped in the detector) from other reactions dominate while the Coulomb excitation is suppressed.

Well-separated γ spectra are generated by gating on specific particle groups. Individual spectra are shown in figure 4 for ⁹⁶Ru and ¹⁰⁰Pd.

Requiring a particle-γ coincidence selects an ensemble of aligned nuclei which decay with a characteristic angular distribution. The spin rotation in the transient magnetic field causes a rotation of the angular correlation pattern. This rotation is measured as a rate change in the stationary γ-detectors. The precession effect ϵ = (ρ − 1)/(ρ + 1) is calculated from quadruple ratios involving four detectors, with the same quadrant angle θγ:

$$\rho = \sqrt{\rho_{1,4}/\rho_{2,3}} , \quad \rho_{i,j} = \sqrt{(N^\uparrow_i N^\downarrow_j)/(N^\downarrow_i N^\uparrow_j)} .$$

(3)

N↑ and N↓ are the integrated γ-peak rates for two magnetic field directions. The polarizing field
at the target is reversed every few minutes. The logarithmic slope, $S(\theta_\gamma) = \frac{1}{W(\theta_\gamma)} \cdot \frac{dW(\theta_\gamma)}{d\theta}$, of the angular correlation is needed to transform the rate change at the detector positions into the rotation angle $\Delta \theta = \epsilon / S(\theta_\gamma)$. The particle-\(\gamma\) angular correlation, using the usual notation, $W(\theta) = 1 + A_2^{exp} Q_2 P_2(\cos \theta) + A_4^{exp} Q_4 P_4(\cos \theta)$ can be determined from anisotropy ratios obtained from the same precession data in the individual clover segments, making use of the approximation $A_k^{exp} = A_k^{th}(1 - \eta k(k+1))$ for $\eta \ll 1$. (5)

When measuring $g$ factors across an isotope chain, the $\Delta \theta$ values themselves represent the relative $g$ factors. They can be measured with high statistical accuracy. For absolute $g$ factors the actual transient field strength has to be known. This field strength is taken from a parametrization (calibration). In the medium-heavy nuclei region the Rutgers parametrization $B_{TF} = 96.7 M Z^{1.1}(v/v_0)^{0.45}$ (6)

| Energy (keV) | Counts |
|-------------|--------|
| 500         | 1000   |
| 1000        | 10     |
| 1000        | 10     |
| 1000        | 100    |
| 1000        | 1000   |

**Figure 4.** Gated \(\gamma\) spectra.

| Energy (keV) | Counts |
|-------------|--------|
| 500         | 1000   |
| 1000        | 10     |
| 1000        | 100    |
| 1000        | 1000   |

**Figure 5.** Relative $g(2^+_1)$ of the stable ruthenium isotopes calibrated against $^{106}$Pd.
Table 1. Results from an $\alpha$-transfer reaction measured simultaneously with the Coulomb excitation of the projectiles [5].

| Nucleus | $E_x$(keV) | $I^+$ | Transition | $\tau$(ps) | $|S(67^o)|$ | $g$ |
|---------|------------|-------|------------|------------|-------------|------|
| $^{100}$Pd | 665.5 | $2^+_1$ | $2^+_1 \rightarrow 0^+_1$ | 9.0(4) | 0.324(54) | +0.30(14) |
|        | 1415.9 | $4^+_1$ | $4^+_1 \rightarrow 2^+_1$ | 3.6(3) | 0.550(91) | +0.45(14) |
| $^{96}$Ru | 832.6 | $2^+_1$ | $2^+_1 \rightarrow 0^+_1$ | 4.24(9) | 1.85(5) | +0.46(3) |

is used. Here, $M$ is the magnetization of the ferromagnetic layer. It is measured offline as a function of the temperature and care has to be taken that it does not vary in beam. At beam energies of 300 MeV and higher and at beam currents of $\sim1$pnA, the local beam spot temperature can reduce the magnetization and therefore the effective field.

As example, results for the $2^+_1$ states in the stable ruthenium isotopes, measured with one target and calibrated against the $g(2^+_1,^{106}$Pd), are shown in figure 5 [3]. The results for $^{100}$Pd simultaneously measured with $^{96}$Ru are listed in table 1.

**Conclusion**

- The transient field together with Coulomb excitation in inverse kinematics is a powerful tool to measure magnetic moments of the very short lived excited states in nuclei. The technique is applicable to rare and radioactive nuclei if they are provided as accelerated beams.
- The $\alpha$-transfer reaction allows measurements of magnetic moments using the transient field in inverse kinematic conditions on certain unstable nuclei, for which otherwise a radioactive beam is needed.
- It has proven difficult to measure higher excited states because of low Coulomb excitation cross-sections.
- At beam energies above the Coulomb barrier, as new reaction channels open, the Coulomb excitation becomes minute and the detectors are swamped with undesirable particles and $\gamma$ rays.
- A better knowledge of the transient field itself is desirable.

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