The past and future of magnetic moment measurements of short-lived nuclear states

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Abstract. Over the last few years there has been considerable progress in both experimental facilities and theoretical calculations of magnetic moments of low-lying, short-lived nuclear states. In particular, the competition between collective and single particle excitations in the region around 70 ≤ A ≤ 100 has been examined. Recent data on Pd isotopes are presented. Newly developed techniques are applicable to work with radioactive beams. However, experimental limitations have emerged and will be discussed especially in their relations to the determination of absolute magnetic moments as opposed to relative measurements of moments in chains of isotopes.

1. Introduction
Magnetic moments of excited states provide a specific signature for defining the structure of the states. In particular, the relative importance of neutron and proton configurations can be approximately inferred from even a single determination of the sign of the magnetic moment. Precision magnetic moment measurements, coupled with B(E2) values, enable a definite description of the microscopic configuration.

In general, while calculations based on standard nuclear models are in fair agreement with the measurements, some surprises have sprung in many cases. The superdeformed bands in \(^{194}\text{Hg}\) seem to have \(g \approx Z/A\) while the normal deformation bands in the same isotope exhibit clear aspects of single particle configurations. The \(g\) factors of the Nd isotopes vary from \(Z/A\) for the fully deformed collective states (with spins and parities \(2^+, 4^+, 6^+, 8^+, \text{ or } 10^+\)) in \(^{150}\text{Nd}\) to single-particle values for the lighter isotopes, even reaching negative values for the \(6^+\) state in \(^{144}\text{Nd}\). The \(g(^{12,14}\text{Ca};2^+)\) factors are positive while other Ca nuclei with neutrons in the \(f_{7/2}\) shell have negative \(g\) factors. The \(^{92,94}\text{Zr}\) have both negative and positive \(g\) factors for the first two \(2^+\) states which have been identified as consisting, respectively, of symmetric and antisymmetric proton-neutron configurations.

Many techniques have been applied for these measurements. In the past, the technique yielding the largest magnetic fields involved implanting the isotope of interest in a ferromagnetic foil (IMPAC or IPAC techniques). Recently, the magnetic moments of short-lived \((\approx \text{ps lifetimes})\), low-lying excited states in nuclei across the periodic table have been measured by the “transient field” method, TF [1, 2]. This procedure requires the production of an excited state in an aligned spin state, followed by traversal of a ferromagnetic foil in which the magnetic moment will precess about the induced hyperfine field. In most recent experiments the excitation
of the state of interest has been carried out by Coulomb excitation, in inverse kinematics, of a beam consisting of the isotope of interest by a target (such as $^{12}$C, $^{28}$Si, $^{24}$Mg, or $^{58}$Ni), lighter than the beam isotope. The ferromagnetic foils of choice have been iron or gadolinium. The induced hyperfine fields can not be derived from basic principles. However, the strength of the interaction has been parametrized from the effective hyperfine fields observed in many experiments on nuclei with known magnetic moments.

In this work, the experimental techniques have been pushed to the limits because of the interest in higher excited states such as the $2^+_2$, $4^+_1$ and $0^+_2$ states. The possibility of reaching states in radioactive nuclei not yet available at existing accelerators by capturing $\alpha$ particles from a $^{12}$C target nuclei was explored. This latter technique, fusion evaporation reactions [3] or production by beam fragmentation at intermediate energies [4], result in excitations of nuclei to higher energy levels. These nuclei traverse the ferromagnetic foils while in these precursor states and the precessions observed are often related to the $g$ factors of these higher energy states rather than to the $g$ factor of the state of interest.

The details of the procedures used recently are described in Section 2. The resulting magnetic moment measurements of states in $^{106}$Pd and $^{100}$Pd are described in Section 3.

2. Experimental developments

Almost all current experiments involve the production of the state of interest in a spin aligned mode. The excited ion, moving at moderate velocities [1, 2], traverses a ferromagnetic foil where the nuclear spin (magnetic moment) precesses under the influence of an effective hyperfine field. Coincidences between a target particle, which provided the excitation reaction, and the $\gamma$ rays from decaying excited states of the ion are recorded. The angular correlation and the corresponding slope, evaluated at the angle at which the $\gamma$ detectors are placed with respect to the particle detector, need to be measured quite accurately

2.1. Targets

The targets are similar to those described in previous publications [5, 6, 7]. They consist essentially of a gadolinium foil of appropriate thickness (4-6 mg/cm$^2$). A light scattering material is deposited on the front of this foil. A copper foil in which the probe ions and beam will stop is evaporated on the down-beam side of the target. The target is kept at around 50 - 100K by a closed cycle Displex refrigerator. However, the exact temperature at the target spot under beam conditions cannot be measured. The magnetization as a function of temperature was measured off line in an AC magnetometer. It is noted that for most targets the magnetization remains constant between 50K and 100K, drops by 10 - 20 % at low temperatures and follows a Brillouin curve above 100K.

2.2. Excitation of the state of interest

The most favorable mode of excitation is Coulomb excitation in normal or inverse kinematics. The latter are particularly propitious for work with beams of radioactive isotopes for which targets cannot be prepared.

In the current experiments, Coulomb excitation at energies above the Coulomb barrier was used to excite the $2^+_2$ and $4^+_1$ states in $^{106}$Pd, while the $\alpha$ capture from $^{12}$C target reaction was used to excite the $2^+_1$ state in $^{100}$Pd. At higher beam energies, more energy is deposited in the target than in most previous lower-energy experiments using the transient field. Thus, the temperature of the gadolinium foil at the beam spot position might be higher than expected, leading to a locally reduced magnetization.
2.3. Detectors and acquisition

The $\gamma$ rays were detected usually in four Ge detectors or, if possible, in Clover Ge detectors. The light target particles from which the beam was scattered were detected in a forward-situated particle detector (Canberra PIPS, solar cells, or multidetector array).

2.4. Measurement of the slope of the angular correlation

In general, the angular correlation of the $\gamma$ rays with respect to the recoiling particles is determined by taking coincidence data for various $\gamma$-ray detector angles. However, in order to save beam time, the angular correlation can be derived from the precession data using the segmentation of the Clover detectors. For this purpose, the data in Clover segments located at the same angle with respect to the beam direction are analyzed separately. Each Clover detector has a slightly different geometry inside its housing. Hence the angular separation of the detector segments and their relative efficiencies have to be determined for the specific distance between the detectors and the target that is used in the experiment. The angular correlation parameters are then determined as described in Ref. [6].

2.5. Calibration of the transient field

The transient field $B_{TF}$ was calibrated [8] by measuring the precession of the angular correlation for states for which the $g$ factor was known from independent measurements in nuclei ranging from Ne to Pt [8]. The number of possible calibration points is rather limited and their accuracy varies.

Fig. 1 represents a new summary of calibration points. Only recent measurements for states for which $g$ is known from previous data together with light-ion data compiled by Stuchbery [4] are shown. 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. Here $v$ is the ion’s velocity, $Z$ is the ion atomic number and $v_0 = e^2/\hbar c$ is the Bohr velocity for the K electron. It is generally believed that

![Figure 1. Transient field in gadolinium for nuclei with known $g$ factors](image-url)
Table 1. $g$ factors in $^{106}\text{Pd}$.

| $I^+$  | $\tau(\text{ps})$ | Previous work | Theory Kim [10] | Theory Robinson [13] | This work |
|-------|-------------------|---------------|-----------------|----------------------|-----------|
| $2^+_{1}$ | 17.3(11) | +0.398(21)[11] | +0.392 | +0.5 | +0.48(1) |
| $4^+_{1}$ | 1.9 | +0.453 | +0.47(10) |
| $2^+_{2}$ | 4.5 | +0.30(6) [12] | +0.664 | +0.45(10) |

the transient field arises mainly from vacancies in either the 1s, 2s or 3s electronic shells of the ions traversing the ferromagnetic foil. The hyperfine fields generated by these vacancies vary by orders of magnitude as the major quantum number $n$ of the shell increases. The three regions corresponding to the 1s ($v/Zv_0 \approx 1$), 2s ($v/Zv_0 \approx 0.1$), and 3s ($v/Zv_0 \leq 0.1$) electronic configurations are shown in Fig. 1. The Rutgers parametrization is drawn for the range in which it was originally derived.

Above $v/Zv_0 \approx 1$ the field strength is expected to decrease as more and more ions are fully stripped. New transient field measurements at higher probe ion velocities and with higher statistics suggest a more complex structure than hitherto used in the various parametrization formulas. A better understanding of the transient field requires more precision calibration data and presents a challenge for future experiments.

3. Results and discussion

3.1. The $2^+_2$ and $4^+_1$ states in $^{106}\text{Pd}$: is $^{106}\text{Pd}$ a vibrational nucleus?

$^{106}\text{Pd}$ lies in the region of the Cd isotopes that have, until recently [9, 10], been good examples of vibrational nuclei. For such nuclei definite predictions have been made for the $g$ factors and the ratios of their transition probabilities from the two-phonon excitations, namely the $4^+_1$, $2^+_2$, and $0^+_3$ states. Specifically, if this triplet of states has a vibrational structure, all three states should have the same $g$ factor, namely $g \approx Z/A$.

The $g$ factor of the $2^+_{1}$ state has been measured using the IMPAC technique by Johansson et al., $g(^{106}\text{Pd}; 2^+_1) = 0.398(21)$ [11] and has been one of the components in the calculation of the Rutgers parametrization. The $g$ factor of the $2^+_{2}$ state has also been measured before [12] but $g(4^+_1)$ has not been measured previously.

The current experiments were run at 230, 280 and 290 MeV and on two different targets. The results are displayed in Table 1. The $g$ factors quoted for this work were calculated assuming a transient field strength given by the Rutgers parametrization. The new value of $g(2^+_1)$ is larger than that measured by Johansson. The reason for this discrepancy is not known.

However, the structure information is fully contained in the relative $g$ factors which are independent of any parametrization or calibration. The precision of the $g$ factor measurements for the two-phonon states is relatively low because of the weak excitation of the states even at higher beam energies. Nevertheless, the data show that the $g$ factors for the one-phonon and two-phonon states are indeed comparable.

Two theoretical calculations have been carried out for the $2^+_1$, $2^+_2$, and $4^+_1$ states in $^{106}\text{Pd}$ (Table 1). K.-H. Kim et al. followed an IBM-2 approach [10]. S. J. Q. Robinson [13] used the interaction JJ45PN of Brown and Hjorth-Jensen in shell model calculations which involved 4 proton holes in the $f_{7/2}, p_{3/2}, p_{1/2}$ and $g_{9/2}$ configuration space and 4 neutron holes in the $g_{9/2}$ and $d_{5/2}$ space [14].

The determination of the excitation energies of Kim et al. is close to the experimental values, while Robinson’s are somewhat high and the wave functions are very fractionated, suggesting
collectivity. The B(E2)'s predicted by Robinson are much smaller than the experimental values, while Kim’s results are in fair agreement with experiment. Robinson’s g factors, are in agreement with the measured values. Kim only calculated g(2+1). The quadrupole moment, Q(2+1)= -0.51(7)b [15], is in disagreement with the vibrational model prediction of Q = 0.

In view of the totality of the information it is not possible to assign a definite structure to 106Pd.

3.2. The α capture reaction and 100Pd: 12C(96Ru,8Be)100Pd
The α-capture from the 12C target by the projectile opens for investigations regions of proton-rich radioactive nuclei not available as beams at existing accelerators. The Bonn group has reported similar measurements of g factors in a few isotopes. The method has the advantage of providing a built-in calibrator because the Coulomb excitation of the beam itself, obtained simultaneously with the products of the α-transfer reaction, serves as a check of the analysis. The two reactions are clearly separated experimentally when γ spectra are observed in coincidence with either the 12C or the α-particles from the 8Be breakup (Fig. 2).

However, the method has downsides as well: the cross sections are relatively small, the angular correlation is nearly isotropic, higher excited states are populated, and the kinematics are not well defined. Nevertheless, assuming small side feeding, and with reasonable running time, the g factor g(100Pd;2+1) = +0.35(15) was obtained.

The resulting g factor, g(100Pd;2+1), has a large error that arises from the weak population and small spin alignment of the state of interest (Fig. 3). The option of increasing the beam intensity or energy has to be exercised with caution and applied only if the target temperature can be held low, a challenge for future measurements.

4. Conclusions
- The g factors of the two-phonon states in 106Pd are the same as the g factor of the 2+1, one-phonon state, in agreement with the vibrational model predictions. However, the ratios of B(E2) values and the quadrupole moments are not.
- The α-transfer reaction produces a small spin alignment, hence a small sensitivity for
determination of the precession of the angular correlation.

- New techniques lead to possibly high-precision results but the systematic uncertainties inherent in the parametrization of the transient field need to be reduced. New independent magnetic moment measurements are required as calibration points.

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