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Nuclear structure through moment measurements: exploiting γ-ray detector arrays with ancillary detectors

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Abstract. Experimental methods to measure the magnetic moments of short-lived excited states in beams of rare isotopes are outlined. The emphasis is on the so-called High-Velocity Transient-Field (HVTF) and the Recoil in Vacuum (RIV) methods, and the role of γ-ray detector arrays with ancillary detectors. Insights into the structure of neutron-rich nuclei through such measurements on radioactive beams are discussed. Opportunities for the future development of these techniques, for applications to both stable and radioactive beams, are explored.

Keywords: Magnetic moments, nuclear structure, radioactive beams, γ-ray detector arrays, ancillary detectors

PACS: 21.10.Ky, 21.60.Cs, 27.40.+z, 27.60.+j

INTRODUCTION

The magnetic moment, or g factor, is an important observable to study nuclear structure. Such measurements on short lived excited nuclear states having lifetimes of the order of picoseconds have always been challenging.

In the last decade, methods have been developed that allow g-factor measurements on short-lived excited states of neutron-rich nuclei produced as radioactive beams. This paper will review some of that methodology and some of the resultant insights into nuclear structure.

Irrespective of whether an excited-state magnetic moment is to be measured in a stable or radioactive nuclide, hyperfine fields that produce intense magnetic fields at the nucleus must be exploited in order to produce a measurable effect within the short lifetime of the nuclear state. The consequence is that there are two practical hyperfine fields that can be used for moment measurements on excited nuclear states with picosecond lifetimes. These are (i) the transient magnetic hyperfine field that acts on the nuclei of ions swiftly traversing a ferromagnetic medium, and (ii) the free ion hyperfine fields at the nuclei of highly charged ions moving through vacuum. Consequently, two methods for g-factor measurements on short-lived excited states of radioactive beams are the so-called High-Velocity Transient-Field (HVTF) method and the Recoil in Vacuum (RIV) method.

The oral presentation associated with this paper included some preliminary results of recent experiments which will not be reported here. Instead, this paper includes more details of the methodology and possibilities for future development of the techniques, particularly in terms of the applications of γ-ray detection arrays with ancillary detectors. The HVTF method is discussed first, followed by the RIV method.

HIGH VELOCITY TRANSIENT FIELD TECHNIQUE

HVTF method

The first application of a high-velocity transient-field technique [1] to measure the g factors of excited states of neutron-rich nuclei produced as fast radioactive beams was conducted at the Coupled Cyclotron Facility of the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University [2, 3, 4]. Questions on the nature and origins of deformation between N = 20 and N = 28 were addressed by measuring the g factors of the 2+ states in 38 Ar22, 40 Ar24, and 46 Ar28. More recently, similar measurements have been completed on the neutron-rich argon isotopes 44 Ar24, 46 Ar26, and 48 Ar28.

Beams of the relevant sulfur and argon isotopes with energies of 40 MeV/nucleon were made incident, in turn, upon a target consisting of contiguous layers of Au and Fe, 355 mg/cm2 thick and 110 mg/cm2 thick, respectively. The nuclear state of interest was excited and aligned by intermediate-energy Coulomb excitation on the Au layer of the target. Within the Fe layer, the excited nucleus was subjected to the transient field in the ‘high velocity’ regime, i.e. at velocities near the ion’s K-shell electron velocity, v0, where v0 = c/137 is the Bohr velocity. The effect of the transient field was to cause the nuclear spin to precess. The nuclear precession angle, to which the g factor is proportional, was observed via the perturbed angular correlation of the de-excitation γ-rays, measured using the Segmented Germanium Array (SeGA) [5].

Figures 1 and 2 show the experimental arrangement. The target was held between the pole tips of a compact electromagnet that provided a magnetic field of
The design of these experiments requires careful attention to a number of competing requirements. Further details of the experimental design are discussed by Fiori et al. [6], who measured the g factor of the first excited state in $^{72}\text{Zn}$ at GANIL by the HTVF technique, and in the write-up of a computer code written to help design and analyze these experiments [7].

Comparisons between the experimental and theoretical angular correlations are made in Fig. 3. Precession angles were determined from field-up/field down $\gamma$-ray intensity ratios by standard procedures [2, 3]. The g factors were then extracted from the measured precession angles using a parametrization of the transient field applicable for high ion velocities [1]. In Fig. 4 the experimental results are compared with stable-beam measurements on their isotones. The statistical uncertainties on the radioactive beam measurements rival those on the stable beam studies. This precision is made possible by use of the fast beams and a thick ferromagnetic layer, which produces a precession angle (per unit g factor) that is an order of magnitude larger than those obtained in the stable beam measurements at low velocity.

**Structure of neutron rich S and Ar isotopes**

Fig. 4 also shows shell model calculations performed using the code OXBASH [10] and the sd-pf model space, where (for $N \geq 20$) valence protons are restricted to the sd shell and valence neutrons are restricted to the pf shell. The Hamiltonian was that developed in Ref. [11] for neutron-rich nuclei around $N = 28$, i.e. the SDPF-NR interaction [12]. Further details of the calculations are given elsewhere [2, 3, 4].

Overall, the level of agreement between theory and experiment for the g factors in $^{38}\text{S}$, $^{40}\text{S}$ and $^{40}\text{Ar}$ is
satisfactory, given that there is extreme sensitivity to configuration mixing and a near cancelation of the proton and neutron contributions to the $g$ factors [2, 3, 4]. Many authors have argued on experimental and theoretical grounds that $^{40}$S ($N = 24$) is deformed, some linking it to a weakening of the $N = 28$ shell gap (see Refs. [13, 14, 15, 16, 17, 18, 19] and references therein). Supporting the interpretation that $^{40}$S is deformed, the shell model calculations predict consistent intrinsic quadrupole deformations when derived from either the $B(E2)$ or the quadrupole moment, implying a prolate deformation of $\beta \approx +0.3$, in agreement with the value deduced from the experimental $B(E2)$ [13]. The near zero magnetic moment, however, does not conform to the usual collective model expectation of $g \sim Z/A$. Instead, it is near zero in both theory and experiment [2, 3].

According to the shell model calculations, the microscopic reason for $g(2^+ \rightarrow 0^+) \sim 0$ is that intrinsic-spin contributions from the $f_{7/2}$ neutrons cancel out the positive contribution from the orbital proton current. Moreover, the collectivity stems from the motion of relatively few nucleons. Rather than picture the quadrupole collectivity here in terms of the rotation of a deformed fluid, it is better to understand it in terms of the symmetries of the underlying shell structure: quasi-$SU(3)$ for the $\nu f_{7/2} - \rho_{3/2}$ orbits and pseudo-$SU(3)$ for the $\pi d_{5/2} - s_{1/2}$ orbits [19].

Despite these successes of the SDPF-NR shell model in the case of $^{40}$S, the theoretical $g$ factors for the neighboring $N = 22$ isotones $^{38}$S and $^{46}$Ar both underestimate the experimental values, as shown in Fig. 4. There is a more dramatic disagreement between theory and experiment for $^{42}$Ca$_{22}$ and $^{44}$Ca$_{24}$. In addition to the experimental data shown in Fig. 4, similar trends have been observed in the new $g(2^+)$ measurements on the neutron-rich isotopes $^{42, 44, 46}$Ar performed at NSCL. These experimental $g$ factors suggest that, along with the symmetries in the shell-model space that cause quadrupole collectivity, there may also be contributions from collective core-excitations that are not explicitly included in the shell-model space. Indeed, it has been known since the 1960s that the $2_1^+$ states in the Ca isotopes are not pure $\nu f_{7/2}$ configurations, but in $^{42, 44}$Ca they are a strong mixture of shell model and deformed, multiparticle-multiphole configurations [20]. This mixing makes the $g(2^+_1)$ values positive in $^{42, 44}$Ca. In contrast, the negative $g$ factor in $^{46}$Ca is closer to the shell model value [9], which reflects the fact that the deformed contribution decreases towards $N = 28$.

There is a puzzling discrepancy between theory and experiment [13, 21] for $B(E2; 0^+ \rightarrow 2^+)$ in the $N = 28$ nucleus $^{46}$Ar, where shell model calculations with several alternative interactions in the SDPF model space all overestimate the $E2$ strength. One possibility is that the experimental $B(E2)$ values based on intermediate energy Coulomb excitation are not correct (see [22]). However another possibility, should the Coulomb-excitation data prove correct, is that the discrepancy may stem from the fact that the shell-model interactions have been tuned to fit the energy spectra in a limited basis space, without explicitly including the coupling of the shell-model configurations to the deformed core excitations. The shell model interactions might implicitly include the effect of the core excitations that occur near $N = 20$, but not account for the fact that they diminish toward $N = 28$.

Further experimental and theoretical work is needed. On the experimental side, the $B(E2)$ should be checked. To this end, an analysis of the Doppler broadened line shape in the HVTF measurement is underway. On the theoretical side, an explicit inclusion of the deformed contributions to the wavefunctions could be attempted, and/or further consideration given the renormalization of the $M1$ and $E2$ operators in the SDPF-NR model space.

**Future development of the HVTF method**

*Segmented particle detection*

Future HVTF measurements can be improved by use of a segmented particle counter. This has several advantages. Aside from the trivial advantage that count rate limitations for the particle counter are reduced, the degree of Doppler broadening in the $\gamma$-ray spectrum can also be reduced by reducing the solid angle of each detector element. In the measurements to date, the effect of the opening angle of the particle detector on the Doppler broadening has limited the $\gamma$-ray energy resolution. Future use of a segmented particle detector could thus reduce the resulting line widths and hence improve the peak to background ratios. This consideration is of a spe-
Azimuthal dependence of particle-\(\gamma\) angular correlations in intermediate energy Coulomb excitation.

A recent experiment at GANIL by Fiori et al. [6] has pushed the application of the HVTF technique to higher \(Z\) ions by measuring precession angles for \(^{76}\text{Ge}\) in both iron and gadolinium hosts. The results imply much smaller transient-field strengths than might have been expected based on the data for lower-\(Z\) ions. As discussed by Fiori et al., this reduction in field strength must be associated with changes in the effectiveness with which the \(K\)-shell electrons, bound to the moving ion, can pick up polarization from the ferromagnetic medium. A reduced polarization for \(K\)-shell vacancies in the transient field for high velocity ions is not altogether unanticipated - see, for example, the discussion in Ref. [25] and references therein.

For high-velocity ions with \(v \sim Zv_0\), the transient-field strength can be written as

\[
B_{tf}(v, Z) = p_{1s}q_{1s}(v, Z)B_{1s}(Z),
\]

where

\[
B_{1s} = 16.7R(Z)^3 \text{Tesla},
\]

is the magnetic field produced at the nucleus by a \(K\)-shell (or 1s) electron and \(R(Z) \simeq [1 + (Z/84)^2]^{-1}\) is a relativistic correction; \(q_{1s}\) is the fraction of ions that carry a single \(K\) vacancy, and \(p_{1s}\) is the polarization of these vacancies. The velocity dependence of \(q_{1s}\) at high velocities is expected to resemble that of the hydrogen-like charge fraction for ions emerging into vacuum, but shifted to a lower energy so that the peak value of \(q_{1s}\) is 0.5 occurs when \(v \sim Zv_0\). The velocity dependence of \(q_{1s}\) can conveniently be parametrized as [1]

\[
q_{1s} = \frac{1}{2} \sqrt{v/Zv_0} \, e^{-\frac{1}{2}(v/Zv_0)^4}.
\]

Putting these expressions for \(B_{1s}\) and \(q_{1s}\) into Eq. 1 suggests that a parametrization of the TF strength at high velocity (\(v \approx Zv_0\)) can be based on

\[
B_{tf}(v, Z) = 13.8 \, p_{1s} \, Z^3 \sqrt{v/Zv_0} \, e^{-\frac{1}{2}(v/Zv_0)^4} \text{Tesla},
\]

provided a suitable parametrization of the \(Z\) dependence of \(p_{1s}\) can be found. In previous work on ions with \(Z \leq 16\) traversing gadolinium hosts at high velocity it was found that the data could be described by \(p_{1s} = (1.94 \pm 0.08)/Z\) [1]. This parametrization of \(p_{1s}\) fails, however, for heavier ions with \(Z \sim 30\).
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An extensive series of studies by Speidel and co-workers [26, 27, 28, 29, 30, 31], as summarized in [1] and supplemented by more recent studies on $^{24}$Mg [32], gives experimental transient-field strengths for ions between $^{12}$C and $^{52}$Cr traversing gadolinium hosts with velocities near $Zv_0$. These data have been used with the results of Fiori et al., and Eq. 4, to seek a new parametrization of $p_{1s}$ as a function of $Z$, as shown in Fig. 6.

The solid curve in Fig. 6 is an empirical fit to the function

$$p_{1s} = a \exp[-(\ln Z)^b]$$

where the best fit parameters are $a = 0.32(3)$ and $b = 328(25)$.

These expressions define a new parametrization of the transient field which is applicable for ions with velocities near $Zv_0$ and atomic numbers up to about $Z = 30$:

$$B_{i1}(v/Z_0) = 4.42Z(v/v_0)^2 \exp[-(v/v_0)^4 + (\ln Z)^6/328]$$

As noted above, in light nuclei, $Z < 20$, the experimentally observed polarization of the 1s vacancies in gadolinium hosts was consistent with a 1/Z dependence, which is shown by the dashed line in Fig. 6. The magnitude of the polarization for these light nuclei is $p_{1s} \sim 0.1$. The measured precession for $^{76}$Ge in gadolinium implies that the polarization $p_{1s} \sim 0.002$ is about a factor of 50 smaller than found for the lighter ions. In fact the average transient field strength achieved for these high velocity ions in gadolinium hosts is about a factor of two smaller than was achieved for a conventional transient field measurement at an ion velocity of $3v_0$. On the other hand, the net precession angle is still about twice as large as obtained in conventional low-velocity measurements because the interaction time of the ion within the ferromagnetic target layer is considerably longer in the HVTF measurements.

These findings have important implications for the future development of the HVTF technique and its applications to radioactive beams produced by projectile fragmentation. Clearly, the advantage of the HVTF for light ions ($Z < 20$), where precession angles an order of magnitude larger than in conventional low velocity TF measurements can be achieved, is not as significant for $Z \sim 30$. For measurements of $g$ factors of higher-$Z$ exotic nuclei produced as radioactive beams other techniques like recoil in vacuum and the low-velocity transient field method, should therefore be considered. These techniques require beams with velocities below 5 MeV/amu. Although large precession angles are obtained in HVTF, low velocity measurements may be advantageous in some cases due to higher radioactive beam intensities, and/or the ability to obtain cleaner $\gamma$-ray spectra.

The viability and possible application of the HVTF technique to measurements on ions with atomic number considerably higher than $Z = 30$ requires further investigation. The implication of the trend in $K$-shell polarization shown in Fig. 6 is that the transient-field strengths may become negligibly small. However further experimental data should be obtained before that conclusion is embraced. For lower-$Z$ ions the HVTF method will remain the method of choice in many cases.

**RECOIL IN VACUUM**

**RIV method and nuclear structure near $^{132}$Sn**

When a free ion moves through vacuum, the hyperfine interaction couples the atomic spin $I$ to the nuclear spin $J$ and together they precess about the total spin $F = I + J$, as illustrated in Fig. 7 (left panel). The precession frequency $\omega_{EF}$ is proportional to the nuclear $g$ factor and the magnitude of the hyperfine magnetic field at the nucleus. To measure the $g$ factor, the nuclear state of interest is excited by a suitable reaction and then allowed to recoil into vacuum. The effect of the hyperfine interaction is observed via the perturbation of the angular correlation of the $\gamma$-rays de-exciting the state.

Recoil-in-vacuum (RIV) can refer to two quite distinct experimental techniques, depending on whether the ion has a very simple, few-electron configuration, or whether it has a complex many-electron configuration [33]. A version of the RIV technique to measure the first-excited state $g$ factors of H-like light ions ($Z < 20$) produced by fast radioactive beams has been proposed [34]. As will be discussed below, it is planned to test this technique...
in the near future [35]. We focus first on the application of the RIV technique to slower-moving many-electron radioactive ions as produced by the ISOL method at the Holifield Radioactive Ion Beam Facility (HRIBF) at Oak Ridge National Laboratory [36]. In these g-factor measurements the experimental procedures are identical to those in a $B(E2)$ measurement, however the focus of the analysis is on the angular correlation pattern of the γ rays rather than their total intensity.

Radioactive beams of $^{132}$Te (see Ref. [36]) and $^{134}$Te at an energy of 3 MeV/nucleon were incident on a carbon foil target as illustrated in the right panel of Fig. 7. Calibration measurements on stable beams of $^{122,126,130}$Te were also performed. The first-excited states were Coulomb excited in inverse kinematics at an energy well below the Coulomb barrier, which ensures negligible multiple excitation. The Te ions exited the target with an average velocity of $v/c \sim 6\%$. Recoiling $^{12}$C ions were detected in the HYBALL array while coincident γ-rays de-exciting the Te isotopes were detected in the CLARION array [37]. See Fig. 8.

Figure 9 shows the perturbed angular correlations for $^{130}$Te and $^{132}$Te. The angles are defined in Fig. 7 and $\Delta \phi = \phi_\gamma - \phi_\gamma$. Further details of the angular correla-

![FIGURE 7](image7.png)

**FIGURE 7.** Left: The free-ion hyperfine interaction on which the Recoil in Vacuum technique is based. Right: Reaction kinematics for the $^{132}$Te g-factor measurement.

![FIGURE 8](image8.png)

**FIGURE 8.** The Clarion array at HRIBF during the $^{134}$Te RIV g-factor measurement in February 2012.

FIGURE 9. Angular correlations perturbed by free-ion hyperfine fields for stable $^{130}$Te and neutron-rich $^{132}$Te.

FIGURE 10. Attenuation factors versus $g\tau$ for several isotopes of Sn and Te. For the Sn isotopes and $^{134}$Te the points shown indicate the attenuation factors corresponding to predicted $g$ factors.
Figure 11 compares theory and experiment for the Te isotopes near the $N = 82$ shell closure. There is rather good agreement between theory and experiment for $^{130}\text{Te}$ and $^{132}\text{Te}$, where measurements have been performed. For $^{134}\text{Te}$ and $^{136}\text{Te}$, however, the theories diverge significantly. In the coming months we expect to complete the analysis of RIV measurements on $^{134}\text{Te}$ and $^{136}\text{Te}$, and several even Sn isotopes including $^{124}\text{Sn}$ and $^{126}\text{Sn}$. Fig. 10 shows the locations of points on the $G_k$ versus $g\tau$ curve as predicted by the various models for $g(2_f^+)\text{in}^{134}\text{Te}$. For stable $^{124}\text{Sn}$, the plotted point corresponds to the previously measured $g$ factor [41]. The point labeled $^{126}\text{Sn}$ corresponds to a theoretical estimate of $g ≈ 0.24$, which would be associated with a predominant $v_{11/2}$ configuration. It is evident that the range of predicted $G_k$ values for semimagic $^{134}\text{Te}$ is near the maximum slope of the $G_k$ vs $g\tau$ curve, and hence the RIV measurement has optimum sensitivity to distinguish between the theoretical models.

![Figure 11. Theoretical g factors in the Te isotopes compared with experiment. Shell model calculations are from [42, 43]. QRPA is from [44] and MCSM from [45].](image)

**Characterization of free-ion hyperfine fields**

Although the RIV technique cannot measure the sign of the $g$ factor, the method has a number of advantages for applications to radioactive beams, one being that both the $g$ factor and the $B(E2;0^+\rightarrow 2^+)$ can be determined in the same experiment. At the ANU we have been studying the free-ion hyperfine fields of stable nuclei with a view to the applications of the RIV technique to radioactive beams. In contrast to the radioactive beam measurements, which use large arrays of particle and $\gamma$-ray detectors with large solid angle coverage, the initial stable beam measurements have been made with modest apparatus. Four HPGe $\gamma$-ray detectors operate in coincidence with a small array of photodiode particle detectors called 'Heliotrope', as shown in Fig. 12. Like the radioactive beam measurements, the stable-beam studies have generally been performed in inverse kinematics; the beam ions are Coulomb excited on $^{12}\text{C}$ or $^{18}\text{O}$ targets.

Figure 13 shows an example of measured attenuation coefficients for the stable $^{32}\text{Ge}$ and $^{34}\text{Se}$ isotopes. The surprise in these data was the observed difference in the attenuation for the longer-lived isotopes, i.e. $^{74,76}\text{Ge}$ compared with $^{74,76}\text{Se}$. At first we thought this difference could not be real, but we have since repeated the measurements and the effect persists. As part of the program to check the results in Fig. 13, we ran a cocktail beam of $^{74}\text{Ge}$ and $^{74}\text{Se}$ and performed a simultaneous measurement of the vacuum attenuation for these two ions.

At present we do not have a detailed explanation for this difference between the hyperfine fields for Ge and Se ions recoiling in vacuum under almost identical conditions. However we can draw some qualitative conclusions: Firstly, it is evident that the difference in the ‘hard core’ values of the attenuation coefficients at long lifetimes points to an average atomic spin for the Ge ions of $J ≈ 1$, whereas for the Se ions the average atomic spin must be $J ≈ 1.5$. Secondly, from charge-state measurements, we suggest that in our RIV experiment the Ge ions carry on average 12 to 13 electrons, whereas the Se ions carry 15. The Ge ions are therefore mainly Mg-like and Al-like, with ground state configurations of $3s^2$ and $3s^23p^1$, respectively. These configurations produce the terms $^1S$ and $^2D$, respectively, with corresponding ground-state atomic spins of $J = 0$ and $J = 1/2$. For P-like ions the lowest configuration is $3s^23p^3$, which produces the terms $^4S$, $^2D$, and $^2P$, and the ground-state spin is $J = 3/2$. These observations are qualitatively consistent with the experimental evidence that $J ≈ 1$ for Ge and $J ≈ 1.5$ for Se.

Thus if a significant fraction of the ions reach the

![Figure 12. Array of photodiodes used as heavy-ion detectors for RIV studies at ANU.](image)
lowest atomic configuration within the nuclear lifetime (\(\sim 20\) ps), we can qualitatively account for the difference in hyperfine fields for 175 MeV Ge and Se ions excited on \(^{12}\)C. Further experiments are underway to investigate the velocity dependence of the hyperfine fields and perform detailed measurements of the relevant charge-state distributions. We are also pursuing calculations of the hyperfine fields for specific atomic configurations to provide a more quantitative explanation of the free ion hyperfine fields of these highly charged ions.

**Future development of the RIV method**

*Hybrid transient-field-RIV method*

The RIV method cannot determine the sign of the \(g\) factor. In some cases the sign is important. For example, as shown in Fig. 11, predicted \(g\) factors for the first-excited state of \(^{136}\)Te range from \(-0.17\) (indicating a dominant neutron excitation) to +0.35 (a collective state). These differences stem from differences in the chosen shell model interactions, especially the proton-neutron interactions, which control the onset of collectivity as valence nucleons are added to the \(^{132}\)Sn core. It is important to develop a hybrid TF-RIV method for applications to radioactive beams.

Figure 14 shows a sketch of a possible approach to combine the transient-field and RIV methods, which again exploits a large gamma-ray detector array with ancillary particle detection. The target is magnetized \(^{54}\)Fe, which serves both to Coulomb excite the beam ions (say \(^{136}\)Te) and also provides a medium in which the transient field can act on the excited beam ion. The RIV measurement, which can make use of \(\gamma\)-ray detectors positioned at any angle with respect to the beam, would give the optimal precision for the magnitude of the moment. At the same time, the TF measurement, which can use a few of the \(\gamma\)-ray detectors at special angles, determines the sign. A particle detector with high azimuthal segmentation increases the number of \(\gamma\)-ray detector angles that are sensitive to the sign. Even detectors at \(\theta = 45^\circ\), and \(\theta = 90^\circ\), which would normally show no effect in a conventional transient-field measurement, become useful.

**Time differential RIV method**

So far in this paper we have considered only the time-integral vacuum attenuation. That is, the observed effect is averaged over the decay of the nuclear state:

\[
G_k = G_k(\infty) = \int_0^\infty G_k(t) \exp(-t/\tau) dt/\tau. \tag{7}
\]

By use of a plunger device, it is possible to observe the time differential vacuum attenuation coefficients, \(G_k(t)\). For ions with \(Z \leq 12\), very precise \(g\)-factor measurements have been made for picosecond states, by making use of hydrogen-like electronic configurations [33].

For radioactive beams, the beam ions cannot be stopped in a conventional plunger in view of the \(\gamma\)-ray detectors. An alternative method for fast radioactive beams has been proposed [34] in which the excited ions pass through a thin foil that resets the electronic configuration. It is planned to test this method on \(^{24}\)Mg beams at the Orsay tandem in the near future [35]. This experiment will use an array of \(\gamma\)-ray detectors (ORGAM), an 8-fold segmented fast-plastic particle detector at forward angles, and the recently commissioned Orsay plunger device. Based on ideas presented above in section , the sensitivity of the experiment is improved through observation of the \(\phi\) dependence of the particle-\(\gamma\) angular correlations, particularly for \(\gamma\)-ray detectors near \(\theta = 90^\circ\).

This type of measurement on H-like ions is limited to relatively low Z ions because as Z increases the hyperfine frequencies due to 1s electrons become too large.

*FIGURE 13.* Vacuum deorientation for the stable isotopes of Ge and Se. The solid line is an empirical fit to the data for the Se isotopes.

*FIGURE 14.* Apparatus for hybrid TF+RIV measurements.
To extend the method to higher-$Z$ ions, it must be investigated whether time differential recoil in vacuum (TDRIV) measurements can be performed on Li-like and Na-like ions, where the hyperfine frequencies will be in a suitable range for observation. If it proves feasible, such a method could provide accurate $g$-factor values to calibrate the transient field for nuclei in the $fp$ shell. There have been extensive $g$-factor measurements in the $fp$ shell, but as discussed by East et al. [46], there are problems associated with the calibration of the transient field in that region. In short, the transient-field strength in the $fp$ shell is determined by older $g$-factor measurements on the first excited state of $^{56}$Fe, which are not very precise and may not be accurate.

The RIV results for Ge and Se ions presented above suggest that these ions may have a prominent electronic configuration associated with the atomic ground states of Mg-like and P-like ions. This observation invites speculation that it might be possible to get a permanent population of the atomic ground-state $2S$, $J = 1/2$, configuration for Na-like $^{56}$Fe ions in a plunger experiment. As a first step in assessing the feasibility of TDRIV on Na-like $^{56}$Fe ions, the time-dependent attenuation factors, $G_k(t)$, have been evaluated for Na-like Fe ions (i.e. Fe$^{15+}$), based on the calculation of hyperfine fields using the MCHF atomic structure codes [47]. The results shown in Fig. 15 assume statistical $(2J + 1)$ population of the $2S$ (ground state) and $2P$ (first excited) terms in Na-like Fe ions. The hyperfine frequency associated with the $J = 1/2$ electron configuration is prominent; it is also evident that, conveniently, the period is of the order of the $\tau \sim 10$ ps mean life of the $2^+_1$ state in $^{56}$Fe.

Whether this hyperfine frequency can be observed in a real TDRIV experiment is a matter for further investigation. Empirical charge-state formulas suggest that a 120 MeV beam of $^{56}$Fe Coulomb excited on $^{12}$C will produce Na-like ions. Employing a large array of $\gamma$-ray detectors with an array of particle detectors having sensitivity to the azimuthal angles, along with a modern plunger device, will maximize the chance of observing any periodicity in the free-ion hyperfine fields of an ensemble containing Na-like ions.

**SUMMARY AND CONCLUSION**

Two methods to measure $g$ factors of short-lived excited states in neutron-rich nuclei produced as radioactive beams have been discussed. Both methods use large arrays of $\gamma$-ray detectors, with ancillary particle detectors, to perform measurements on weak radioactive beams, that would have been considered nigh impossible a decade ago.

The high velocity transient field technique, which is the only method suited to fast fragmentation facilities, can be applied to measure the $g$ factors of excited states that live about 5 ps or longer, for ions up to $Z \sim 30$. The applicability of the method for higher-$Z$ nuclei is uncertain, given the observed dramatic decrease in the transient-field strength for high-velocity high-$Z$ ions. For many cases, however, such as the neutron-rich isotopes of Ti, Cr and Fe, which are produced by fragmentation, HVTF would be the method of choice. Future experiments can benefit by employing an array of particle detectors to reduce Doppler broadening, improve peak to background ratios, and increase the anisotropy of the angular correlations.

The recoil in vacuum method has proved powerful for applications to $g$-factor measurements on radioactive beams. There is scope for significant development of the method in future. In particular, time differential measurements with plunger devices may open up new opportunities for precise and accurate $g$-factor measurements on both stable and radioactive beams.

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