Electron-configuration-reset time-differential recoil-in-vacuum technique for excited-state g-factor measurements on fast exotic beams

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A modified version of the time-differential recoil-in-vacuum (or plunger) technique is proposed as a method for measuring the g factors of excited states in rapidly moving exotic nuclei with $Z \lesssim 20$.

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Magnetic moments are generally very sensitive to the single-particle configuration of a nuclear state. In exotic nuclei far from the valley of stability, new shell structures are expected (see, e.g., Ref. [1] for a review). Indeed, changes in shell structure for neutron-rich nuclei have become evident already [1,2]. If the gyromagnetic ratios of excited states can be measured in exotic nuclei, they will provide a powerful means of identifying the orbits near the Fermi surface and thus expose new level order and new shell gaps.

Based on experience with stable beams, the two most appropriate approaches for applications to g-factor measurements on radioactive ion beams (RIBs), especially those produced as fast fragments, are the transient-field (TF) technique [3,4] and the recoil-in-vacuum (RIV) technique [5]. Both approaches must be modified and developed for applications to RIBs. Application of the TF technique to fast exotic beams has been discussed elsewhere [6], and a measurement of $g(2_1^+)$ in a radioactive beam of ^{76}Kr with energy $E/A = 3$ MeV has been reported recently [7]. Here we focus on the modification of the time-differential RIV technique for applications to relatively low Z nuclei up to the $f_{7/2}$ shell, or thereabouts ($Z \lesssim 20$), produced at intermediate-energy fragmentation facilities such as the NSCL, RIKEN, and GANIL.

The traditional recoil-in-vacuum, or "plunger," technique for measuring the g factors of excited states in light nuclei has been reviewed by Goldring [5]. This technique was employed, mainly in the 1970s and early 1980s, to measure the g factors of ∼20 excited states in nuclei ranging from ^{13}C to ^{24}Mg. The states studied had $I^\pi = 1^-, 2^\pm, 5/2^+$, and 3^-. Their mean lives ranged from ∼1 ps to ∼3 ns [8,9].

In this technique, excited reaction products emerge from a target foil as ions carrying one or more electrons. The nuclear spin $\boldsymbol{I}$ is aligned by the reaction whereas the atomic spin $\boldsymbol{J}$ is oriented randomly. For each electron configuration the hyperfine interaction couples the atomic spin to the nuclear spin, and together they precess about $\boldsymbol{F} = \boldsymbol{I} + \boldsymbol{J}$ with a frequency ω_L. Thus the orientation of the nuclear spin is periodically reduced and restored as it precesses about $\boldsymbol{F}$.

Figure 1 illustrates the proposed new version of the technique for applications to RIBs. An exotic beam is excited by intermediate-energy Coulomb excitation [10,11] on a high-Z target from which the excited nuclei emerge with velocity v. As illustrated in Fig. 2, the ions leave high-Z target foils largely as H-like ions over a wide velocity range. At intermediate energies it is possible to obtain a charge distribution for the emerging ions that is ∼50% H-like and ∼50% fully stripped.

The hyperfine field at the nucleus due to a 1s electron is $B_{1s} = 16.7 Z^3 R(Z)$ T, where the relativistic correction factor $R(Z) \simeq [1 + (Z/84)^{2.5}]$ is very near unity for the ions of present interest. The resulting precession frequency is

$$\omega_L = g(2I+1)\frac{\mu_N}{\hbar}B_{1s} = g(2I+1)800Z^3 \text{ MHz}, \tag{1}$$

where g is the nuclear g factor. For simplicity the following discussion assumes that the H-like ions have the ground-state configuration $(1s)^1$. This assumption is justified because the only other configuration that is long-lived in light nuclei is $(2s)^1$, which produces a much weaker hyperfine field [14]. Furthermore, the de-excitation of the electronic configuration to the 1s ground state is expected to be completed within about 10^{-13} s [14] and give rise to relatively small effects (a phase shift and reduction of the amplitude [15]).

The precession of the nuclear spin can be observed via the perturbed angular correlation of the γ rays that de-excite the state. In most cases the time-dependent particle-γ angular correlation has the form

$$W(\theta, t) = 1 + a_2 G_2(t) P_2(\cos\theta) + a_4 G_4(t) P_4(\cos\theta), \tag{2}$$

where θ is the angle of γ-ray detection with respect to the beam axis. In the case of H-like ions the perturbation factors, also called attenuation or deorientation coefficients, are [5]

$$G_k(t) = 1 - b_k(1 - \cos\omega_L t), \tag{3}$$

where $b_k = k(k+1)/(2I+1)^2$.

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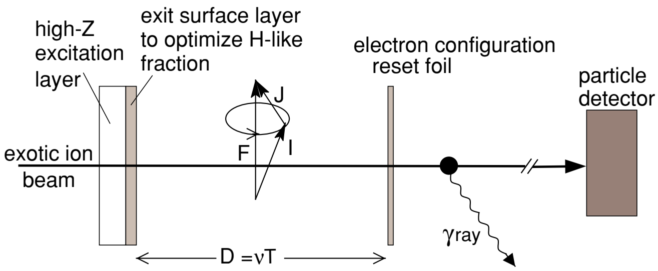

FIG. 1. (Color online) The proposed technique to measure excited-state g factors of fast radioactive beams replaces the "stopper" of the traditional plunger technique with a thin foil that resets the electron configuration of H-like ions. The particle detector is located downstream away from the view of the γ-ray detectors.

In the traditional technique the hyperfine interaction is quenched, thus freezing the orientation of the nuclear spin, by stopping the excited ions in a thick metallic foil after a flight time $T = D/v$, where D is the flight distance (or plunger separation). The perturbation factor for the stopped ions is therefore [5]

$$G_k^{\text{stopped}}(T) = G_k(T), \tag{4}$$

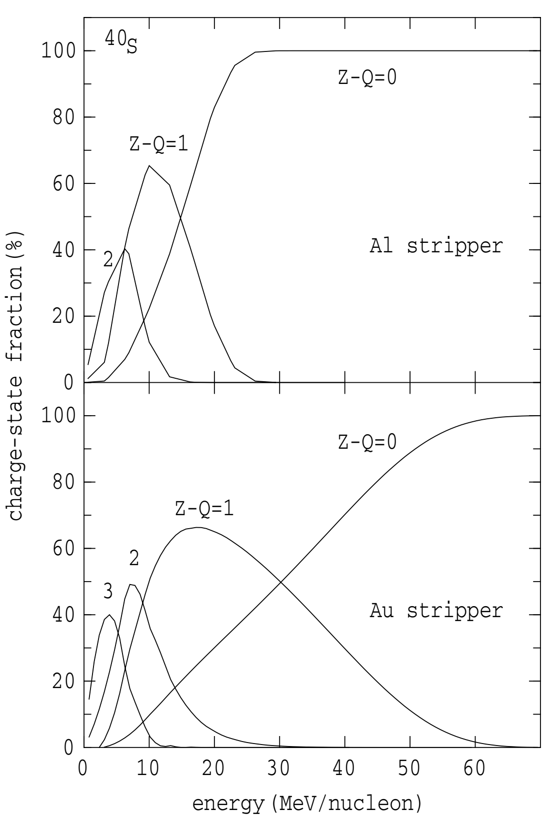

FIG. 2. Charge-state distributions for ^{40}S ions emerging from Au and Al foils, evaluated using the code LISE [12], with a charge-state parametrization based on Ref. [13].

whereas the ions that decay in flight have an average deorientation coefficient of

$$G_k^{\text{flight}}(T) = \int_0^T G_k(t)e^{-\lambda t}\lambda \mathrm{d}t \Big/ \int_0^T e^{-\lambda t}\lambda \mathrm{d}t \tag{5}$$

$$= 1 - b_k(1 - F(T)), \tag{6}$$

where

$$F(T) = \frac{1 - e^{-\lambda T}(\cos\omega_L T - \omega_L T \sin\omega_L T)}{\left(1 + \omega_L^2\tau^2\right)(1 - e^{-\lambda T})}. \tag{7}$$

In the limit that $T \to \infty$, the integral perturbation factors are obtained,

$$G_k(\infty) \equiv G_k^{\text{flight}}(\infty) = 1 - b_k\left(\frac{\omega_L^2\tau^2}{1 + \omega_L^2\tau^2}\right). \tag{8}$$

If $\omega_L\tau \gg 1$, the integral attenuation coefficients approach their hard core values, $G_k(\text{h.c.}) = 1 - b_k$. For $I = 2$ and H-like ions ($J = 1/2$), $G_2(\text{h.c.}) = 0.76$, so the nuclear spin can retain a significant level of alignment despite the hyperfine-induced deorientation.

To illustrate the new version of the technique proposed for RIBs, it will be assumed that 40 MeV/nucleon ^{40}S ions impinge upon a ^{197}Au target and emerge into vacuum with ~25 MeV/nucleon, or 1 GeV. Assuming also that $g = 0.5$ implies that $\omega_L \sim 8$ rad/ps. At first sight this frequency may appear too large to be measured. However, the velocity of 1-GeV ^{40}S ions is $v \sim 70$ μm/ps, which means that a subpicosecond time resolution can be obtained with flight distances of tens of micrometers, which are readily achieved with plunger devices [16,17]. The mean life of the 2_1^+ state in ^{40}S is $\tau = 21 \pm 3$ ps [18,19].

As a starting point, the perturbation factors corresponding to the "stopped" and "flight" γ-ray decays *in the traditional technique* are plotted as a function of the flight time T in Fig. 3. Note that the flight peak has a strongly damped oscillation and quickly approaches $G_k(\infty)$, whereas the stopped peak shows a persistent oscillation, which is more amenable for a g-factor measurement. If the stopped and flight peaks cannot be resolved in the γ-ray spectrum, the observed perturbation factor is the sum of the flight and stopped terms, $G_k^{\text{total}} = (1 - e^{-t/\tau})G_k^{\text{flight}} + e^{-t/\tau}G_k^{\text{stopped}}$. This sum is shown in the lower panel of Fig. 3 (for $\tau = 20$ ps). The presence of the oscillation in G_k^{total} demonstrates that it is not necessary to resolve the flight and stopped γ rays to measure ω_L. This feature is clearly an advantage for measurements on fast exotic beams where Doppler broadening can be severe.

The traditional technique, using a thick foil to stop the excited nuclei, is unsuitable for RIB experiments: First, RIB experiments, as shown in Fig. 1, will generally use Coulomb excitation [10,11] of the beam itself followed by detection further downstream. Second, even if an experiment were designed so that detection along the beam direction is not essential, the buildup of radioactivity in a stopping foil viewed by the γ-ray detectors must be avoided.

We propose that the plunger technique can be modified for applications to RIBs simply by replacing the thick stopper foil with a much thinner foil that resets the charge-state distribution. For nuclei that decay before reaching the "reset"

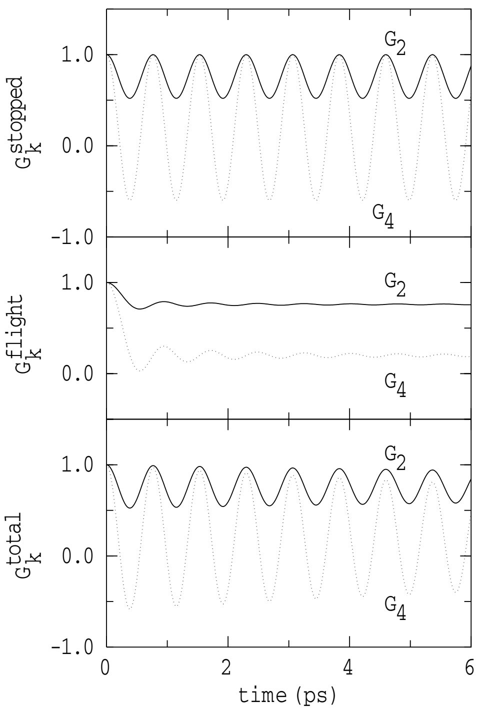

FIG. 3. Perturbation factors for $\omega_L = 8$ rad/ps.

foil, the perturbation factor is unchanged compared with the traditional technique. The average perturbation factor for decays that occur beyond the reset foil is just the product of $G_k(T)$ and the appropriate $G_k(\infty)$. In other words, the physical process is identical to the traditional technique up until the ion strikes the reset foil. At that point the electronic configuration is reset randomly and the nucleus experiences further perturbations identical in effect to those of the flight peak for an infinite flight path. Assuming, for example, that the ion that enters the reset foil is H-like and emerges from it again as an H-like ion (after several electron exchanges within the foil), the perturbation factor is

$$G_k^{\text{reset}}(T) = G_k(T) \cdot G_k(\infty). \qquad (9)$$

Should the ion become fully stripped after the reset foil, then $G_k^{\text{reset}}(T) = G_k(T)$. Thus for $T = 2$ and $J = 1/2$, $G_2^{\text{reset}}(T) = 0.76 G_2(T)$ in the worst case.

For intermediate-energy beams the reset foil can be made thick enough to ensure several electron exchanges during transit through the foil and yet sufficiently thin that the ions emerge with essentially the same charge-state distribution. Because the electron stripping efficiency is generally higher for low-Z materials (see Fig. 2), the experimenter can choose the reset foil and the exit surface of the target to optimize the charge-state distributions. A high-Z target such as Au would be chosen to optimize the Coulomb-excitation cross section and the H-like component of the charge-state distribution; a low-Z reset foil such as Al would minimize unwanted Coulomb excitation and increase the fraction of fully stripped ions beyond the reset foil. For the following simulations it will be assumed that the charge distribution is 50% H-like and 50% fully stripped before and after the reset foil. Thus for the traditional technique the "flight" and "stopped" peaks

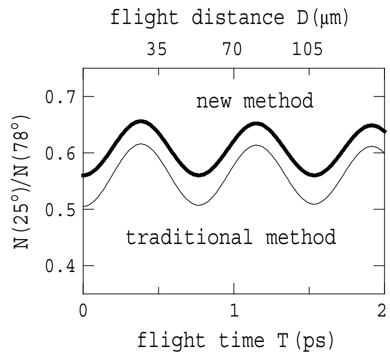

FIG. 4. Comparison of the traditional and new methods for the example of 1-GeV ^{40}S discussed in the text.

each have two components: an attenuated component from the H-like ions and an unattenuated component from the fully stripped ions. In the new technique the flight peak has the same two components, but the "reset" peak now has four, since the ion can carry one or no electrons after it passes through the reset foil, independent of whether it had an electron when it entered the reset foil.

In the limit of very high beam energies the angular correlation coefficients after Coulomb excitation in the projectile-excitation geometry of Fig. 1 are $a_2 = -2F_2(2, 2, 0, 2)^2 = -0.714$ and $a_4 = -0.25F_4(2, 2, 0, 2)^2 = -0.286$ [11]. These values represent the ideal case. For the realistic case of 40 MeV/nucleon ^{40}S on ^{197}Au considered here, $a_2 = -0.50$ and $a_4 = -0.14$ were obtained for a distance of closest approach, $b_{\min} = 12.7$ fm, using the code COULINT [11].

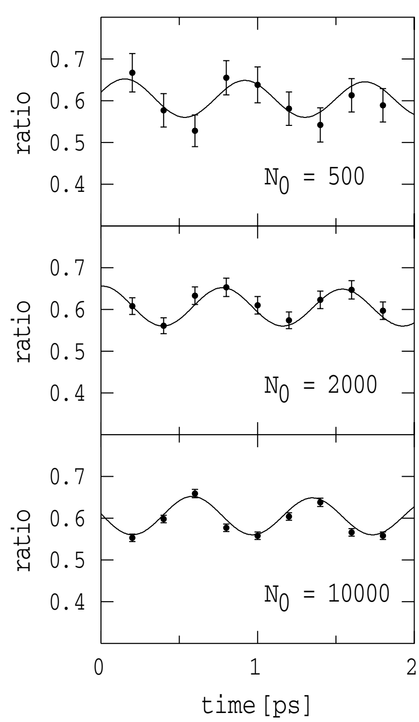

FIG. 5. Simulated data to evaluate the counting statistics required to determine ω_L and hence the g factor.

To measure the precession frequency, γ-ray detectors are ideally placed at the angles where $P_2(\cos\theta)$ has its extreme values, namely at $\theta_1 = 0^\circ$ and $\theta_2 = 90^\circ$. The ratio of counts $N(\theta_1)/N(\theta_2) \propto W(\theta_1, T)/W(\theta_2, T)$ oscillates with ω_L as a function of flight time $T = D/v$. Placing the γ-ray detectors at precisely 0° and 90° is likely to be impossible in most RIB experiments; thus $\theta_1 = 25^\circ$ and $\theta_2 = 78^\circ$ are used here. In Fig. 4 the theoretical ratios, $N(25^\circ)/N(78^\circ)$, are compared for the new and traditional techniques. The use of a reset foil rather than a stopping foil introduces a modest offset in the ratio, which stems from the hyperfine interactions of those ions that carry an electron beyond the reset foil.

Simulated data can be used to estimate the number of plunger separations required and the number of counts needed at each distance. In the examples shown in Fig. 5, a simulated number of counts for each detector was generated at 0.2-ps (or 14-μm) intervals. A realistic scatter of the data points was obtained by putting $N = N_0 W(\theta, T) + r\sqrt{N_0}$, where r is a normally distributed random number with unit standard deviation, centered on the origin, and N_0 determines the counting statistics. A random phase was also introduced as a precaution, in case the zero of time cannot be well determined by independent means. The examples shown suggest that the precession frequency can be determined with reasonable precision if a few thousand counts are recorded for the two angles at 8–10 plunger distances. The proposed applications to rapidly moving exotic nuclei benefit from the high beam velocity, which (i) ensures that the H-like configuration dominates and (ii) means subpicosecond flight times correspond to path lengths of the order of tens of micrometers. These advantages help compensate for the low intensity of radioactive beams compared with stable beams. However, the technique would be applicable only for the most intense radioactive beams currently available ($\gtrsim 10^5$ particles/s).

Although the focus here has been on nuclei excited by intermediate-energy Coulomb excitation, the technique need not be restricted to this reaction. There are indications that considerable alignments of the nuclear spin can also be produced in fragmentation and knock-out reactions at intermediate energies (see Refs. [20,21] and references therein).

We plan to test the technique using stable beams with the expectation that it will become more generally applicable as the intensities of radioactive beams continue to improve.

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