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Nuclear g -factor measurement with time-dependent recoil in vacuum in radioactive-beam geometry

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Abstract.

A modified version of the time-differential recoil-in-vacuum (TDRIV) method, adapted for use with radioactive beams, was applied for the first time to perform a g -factor measurement on the first-excited state in ^{24}Mg ($E_x = 1.369$ MeV, $\tau = 1.97$ ps). A high precision g -factor value was obtained using predominantly H-like ions. The results obtained demonstrate the versatility of the new approach and have the precision needed for stringent tests of shell model calculations.

1. Introduction

The strong nuclear interaction establishes the distribution and motion of nucleons in the nucleus, and we can probe that distribution with the electromagnetic interaction. Magnetic moments are very sensitive probes to the details of the single-particle configuration of a nuclear state. The g factor reveals which single particle orbits are occupied by the valence nucleons and can be used as a rigorous probe for the proton-neutron character of the nuclear states. The development of radioactive beam facilities requires the development of reliable methods to measure magnetic moments of exotic nuclei produced as radioactive beams.

In order to measure a magnetic moment, a spin oriented ensemble of excited nuclear states (spin I , magnetic moment μ) needs to be produced by suitable reaction. One can perturb this ensemble with a magnetic field, either an external one or a hyperfine field (B), which



creates a torque that causes a rotation of the spin-oriented ensemble with Larmor frequency ($\omega_L = g\mu_N B/\hbar$) around the magnetic field direction. The rotation angle for a specific time can be determined as $\Delta\theta = \omega_L \cdot t$. This rotation can be observed by measuring the modification of the angular distribution of the associated γ rays. If the lifetime of the state of interest is of the order of picoseconds, strong magnetic fields (kTesla) are required to induce a detectable precession. Laboratory magnets cannot provide such strong fields, and therefore one has to rely on hyperfine magnetic fields.

The useful hyperfine magnetic fields are the transient magnetic field (TF) [1] and the free-ion hyperfine fields of ions recoiling in vacuum (RIV) [2, 3]. In the case of the RIV technique, as applied recently to heavy radioactive ion beams [4, 5, 6], the averaging of the hyperfine frequency over the different electronic configurations gives a quasiexponential dependence of the vacuum attenuation factors, G_k , as a function of the lifetime of the state of interest. It is not trivial to obtain the exact form of this dependence without knowing the precise charge state distribution and the exact electron configurations involved, therefore, calibration measurements with known g factors are needed. For light nuclei this short-coming of the time-integral RIV can be overcome by using the highly-stripped ions that provide fewer charge-states, as well as by performing time-differential measurements (TDRIV).

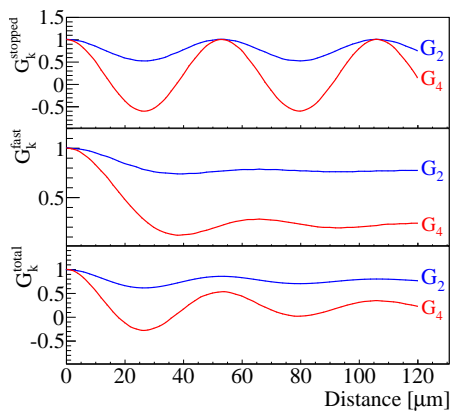


Figure 1. Attenuation factors of H-like ^{24}Mg ions in the conventional technique.

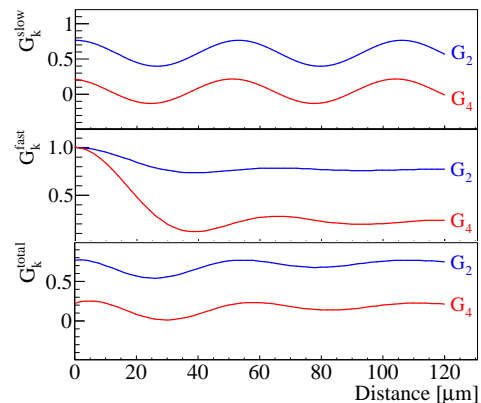


Figure 2. Attenuation factors of H-like ^{24}Mg ions in the modified TDRIV method.

In the conventional TDRIV technique, the interaction time is defined experimentally using a plunger device. After the ions leave the target, and before they reach the stopper, the nuclear and atomic spins \mathbf{I} and \mathbf{J} precess around the total \mathbf{F} with a frequency ω_L . After one period of rotation the spins return to their initial orientation. The precession frequency is proportional to the nuclear g factor and the magnitude of the hyperfine magnetic field at the nucleus. Therefore, although the atomic spins are randomly oriented, the initial angular distribution of γ rays is restored after each period of the rotation. At the moment the ions enter the stopper material, the interaction between the atomic and the nuclear spins is ‘switched off’ and the nuclear spins are ‘frozen’ to the direction in which they enter the stopper. All these nuclei have therefore experienced the hyperfine interaction for the same time T . By changing the position of the stopper foil, we can vary the recoil distance, and thus the interaction time, so the nuclear orientation can be measured time differentially. In TDRIV there are two components of the angular distribution, namely, a ‘fast’ and a ‘stopped’ component. As can be seen in Fig. 1, for the G_k stopped component the exact interaction time is well defined and the amplitude of

the observed oscillation pattern is preserved. For the G_k fast component, however, the state of interest has decayed in flight and its interaction time is not well defined, therefore the amplitude of the oscillation pattern decreases with flight time.

Until recently, measurements of $g(2^+)$ were largely confined to stable nuclide. This limitation is being overcome through measurements using radioactive ion beams (RIB). The methods usually applied for moment measurements of short-lived states, the TF and RIV techniques, are also being adapted for radioactive ion beams. TF technique has been developed for use with radioactive ion beams [7, 8, 9]. Here we are focusing on the modification of the TDRIV technique [10] for application with low- Z radioactive beams, and testing it on stable ^{24}Mg .

A measurement of $g(2^+)$ in ^{24}Mg with the conventional technique was performed by Horstman *et al.* [2] following the $^{12}\text{C}(^{16}\text{O},\alpha\gamma)^{24}\text{Mg}$ reaction. In that measurement only $\sim 15\%$ of the Mg ions exiting the target were in H-like charge state. This required the evaluation of complex atomic configurations in order to derive the g -factor value. The importance of the use of H-like ions comes from the simplicity of the electron configuration, which allows for a precise determination of the hyperfine field from first principles.

The conventional TDRIV method, in which the beam is stopped at the target, cannot be used for radioactive beams because the build-up of radioactivity becomes prohibitive. To overcome this problem, Stuchbery *et al.* [10] proposed a modification as shown in Fig. 3. The stopper is replaced by a thin foil in order to reset the electron configuration.

The new TDRIV method again has two components of the angular distribution. For the fast component, the state of interest has decayed in flight before the reset foil. After the ion strikes the reset foil several electron exchanges occur, so the charge distribution and electronic configuration is reset randomly. Beyond the reset foil the attenuation factor is just the product of $G_k(T)$ and $\bar{G}_k(\infty)$. The nucleus experiences further perturbations identical in effect to those of flight peak for an infinite flight path, which reaches a ‘hard core’ value. For convenience, we refer to ions that decay between the target and the reset foil as ‘fast’ and those that decay after the reset foil as ‘slow’. As shown in Fig. 2, the TDRIV method does not require that the γ rays emitted from fast and slow ions are separated in the observed energy spectrum.

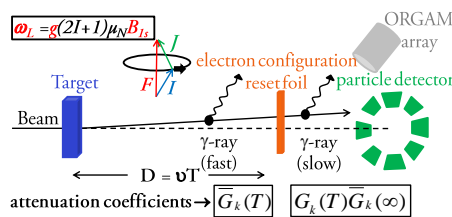


Figure 3. Sketch of the experiment.

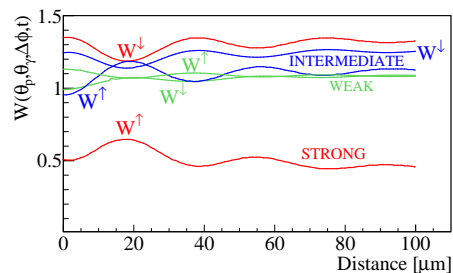


Figure 4. Time dependence of particle- γ angular correlations for different particle segments and HPGe detectors based on simulations. The red, blue and green lines are respectively strong, intermediate and weak oscillation amplitude.

2. Experiment

The experiment was performed at ALTO, Orsay, France. To perform particle- γ correlations, the experimental setup comprised of the 13 ORGAM (ORsay GAMma-ray) detectors, surrounding the Orsay plunger (OUPS) [11]. An 8-fold segmented plastic scintillator particle detector was

located 61 mm downstream from the target. The breaking of the azimuthal symmetry, due to the use of the 8-fold segmentation, considerably improved the experimental sensitivity. A beam of ^{24}Mg ions at an energy of 120 MeV was provided by the TANDEM accelerator with about 0.3 pA intensity and was excited on a stretched foil of ^{93}Nb with a thickness of 2.4 mg/cm^2 . The movable, stretched reset foil, positioned downstream of the target, was a 1.7 mg/cm^2 thick ^{197}Au foil. The experiment was performed for a total of four days.

3. Analysis

A triggerless data-acquisition system was used for collecting the data. Coincidence events, corresponding to a γ -ray detected in the ORGAM array and a beam particle detected in the plastic scintillator, were constructed using an universal time stamp and imposing a narrow time gate. The γ -ray background, originating from radioactive decay and/or reactions, was suppressed by the particle- γ coincidence condition.

The data were analyzed by ordering of the amplitude of the oscillations in the time-dependent angular correlations, and whether the γ -ray intensity should initially increase (W^\uparrow) or decrease (W^\downarrow) with the time, as shown in calculated examples in Fig. 4. An $R(t)$ function was constructed for the gamma-ray intensity of the $2^+ \rightarrow 0^+$ transition in ^{24}Mg formed using a geometric ratio.

$$R(T) = \left(\prod_{i=1}^n \frac{W_i^\uparrow(T)}{W_i^\downarrow(T)} \right)^{1/n} \quad (1)$$

Damped oscillations in $R(t)$ were observed as expected, and the g factor was determined precisely, in agreement with the previous value at the level of one standard deviation.

4. Discussion

The new TDRIV method proposed for applications to radioactive beams has been tested using a stable beam giving a precise result. This is the only g -factor measurement with the precision needed to test recent shell model predictions [12] that the $g(2^+)$ values should exceed 0.5 by up to about 10% in $N = Z$ nuclei in the sd shell. The method is ready for applications to radioactive ion beams.

Acknowledgments

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