First Nuclear Moment Measurement with Radioactive Beams by the Recoil-in-Vacuum Technique: The g Factor of the 2_1^+ State in ^{132}Te

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Following Coulomb excitation of the radioactive ion beam (RIB) ^{132}Te at HRIBF we report the first use of the recoil-in-vacuum (RIV) method to determine the g factor of the 2_1^+ state: $g(973.9\ \text{keV}\ 2^+\ ^{132}\text{Te}) = (+)0.35(5)$. The advantages offered by the RIV method in the context of RIBs and modern detector arrays are discussed.

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The advent of radioactive ion beams (RIBs) constitutes a major new initiative in nuclear structure investigations, opening up many new opportunities. However, the new beams, being not only orders of magnitude weaker than stable ones, but also producing background radioactivity levels which can mask useful reaction yields, present fresh challenges to experimenters to design methods appropriate for their best exploitation.

The g factors of nuclear excited states yield valuable information as to the makeup of their wave functions. This Letter presents the first result of applying the little-used technique of recoil in vacuum (RIV) to exploit its considerable advantages for g-factor measurements in the new RIB regime using modern detector arrays.

When an energetic ion beam emerges from a solid into a vacuum, the ions have a range of charge states and many differing electronic configurations, each with its own total angular momentum $\mathbf{J}$ which is assumed to be randomly oriented in space. The hyperfine interaction couples the nuclear spin $\mathbf{I}$ and $\mathbf{J}$ and causes them to precess about their resultant $\mathbf{F}$. Whenever the nuclear spin is initially oriented by a nuclear reaction, such precession forms a deorientation mechanism. Particularly in highly ionized states, the deorientation is dominated by the large magnetic interactions with angular frequency proportional to the nuclear g factor. This is the basis of the so-called recoil-in-vacuum method of measurement of the nuclear g factor, which was first studied in the 1970s [1].

In recent years the method most widely used for g-factor studies of states of half-life $\sim$ns has been the transient field (TF) method. After excitation into an oriented excited state (usually by Coulomb excitation), the nuclei traverse a magnetized ferromagnetic layer of the target in which they precess due to the action of the transient field. The precession is measured by the change in angular distribution of the gamma decay of the excited state when the magnetization is reversed and can be analyzed to give the magnitude and sign of the g factor. Giving the sign of the g factor is an advantage of the TF method as compared to the RIV method. An advantage of the RIV method is that the attenuation can be measured utilizing all detectors in a 2π or 4π array, whereas the optimal precession sensitivity for the TF technique is achieved only for detectors in the plane perpendicular to the magnetization axis.

Problems which arise for the TF method with RIBs, several orders of magnitude weaker than stable beams, are that precession angles observed are small, and thus good statistics are required to give an accurate g factor, and that the beam is usually stopped in the target producing high radioactive background. Even if the beam and excited nuclei are allowed to recoil out of the thick target (when the longer lived beam activity will leave the target area and the excited nuclei decay nearby), the possibility of contaminant activity can cause large undesirable background. The RIV method by contrast has attractive features when used with RIBs. There is no need for a thick target, so the beam escapes, and the unperturbed angular distributions can be very anisotropic so that attenuations can be measured with relatively poor statistics yet yield a useful g factor. This paper describes the first application of the RIV method to obtain the g factor of the first 2^+ state of an RIB isotope: ^{132}Te.

The experiments were carried out at the HRIBF Facility at Oak Ridge National Laboratory using the devices

CLARION for γ detection and Hyball, an array of CsI particle detectors [2]. In the RIB measurement a beam of 3×10^7 ^{132}Te ions/s at 396 MeV was incident on a 0.83 mg/cm^2 self-supporting C target for 3 days. In coincidence with C recoils, 29 000 deexcitation γ rays from the 973.9 keV, 2_1^+, state were recorded [3].

Data were taken in event-by-event mode, registering the energies and identifications of the particles detected in the Hyball segments, and the energies deposited in all CLARION detector segments. Data were analyzed by setting particle identification gates on carbon recoils, applying Doppler correction to the γ energy, and correcting for random coincidences.

Similar experiments were carried out with stable beams of ^{122,126,130}Te. The beam energies were, respectively, 366, 378, and 390 MeV, chosen to ensure that the velocities, and hence the hyperfine interactions, of the Te ions emerging from the back of the C target would be very similar for all isotopes. For each stable isotope, data were taken with two different targets. The first was a 0.956 mg/cm^2 self-supporting C foil, from which both Te ions and C recoils escaped into vacuum, and the second consisted of a 0.630 mg/cm^2 layer of C, backed with 14.3 mg/cm^2 Cu. The Cu backing stopped the Te recoils but allowed the C recoils to emerge and reach the Hyball array without appreciable angular straggling. Results from the unbacked C target show attenuation of the unperturbed distribution, observed from the Cu-backed target.

Analysis of the C-γ coincident data was made taking full advantage of the segmented nature of the CLARION and Hyball devices to give a detailed angular distribution. CLARION consists of 11 detectors in the backward hemisphere with respect to the target, five in a ring at 90°, four at 132°, and two at 155° to the beam (z axis). The Hyball particle detection array is in the forward hemisphere. In this work three rings of detectors were used, set in circles about the beam axis. The first ring is segmented into six detectors and receives particles scattered at angles between $7° < \theta_p < 14°$, the second ring has ten detectors with $14° < \theta_p < 28°$, and the third ring has 12 detectors with $28° < \theta_p < 44°$. Requiring the carbon recoil to be in a specific segment of a Hyball ring defines, along with the beam axis, the azimuthal angle ϕ_p of the reaction plane for each event. Combining this information with ϕ_γ of each CLARION detector, the angular distribution of the γ rays as a function of both θ_γ and $\phi = \phi_p - \phi_\gamma$ was obtained. This geometry, standard in measurement of particle-γ correlation following Coulomb excitation, is discussed, for example, in [4].

The stable-beam ^{122,126,130}Te experiments with the Cu-backed target aimed to establish not only that the unperturbed γ anisotropy was independent of the isotope, but also to demonstrate that it could be calculated from first principles. The calculation was carried out using standard formalism for perturbed particle-γ correlation from nuclei oriented in Coulomb excitation

$$W(\theta_\gamma, \phi) = \sum_{k,q} \sqrt{2k+1}\, \rho_{kq} G_k A_k Q_k D^{k*}_{q0}(\phi, \theta_\gamma, 0), \quad (1)$$

where G_k are the vacuum deorientation coefficients, dependent on the nuclear g factor. ρ_{kq} are statistical tensors, evaluated using Coulomb excitation scattering amplitudes [5] obtained from the Winther–de Boer computer code [4]. The rotational matrices $D^{k*}_{q0}(\phi, \theta_\gamma, 0)$ [6] represent the angular dependence of the correlation function and can be expressed in terms of associate Legendre polynomials $P^k_q(\cos\theta_\gamma)$ and a phase factor dependent on ϕ [7]. All the other symbols have their standard meaning, explained, for example, in Ref. [8]. Figure 1 shows the comparison of the calculated correlation with data taken with ^{130}Te. The data have been obtained by normalizing the counts in each CLARION detector coincident with a specific element of a Hyball ring to the sum of counts in the complete Hyball ring. The theory was normalized to the calculated value of $W(\theta_\gamma) = \int_0^{2\pi} W(\theta_\gamma, \phi) d\phi$. The data have not been fitted to the theory in any way.

The agreement is extremely good for all nine combinations of Hyball rings and CLARION angles. This is an important result as it gives encouragement that such calculations may be used in the future to give the unattenuated distribution in cases where it is not possible to measure it directly.

Performing similar analysis of the data from the unbacked C targets, RIV attenuated distributions were found for all three stable Te isotopes and for ^{132}Te. For each isotope, the full data set, comprising a total of 308 individual $W(\theta_\gamma, \phi)$ points, were fitted simultaneously to yield the best values of the attenuation parameters as described below. The interaction strength depends upon recoil velocity; the small variation of this recoil velocity between the three Hyball rings has been neglected. The 10% difference between the C target thickness used for ^{132}Te and ^{122,126,130}Te introduces an even smaller variation in recoil velocity and has also been neglected. Figure 2 shows the

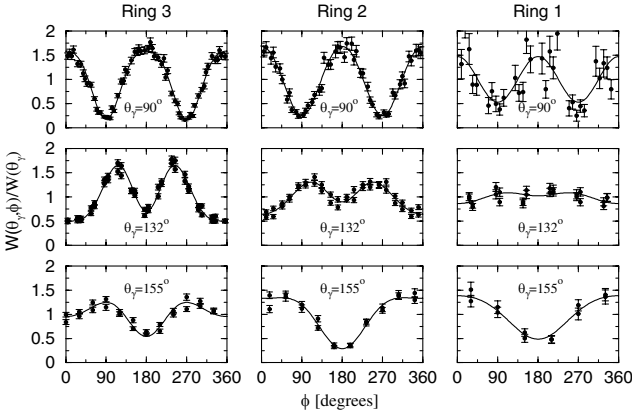

FIG. 1. Unattenuated experimental and calculated angular distributions for ^{130}Te measured using CLARION detectors at $\theta_\gamma = 90°$, 132°, and 155° and Hyball rings 1, 2, and 3.

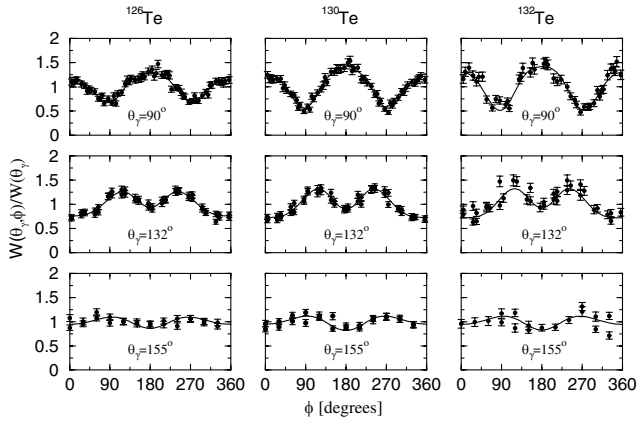

FIG. 2. Experimental and fitted attenuated angular distributions for $^{126\,130\,132}$Te measured using CLARION detectors at $\theta_\gamma = 90°$, 132°, and 155° and Hyball ring 3.

ring 3 attenuated angular distributions and best fits for ^{126,130,132}Te. ^{126}Te (longer lifetime) shows stronger attenuation than the other two isotopes, while ^{132}Te is somewhat less attenuated than ^{130}Te.

A detailed theoretical description of the RIV attenuation process is complex. It requires full knowledge of the range and weighting of ionic charge states, electron angular momentum states, and their hyperfine interaction strengths and lifetimes. To date two extreme models of the process have been considered. In the first, the ''rapid fluctuation'' model, the electronic state is assumed to change frequently during the nuclear lifetime, giving abrupt changes in both magnitude and direction of the hyperfine interaction. This chaotic process leads eventually to complete attenuation of the γ anisotropy and can be described, within fairly broad limits, by a single relaxation time τ_2 [9,10]. For purely magnetic hyperfine interactions, the parameters G_2 and G_4 in Eq. (1) are given as functions of a single variable τ_2 and the nuclear mean life τ by $G_2 = \tau_2/(\tau_2 + \tau)$ and $G_4 = 0.3\tau_2/(0.3\tau_2 + \tau)$. In this model $\tau_2 = C/g^2$, where C is a constant for isotopes having the same ionic state distribution and there is a relationship $G_4 = 0.3G_2/(1 - 0.7G_2)$.

The second extreme, a ''static'' model, considers the case that the electronic state lifetime is long compared to the nuclear state mean life. For this limit the nuclei undergo Larmor precession about an axis in space determined by their individual $\mathbf{F}$ quantization axis $\mathbf{F} = \mathbf{I} + \mathbf{J}$, which is related to their randomly oriented $\mathbf{J}$ angular momentum. For each pair of quantum numbers I and J integration over time, weighting by the nuclear decay $e^{-t/\tau}$, yields [11]

$$G_k = \sum_F \frac{(2F+1)^2}{2J+1} \begin{Bmatrix} F & F & k \\ I & I & J \end{Bmatrix}^2 + \sum_{F \neq F'} \frac{(2F+1)(2F'+1)}{2J+1} \begin{Bmatrix} F & F' & k \\ I & I & J \end{Bmatrix}^2 \frac{1}{\omega_{FF'}^2 \tau^2 + 1}. \quad (2)$$

The full expression for G_k averaged over the charge state and electronic excitation is a weighted sum of G_k's of the form of Eq. (2), each having two terms, a ''hard core'' maximum attenuation plus a term involving $g^2\tau^2$ (since $\omega \sim g$). There is no simple algebraic form for the result of such a summation. Simulations of this model for a wide range of values of J and different hyperfine interaction strengths have been made [12]. The dependence of G_k upon $g\tau$ is sensitive to these electronic state parameters, as is the ratio G_2/G_4 to a lesser degree. Thus, in this model the relationship between G_2 and G_4 is not predictable without detailed knowledge of the distribution of the states of the ions and their hyperfine interactions. The experimental values of G_k for each isotope, their 2_1^+ state mean lifetimes, energies, and weighted mean g factors, are given in Table I, which also includes the best fit values of G_2 and G_4 taken as independent parameters. A simple check shows that these best fit G_k values are in clear disagreement with the relationship required by the random fluctuation model so this model was discarded as a possible route to the g factor. The experimental values of G_2 and G_4 for the three ''calibration'' isotopes ^{122,126,130}Te, taken as a function of $g\tau$, were then fitted using the static model by adjusting the distribution of $\mathbf{J}$ states and the magnitude of the hyperfine interaction (Fig. 3). This was an essentially empirical exercise to find dependencies consistent with the calibrations which could be extrapolated to obtain $g\tau$ for ^{132}Te. Two sets of the model parameters were found which gave extremum fits constituting upper and lower limits of the variation of G_2 and G_4 with $g\tau$. The experimental values of G_2 and G_4 for ^{132}Te then each yielded a range for $g\tau$ for the first 2^+ state. The results, $g\tau$(from G_2) = 0.92(14) ps and $g\tau$(from G_4) = 0.90(10) ps agree very well with each other. Thus, taking the lifetime of ^{132}Te given in Table I, we obtain, using the more precise $g\tau$, the result $g = 0.346(38)(35)$ where the first error arises from the variation between the two sets of model parameters and the second stems from the uncertainty in the lifetime. The

TABLE I. Te 2_1^+ excited state data and fit to attenuated distributions (see text for details).

Isotope	$E_{2_1^+}$ (keV)	$\tau_{2_1^+}$ (ps) [13]	g factor [14]	$g\tau$ (ps)	G_2	G_4
^{122}Te	564.1	10.8(1)	0.340(10)	3.67(12)	0.355(18)	0.214(11)
^{126}Te	663.3	6.5(2)	0.275(30)	1.79(20)	0.505(19)	0.366(12)
^{130}Te	839.5	3.3(1)	0.295(35)	0.97(12)	0.629(19)	0.503(12)
^{132}Te	973.9	2.6(2) [15]		0.90(10)	0.715(26)	0.522(17)

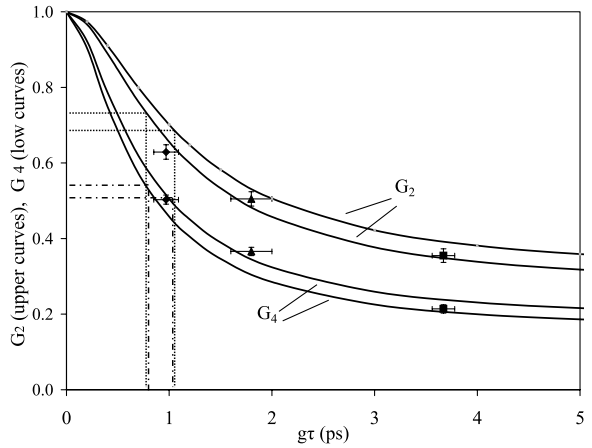

FIG. 3. G_2 and G_4 as a function of $g\tau$. For details see text.

final result (with sign from systematics) is

$$g(973.9\ \text{keV}\ 2^+\ ^{132}\text{Te}) = (+)0.35(5). \quad (3)$$

Theoretical interest in the g factor of this state arises from the proximity of ^{132}Te to doubly magic ^{132}Sn. As the number of valence neutron holes in the double magic configuration decreases, the g factor is expected to rise since proton contributions to the 2^+ excitation will become more important. Table II displays recent calculated values for the g factors of heavy Te isotopes close to the closed shell. The present result is consistent with a modest increase in the g factor between ^{130}Te and ^{132}Te. This experiment has shown that the RIV method can provide a good-quality g-factor measurement for ^{132}Te RIB. The result further indicates the possibility of performing experiments of useful precision in favorable cases with beams that are at least 1 order of magnitude weaker than in this work. Since RIV attenuations are available for study whenever Coulomb-excited states recoil from and decay beyond a thin target, this method is expected to be generally useful for g-factor determinations of short-lived excited states using RIBs. To maximize the potential of the method requires short calibration experiments with stable beams of nuclei having known g factors, suitable lifetimes and the same spin as the RIB nuclei. More meaningful *a priori* modeling of the RIV process should emerge as further results become available.

TABLE II. Calculated and experimental g factors for 2_1^+ states in Te isotopes close to $N = 82$.

Nuclear model	^{130}Te	^{132}Te	^{134}Te	^{136}Te	Ref.
Shell model	+0.341	+0.480	+0.833	+0.348	[16]
QRPA	+0.314	+0.491	+0.695	−0.174	[17]
Experiment	+0.295(35)[a]	(+)0.35(5)	···	···	

[a]Taken from Ref. [18].

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