g factors, spin-parity assignments, and multipole mixing ratios of excited states in $N = 82$ isotones ^{134}Te, ^{135}I

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The g-factor of the 4^+ state in ^{134}Te has been measured for the first time by using a new technique developed for measuring angular correlations with Gammasphere. Also reported is the first measurement of the g-factor of the $15/2^+$ state in ^{135}I and the mixing ratios of several transitions. Furthermore, spins and parities are assigned to several levels in ^{134}Te and ^{135}I. The g-factor measurements are compared to shell model predictions and good agreement is found between experiment and theory.

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I. INTRODUCTION

The magnetic moments of nuclei with a few nucleons outside doubly-closed shells can give direct insight into the single particle structure of the orbitals outside the shells. The g-factor is also sensitive to the two body interactions of the valence particles and their interactions with the core. Therefore, the measurements of g-factors of excited states in nuclei just outside doubly magic ^{132}Sn provide an important key in understanding the shell structure of nuclei in this region. Furthermore, the determination of the spin and parity of excited states in these nuclei provides a test of shell model calculations. The multipole mixing ratios of transitions between single particle states can also give some indication of their structure. Therefore, the previously unknown g-factors of the 4^+ state in ^{134}Te and the 1422 keV $15/2^+$ state in ^{135}I are determined in this work and compared with the results of a shell-model calculation with a two-body effective interaction derived from the CD-Bonn nucleon-nucleon potential [1]. The measured angular correlation coefficients were used to extract mixing ratios of several transitions along with spins and parities for several levels for the first time.

II. EXPERIMENT AND DATA ANALYSIS

The data for this analysis were taken by using the Gammasphere detector array located at Lawrence Berkeley National Laboratory. A ^{252}Cf spontaneous fission source with an α activity of 62 μ Ci was placed between two iron foils. The foils were thick enough to stop the fission fragments, eliminating the need for a Doppler correction. Approximately 4×10^{11} triple and higher fold γ coincidence events were recorded. More details about this experiment can be found in Luo *et al.* [2].

Since the fission fragments were stopped in iron foils, they were therefore subject to the magnetic hyperfine fields (B_{HF}) in the iron lattice caused by their implantation in substitutional sites. For a nuclear state with lifetime τ, the spin vector of the nucleus will rotate about B_{HF} over the lifetime of the state, with the frequency of the rotation proportional to the strength of the field and the g-factor of the state. For this experiment, the magnetic domains in the iron foils remained randomly aligned; the foils were not cooled and there was no applied external field. The net result of the rotation of the implanted nuclei about the randomly oriented fields is an attenuation of the expected angular correlation. The attenuation factor G_k is related to the Larmor precession frequency ω_L and the lifetime τ via Eqs. (1), (2), and (4) [3]:

$$G_k = \frac{1}{2k+1}\left(1 + 2\sum_{q>0}^{k}\frac{1}{1+q^2\phi^2}\right), \tag{1}$$

$$\phi = \omega_L \tau. \tag{2}$$

Experimentally, the attenuation factors $G_{2,4}$ are defined by fitting the measured angular correlation to the parameters $A_2^{\exp}$ and $A_4^{\exp}$

$$W(\theta) = 1 + A_2^{\exp} P_2(\cos\theta) + A_4^{\exp} P_4(\cos\theta), \tag{3}$$

$$G_k = \frac{A_k^{\exp}}{A_k^{\mathrm{theory}}}. \tag{4}$$

The $A_{2,4}^{\mathrm{theory}}$ are calculated for various values of the mixing ratio, δ, with the Wigner $3j$ and $6j$ coefficients, as outlined and tabulated by Taylor *et al.* [4]. With these theoretical values, the attenuations of the angular correlation coefficients can be used to calculate the g-factor by using Eqs. (1) and (5),

$$g = -\frac{\hbar\phi}{\mu_N B_{\mathrm{HF}}\tau}. \tag{5}$$

Since the G_k are functions of ϕ^2, only the absolute value of the g-factor is given by this method. Although it is possible to use triple coincidences for added selectivity, it was not necessary to use additional gates on the correlations for this work because the γ-γ coincidence spectrum is relatively clean for transitions >1 MeV. Furthermore, most of the correlations in this work are unattenuated because the decay energies are typically large for $N = 82$ isotones. In fact, only correlations through the 4^+ state in ^{134}Te and the $15/2^+$ state in ^{135}I are attenuated.

III. RESULTS

Partial level schemes for ^{134}Te and ^{135}I are given in Fig. 1, where the spins and parities given for some of the states are as determined through angular correlations measured in this work. A detailed discussion of the assignments for each level and multipole mixing ratios of the transitions will be given below.

A. ^{134}Te

The g-factor of the 4^+ state in ^{134}Te is measured here for the first time. The $4^+ \to 2^+ \to 0^+$ cascade ($A_2 = 0.101(3)$, $A_4 = 0.006(4)$) is unattenuated. The angular correlation between two gamma rays in a cascade is unchanged by an unobserved intermediate stretched $E2$ transition in the cascade, as long as the intermediate transition does not cause attenuation through precession in the 2^+ state, which is so short-lived as to preclude measurable precession. Therefore, the $4^+ \to 2^+$ transition can be skipped in the $6^+ \to 4^+, 2^+ \to 0^+$ angular correlation without affecting the A_2 and A_4 values. The $6^+ \to 4^+, 2^+ \to 0^+$ correlation is shown in Fig. 2. This correlation shows attenuation from the theoretical values of $A_2 = 0.102$. $A_4 = 0.009$, with the attenuation factor $G_2 = 0.28(5)$.

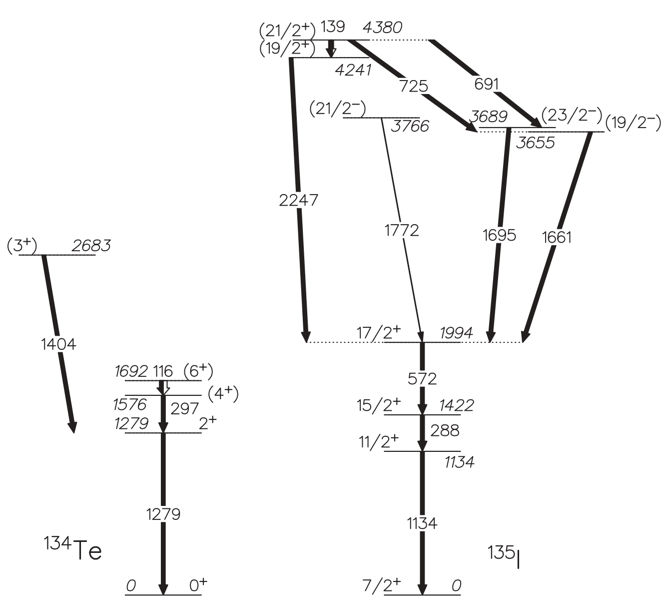

FIG. 1. Partial level scheme of ^{134}Te and ^{135}I [6] with spins and parities assigned in this work.

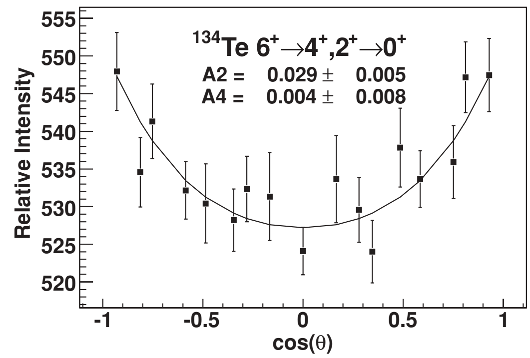

FIG. 2. The correlation for the $6^+ \to 4^+, 2^+ \to 0^+$ cascade in ^{134}Te. This correlation gives an attenuation coefficient of $G_2 = 0.28(5)$.

To extract the g-factor from the attenuation, the hyperfine field acting on the nuclei and lifetime of the state must be known. The lifetime of the 4^+ state is measured to be $\tau = 1.96(6)$ ns [6]. The comprehensive hyperfine field compilation by Rao [5] gives a wide range of fields for Te in iron for samples with different preparation methods and at different temperatures. For liquid helium temperature preparation there is good agreement that the field B_{HF}(Te<u>Fe</u>) is close to 69 T. Adoption of this value yields $|g| = 0.36^{+0.23}_{-0.09}$, which falls somewhat below our theoretical calculation (see discussion below). However Rao's [5] table includes experiments on Te implanted at room temperatures revealing a range of lattice sites and a seriously reduced average field with values of 34(16) T and 19(6) T being reported which are likely to be more relevant to the present analysis. These lower fields yield g-factors of $|g| = 0.70^{+0.55}_{-0.38}$ and $|g| = 1.31^{+0.31}_{-0.14}$, respectively, which show the sharp increase compared to lighter Te isotopes predicted by the calculations. Better knowledge of the hyperfine field acting at Te nuclei directly implanted at room temperature would allow a better g-factor result from the present data.

The large asymmetric errors arise from the fact that the error in Eq. (1) increases dramatically as G_2 approaches the lower asymptotic limit of 0.20. This is demonstrated in Fig. 3, which shows a plot of Eq. (1) with $k = 2$. The experimental range of $G_2 = 0.26(4)$ for ^{134}Te is shown in the left figure as dashed horizontal lines. A hypothetical measurement with the same error bars, but for $G_2 = 0.70(4)$, is shown on the right. The dotted vertical lines then show the resulting range of ϕ values that come from solving Eq. (1). This range is directly proportional to the resultant error in the g-factor, and it is clear that as the correlation moves closer to the lower limit of $G_2 = 0.2$, the resultant error in ϕ increases dramatically. Therefore, although the quality of the experimental measurement is quite good, the fundamental limitations of this technique give a large uncertainty in the resultant g-factor.

The spin and parity of the 2683 keV level in ^{134}Te are assigned in this work by measuring the angular correlation

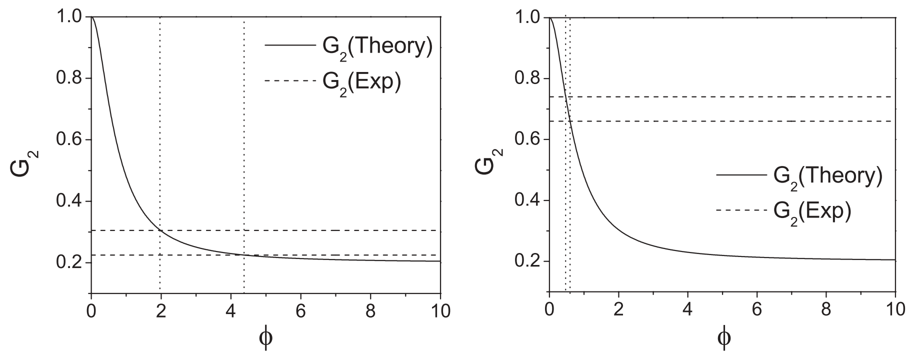

FIG. 3. These plots demonstrate how the error in $G_2(\phi)$ increases dramatically with ϕ and as discussed in the text. Left pannel shows how the uncertainty in ϕ increases as G_2 approches 0.2. In the right pannel, we show how the uncertainty in ϕ changes as G_2 approches 1.0. This is a fundamental limitation of the method for attenuation approaching $G_2 = 0.2$.

between the 1404 keV and 1279 keV transitions. Because the 2683 keV level decays strongly to the 2^+ state at 1279 keV, the level likely has a spin of 2, 3, or 4. Because the level also decays to the 2^+ and 4^+ levels of the $\pi g_{7/2}d_{5/2}$ multiplet around 2.5 MeV, it was tentatively assigned as 3^+ in [8] and proposed to have a $\pi g_{7/2}d_{5/2}$ configuration as well. The result of this correlation is shown in Fig. 4.

In order to verify the assignment of 3^+ for the 2683 keV level, the theoretical A_2 and A_4 values for a $2 \to 2 \to 0$, $3 \to 2 \to 0$, and $4 \to 2 \to 0$ cascade are plotted in Fig. 5. From this figure, it is clear that the measured angular correlation is only consistent with an assignment of 3 for the spin of the 2683-keV level. Furthermore, the quadrupole-dipole mixing ratio of the 1404-keV transition can be found from this angular correlation to be $\delta(Q/D; 1404) = -2.1(5)$. The level must have positive parity for such a high degree of mixing to occur in the 1404 keV transition, so it is assigned a spin and parity of 3^+.

B. ^{135}I

1. *Spin/parity assignments and mixing ratios in ^{135}I*

The spin and parity of the ground state of ^{135}I were measured by Janecke *et al.* [9] to be $7/2^+$. The spin and parity assignments of excited states have been made from shell model calculations by [8,10–12]. In order to verify these assignments, angular correlations for transitions in ^{135}I are measured.

Table I shows the A_2 and A_4 values measured for various angular correlations and the resulting spin and parity assignments, which are discussed in detail below. The theoretical values of the A_2 and A_4 coefficients for the given spin assignments are also given for comparison and to show the consistency of the present assignments.

The 1422 and 1134 keV levels: The angular correlation between the 288 keV and 1134 keV transitions ($A_2 = 0.099(4)$, $A_4 = 0.004(5)$) is consistent with an unattenuated stretched $E2$ cascade, for which $A_2 = 0.102$, $A_4 = 0.009$. Therefore, with the spin of the ground state known as $7/2^+$, the 1134-keV level is assigned a spin of $11/2^+$ and the 1422 keV level is assigned a spin of $15/2^+$, which is in agreement with the spins proposed in various theoretical calculations [8,10–12].

The 1994 keV level: Theoretical calculations [8] indicate that the level at 1994 keV has to be $17/2^+$. Calculations performed for this work (discussed in the following section) indicate that the lifetime of the 1422 keV level is about 2 ns. Therefore, correlations between the 572 keV and 1134 or 288 keV transitions will be attenuated and cannot be used independently to determine the spin of the 1994 keV state. However, it is true that the magnitude of the A_k^{exp} values will be less than or equal to the expected unattenuated value for a given spin sequence. Therefore, the angular correlation between the 572 keV and 1134 keV transitions can be used to constrain the possible spin value. The result of the 572–1134 keV angular correlation is shown in Fig. 6. Because of the relatively strong decay of the 572 keV transition, only $E1$, $M1$, or $E2$

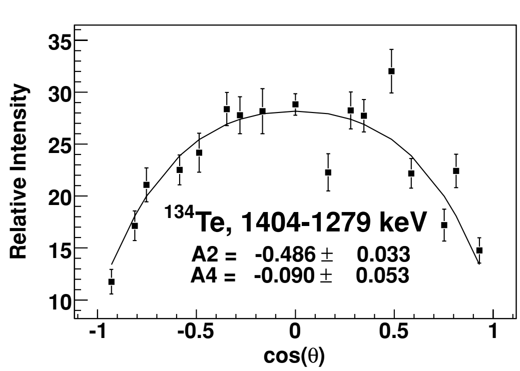

FIG. 4. The angular correlation between the 1404-keV and 1279-keV transitions in ^{134}Te.

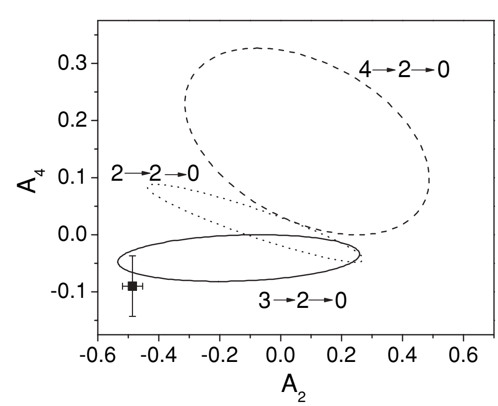

FIG. 5. Possible spin sequences for the 1404-1279-keV angular correlation in ^{134}Te. The experimental value is the square point, and the theoretical values for a spin of 4, 3, and 2 are given by the dashed, dotted, and solid lines, respectively.

TABLE I. Angular correlations measured for ^{135}I. Note that the 572–1134-keV angular correlation is attenuated from the theoretical value of $A_2 = -0.241$. $\delta(E2/M1; 572) = -3.9(3)$ from A_2^{exp} and A_4^{exp} of the 1695–572 cascade.

$E_{\gamma1}$–$E_{\gamma2}$ (keV)	Spin sequence	A_2^{exp}, A_4^{exp}	A_2^{theory}, A_4^{theory}
288–1134	$15/2^+ \rightarrow 11/2^+ \rightarrow 7/2^+$	0.099(4), 0.004(5)	0.102, 0.009
572–1134	$17/2^+ \rightarrow 15/2^+, 11/2^+ \rightarrow 7/2^+$	−0.044(6), 0.006(9)	−0.241, −0.045
1661–572	$19/2^- \rightarrow 17/2^+ \rightarrow 15/2^+$	0.103(23), −0.037(35)	0.103, 0.0
1695–572	$23/2^- \rightarrow 17/2^+ \rightarrow 15/2^+$	−0.231(12), 0.022(18)	−0.231, 0.0
725–1661	$17/2^+ \rightarrow 19/2^- \rightarrow 17/2^+$	0.71(22), −0.014(35)	0.068, 0.0

multipolarities are likely. Based on this consideration, the possible spin and multipolarity assignments for the 1994 keV level are $13/2^{\pm}$, $15/2^{\pm}$, or $17/2^{\pm}$. The fact that the level does not decay to the $11/2^+$ state at 1134 keV rules out either the $13/2^{\pm}$ or $15/2^+$ assignments. Therefore, it can be concluded that the 1995 keV level is either $17/2^{\pm}$ or $15/2^-$. It will be demonstrated below that, when taken with the 1695–572 keV and 1661–572 keV angular correlations, an assignment of $17/2^+$ is most consistent with the measured angular correlations.

The 3689 keV level: There are three close-lying states around 3.7 MeV that all decay to the state at 1994 keV. The result of the 1695–572 keV angular correlation is shown in Fig. 7. Previously, the 3689 keV level has been assigned as $23/2^-$. This assignment is consistent with shell model calculations [8,12]. Our angular correlation data for the 1695–572 keV transitions (see Fig. 7) is best fitted, assuming $23/2^-$ for the 3689 keV level, by taking the 572 keV transition as of mixed $E2/M1$ multipolarity following a pure $E3$ 1695 keV transition. The mixing ratio for the 572 keV transition is required to be $\delta(E2/M1; 572) = -3.9(3)$. The mixed multipolarity sets the spin-parity/of the 1994 keV level as $17/2^+$.

The 3655 keV level: The angular correlation between the 1661 keV and 572 keV transitions is shown in Fig. 8. With the mixing ratio of the 572 keV transition known, the results for the 1661–572 keV cascade are fully consistent with $E1$ multipolarity for the 1661 keV transition and spin assignment of $19/2^-$ for the 3655 keV level, in agreement with the shell model calculation.

2. *g-factor of the* $15/2^+$ *state*

With the mixing ratio of the 572 keV transition fixed at $\delta(E2/M1) = -3.9$, the expected angular correlation coefficient for the 572–1134 keV correlation is $A_2^{theory} = -0.241$. The observed value is $A_2^{exp} = -0.044(6)$, as shown in Fig. 6. This gives $G_2 = 0.183(25)$. It can be seen from Eq. (1) that as ϕ approaches infinity (as $gB_{HF}\tau \rightarrow \infty$) the value of G_2 approaches the "hard core" value of 0.2. Therefore, since the measured attenuation spans the "hard core" value, only a lower error bar can be placed on the g-factor from this measurement.

The hyperfine field for iodine is taken from [5] as 115(1) T. Although the field for a room temperature foil has not been measured, it is clear from the values listed in [5] that the strength of the field is not strongly dependent on temperature. For example, the value measured at 100 °K is 113 (4) T, while at ~ 0 °K, it is 114(2) T.

The lifetime of the $15/2^+$ state is calculated to be 2 ns. The details of the calculation can be found in the following section. With these parameters, it is found that $g(15/2^+) \geqslant 0.76$. If the half-life of the $15/2^+$ state is measured in future to be different from 2 ns, then our proposed value can easily be scaled by the factor $\frac{\tau_{exp}}{\tau_{calc}}$.

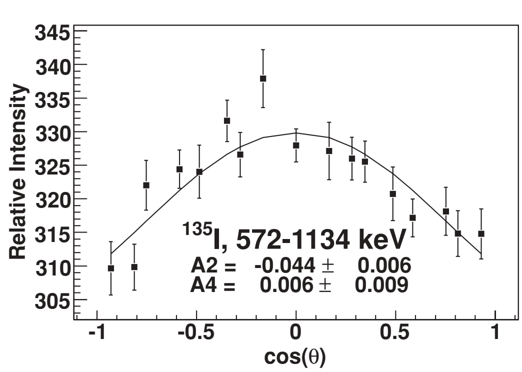

FIG. 6. The correlation for the 572–1134 keV, $17/2^+ \rightarrow 15/2^+, 11/2^+ \rightarrow 7/2^+$ transitions in ^{135}I. This correlation is attenuated from the expected value of $A_2 = -0.241$.

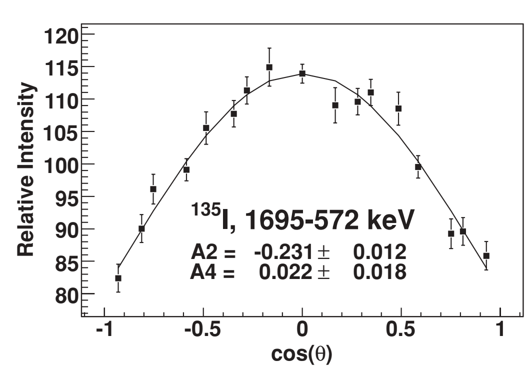

FIG. 7. The correlation for the $23/2^- \rightarrow 17/2^+ \rightarrow 15/2^+$, 1695-572-keV cascade in ^{135}I.

TABLE II. g-factors measured in this work, as well as previous measurements by Wolf *et al.* [13] and White *et al.* [14]. The g-factors calculated in this work and by Brown *et al.* [7] are also shown.

Nucleus	J^{π}	τ (ns)	B_{HF}(T)	g_{exp}	g_{calc} (This work)	g_{calc} (Brown *et al.*)
^{134}Te	4^+	1.96(16)	34(16)	$\pm0.70^{+0.55}_{-0.38}$	0.72	0.83
			69	$\pm0.36^{+0.23}_{-0.09}$[b]		
			19(6)	$\pm1.31^{+0.31}_{-0.14}$		
^{134}Te	6^+			0.846(25) [13]	0.72	0.83
^{135}I	$7/2^+$			0.8400(6) [14]	0.71	
^{135}I	$15/2^+$	2[a]	115(1)	$\pm\geqslant0.76$	0.73	

[a]Calculated lifetime.

[b]This result is based on a low temperature hyperfine field value and is likely to be too low [see text].

IV. DISCUSSION

In this section, the measured g-factors for ^{134}Te and ^{135}I are compared to the values obtained from a shell-model calculation. The results of the experiment and calculation are summarized in Table II. The calculation has been performed assuming ^{132}Sn as a closed core and letting the two and three valence protons of ^{134}Te and ^{135}I, respectively, occupy the five levels $0g_{7/2}$, $1d_{5/2}$, $1d_{3/2}$, $2s_{1/2}$, and $0h_{11/2}$ of the 50–82 shell. The corresponding single-particle energies have been taken from the experimental spectrum of ^{133}Sb [6], the only exception being that of the $2s_{1/2}$ level, which is still missing. Its value has been taken from [12], where it was determined through a study of the $N = 82$ isotones. All the adopted values are reported in [15].

As regards the two-body matrix elements of the effective interaction, they have been derived from the CD-Bonn nucleon-nucleon potential renormalized by use of the V_{low-k} approach [16]. The Coulomb force has been explicitly taken into account. Details of this derivation which is performed within the folded-diagram theory, can be found in [17].

The calculations in this work have been carried out with the OXBASH shell-model code [18]. Starting from the obtained wave functions, the g-factors are calculated using an effective $M1$ operator which takes into account core-polarization effects.

A recent calculation by Brown *et al.* [7] is similar to the one in this work. They calculated the g-factors of 2^+, and in some cases 4^+ and 6^+, states of $N = 82$ isotones. Their calculation uses an earlier version of the CD-Bonn potential [19] with a similar model space. For the calculation of g-factors, Brown *et al.* use different effective operators than the present calculation. Namely, the calculation in this work includes first-order diagrams in V_{low-k}, while Brown *et al.* also include higher-order core polarization and mesonic exchange current corrections.

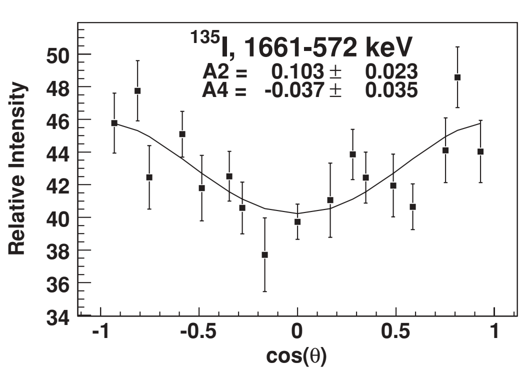

FIG. 8. The correlation for the $19/2^- \to 17/2^+ \to 15/2^+$, 1661–572-keV cascade in ^{135}I.

Regarding the 4^+ and 6^+ states in ^{134}Te, both calculations predict that they have the same g-factor, arising from the fact that they both, as well as the first 2^+ state, are dominated by the same $(\pi g_{7/2})^2$ configuration with percentages ranging between 96 and 98 %. This prediction, made also by earlier calculations [7,8,10–12,20], is consistent with the experimental g-factor results for the two states.

Analogously, the lower limit found for the g-factor of the $15/2^+$ state suggests similarity with the precisely known value for the ground $7/2^+$ state which is well reproduced by calculations. Again these two states are calculated as arising from the same $(\pi g_{7/2})^3$ configuration, 80% for the ground state and 98% for the $15/2^+$ state.

V. CONCLUSIONS

The knowledge of magnetic moments in nuclei with a few particles outside ^{132}Sn has been extended in this work with the first measurement of $g(4^+)$ in ^{134}Te and $g(15/2^+)$ in ^{135}I. For ^{134}Te, a value consistent with both previous experiment and calculations is found. For ^{135}I, the g-factor of the $15/2^+$ is also consistent with our shell model calculation, although no experimental upper limit can be determined.

Spins and parities are assigned for several levels in ^{134}Te and ^{135}I. These assignments are in good general agreement with the predictions of the single particle structure given by [8]. Furthermore, the mixing ratio of the 1404-keV transition in ^{134}Te and the 572 keV transition in ^{135}I are also determined to be $\delta(E2/M1;1404) = -2.1(5)$ and $\delta(E2/M1;572) = -3.9(3)$, respectively.

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