Magnetic moments of the 2_1^+ states of even-even Te isotopes

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The magnetic moments of the 2_1^+ states of $^{120-130}$Te isotopes have been measured by the thin-foil transient field technique. The resulting magnetic moments are discussed in the light of predictions of the vibrational, the quasiparticle, and the interacting boson approximation models.

[NUCLEAR REACTIONS $^{120-130}$Te (^{32}S,^{32}S′) $^{120-130}$Te(2_1^+); $E_S \sim 80$ MeV; enriched targets; measured $W(\theta,B,\infty)$ through polarized iron; deduced $g(2_1^+)$.]

INTRODUCTION

The even Te isotopes exhibit general collective-nuclei properties. Theoretical calculations of the magnetic moments of these nuclei have been based on the vibrational model, the quasiparticle model, and the interacting boson approximation (IBA) model. The present experiment was undertaken to accurately measure the g factors of the even Te isotopes in order to discriminate between different theoretical predictions. The magnetic moments of the first excited 2^+ states of the stable even-even $^{120-130}$Te isotopes were measured here for the first time by the thin-foil transient field technique.

It has been established in recent experiments[1] that the transient field acting on fast ions traversing thin iron foils is a smooth function of the ion velocity for ions in the velocity range $0.014 < v/c < 0.027$ and atomic number $8 < Z < 78$. The transient field has been calibrated by measuring the effects of the field on nuclear states with magnetic moments determined by unambiguous techniques. Various parametrizations of the field have been proposed. The parametrization adopted for this work has been described in previous publications.[1,2]

There are two isotopes of Te, ^{122}Te and ^{124}Te, whose magnetic moments have been measured by precession in the static hyperfine field of a host ferromagnet into which the parent radioactive nuclei, ^{122}Sb and ^{124}Sb, respectively, have been implanted. Many measurements have been carried out on these isotopes but the experimental values exhibit a scatter wider than warranted by the quoted errors. Thus, it is not possible to use these measurements to calibrate the transient field and the determination of the moments must rely on the average parametrization discussed above.

The magnetic moments of the 2_1^+ states in the Te isotopes have also been measured previously[3] by ion implantation perturbed angular correlation (IMPAC) techniques; however, these experiments suffer from serious systematic errors due to the dependence of the data on the accurate knowledge of the static hyperfine field, low velocity stopping powers, the lifetimes of the states, and radiation damage effects. The thin-foil technique data are independent of the above factors and henceforth expected to be more reliable.

Recently, the thin foil transient field technique has been applied to systematic measurements of the g factors of the 2_1^+ states of Pd, Cd, and Ba nuclei.[2] The data have been used here to extract the parameters of a semiempirical formula derived from the first order IBA model.

EXPERIMENTAL TECHNIQUE AND RESULTS

The essential feature of the technique involves the use of a triple layered target. The first layer consists of thin enriched Te isotopes electroplated onto an annealed natural iron foil which is backed by a thick copper stopper. The composition of the targets is given in Table I, which also lists the energies and meanlives[4] of the 2_1^+ states of the Te isotopes. The details of the technique have been extensively

TABLE I. Summary of the energy levels and lifetimes of the 2_1^+ states of the even Te isotopes and the composition of the targets.

Nucleus	Isotope L (μg/cm^2)	Iron L (mg/cm^2)	Copper L (mg/cm^2)	$E_{2_1^+}$ (MeV)	τ^a (psec)
^{120}Te	375	1.39	15	0.562	14.4(2.6)
^{122}Te	470	1.38	18	0.564	11.5(1.1)
^{124}Te	370	1.43	12	0.603	5.8(0.5)
^{126}Te	450	1.37	20	0.667	5.8(0.7)
^{128}Te	450	1.47	18	0.743	4.3(0.6)
^{130}Te	300	1.31	18	0.840	2.7(0.3)

[a]Reference 4.

and frequently described in previous publications.[5–8]

A beam of 80 MeV sulfur ions from the Rutgers-Bell tandem accelerator was used to Coulomb excite the nuclei, which then recoil *through* the thin iron foil into the copper backing, where they stop and subsequently decay. A small external polarizing magnetic field of 300 G was applied perpendicular to the beam direction to magnetize the iron foil to saturation. The direction of the field was reversed approximately every 3 to 5 min. The decay gamma radiation was detected in four 12.7 cm $\times$ 12.7 cm matched NaI (Tl) detectors, in coincidence with the backscattered sulfur beam particles, which were detected in an annular surface barrier detector. The NaI(Tl) detectors were located at a distance of 16.7 cm from the target and were placed at the angles $\theta_\gamma = 67.5°$ and 112.5 °, where normalized slopes S of the gamma-ray angular correlations $W(\theta)$ were a maximum, $S = -(1/W)(dW/d\theta)_{\theta_\gamma} \approx -3.0$. A typical particle-gamma-ray angular correlation is shown in Fig. 1 for the $\Delta m = 0, 2_1^+ \rightarrow 0_1^+$ transition in the nucleus of ^{124}Te. The effect of the 300 G external magnetic field on the precession of the angular correlation was reduced to negligible proportions by effective shielding of the incoming beam with a soft iron cone. The net precession $\Delta\theta$ of the gamma ray angular correlation is related to the magnetic moment and the hyperfine field by the following expression, which takes into account the nuclear decays within the moving ion as these traverse the iron foils:

$$\Delta\theta = -\frac{g\mu_n}{\hbar}\int_0^T Be^{-t/\tau}dt \ ,$$

where τ is the mean life of the state and T is the time spent by the ion in the iron foil. The parametrization chosen to represent the transient field in the iron was

$$B(v,Z) = 97\left[\frac{v}{v_0}\right]^{0.45} Z^{1.1}\mu_B N_p \ , \qquad (1)$$

where $v_o = e^2/\hbar$ is the Bohr velocity, v is the ion velocity, Z is the atomic number of the ion, μ_B is the Bohr magneton, N_p is the volume density of polarized electrons, and $\mu_B N_p = 1752$ G is the saturation magnetization of the iron foil.

The initial and final energies of the Te ions traversing the iron foils of thickness L, the time spent by the ion in the ferromagnet, the precession

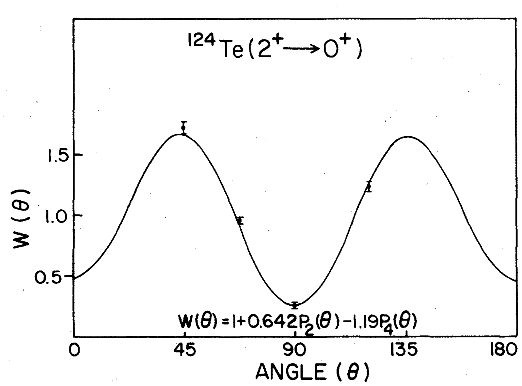

FIG. 1. Typical particle-γ angular correlation for ^{124}Te. The four NaI(Tl) detectors are placed at angles $\theta = \pm 67.5°$ and $\pm 112.5°$ for the precession experiments.

TABLE II. Summary of the measured net precession angles $\Delta\theta$ for the Te isotopes and the deduced g factors. E_{in}, E_{out}, $(v/v_0)_{\text{in}}$, and $(v/v_0)_{\text{out}}$ are, respectively, the energies and velocities of the moving ions as they enter and leave the iron foil. L is the thickness of the foil and T is the time spent by the ion in the ferromagnet. The g factors for ^{122}Te and ^{124}Te determined by radioactivity methods are shown in the last column.

Nucleus	E_{in} (MeV)	E_{out} (MeV)	$\left(\frac{v}{v_0}\right)_{\text{in}}$	$\left(\frac{v}{v_0}\right)_{\text{out}}$	L (mg/cm^2)	T (psec)	$\Delta\theta$ (mrad)	g factor This work	g factor Radioactivity
^{120}Te	48.55	21.65	4.04	2.70	1.391	0.244	−7.9(9)	0.29(3)	
^{122}Te	47.08	21.08	3.94	2.65	1.380	0.248	−9.0(8)	0.33(3)	0.31(3)[a]
									0.39(3)[b]
									0.46(5)[c]
									0.34(7)[d]
^{124}Te	47.69	20.98	3.94	2.62	1.425	0.258	−7.4(8)	0.26(3)	0.21(5)[a]
									0.35(5)[e]
									0.27(13)[f]
^{126}Te	46.36	21.16	3.85	2.61	1.371	0.251	−5.1(8)	0.19(3)	
^{128}Te	45.90	16.20	3.80	2.27	1.44	0.344	−8.9(12)	0.31(4)	
^{130}Te	46.95	22.85	3.82	2.67	1.305	0.238	−7.3(15)	0.29(6)	

[a] Reference 9.
[b] Reference 10.
[c] Reference 11.
[d] Reference 12.
[e] Reference 13.
[f] Reference 14.

angles, and the deduced g factors are listed in Table II with the g factors derived from other (radioactivity) methods.[9–14] The radioactivity measurements of Bhattacherjee *et at.*[9] on the 2_1^+ levels of ^{122}Te and ^{124}Te agree best with the present results. The g factors are plotted in Fig. 2.

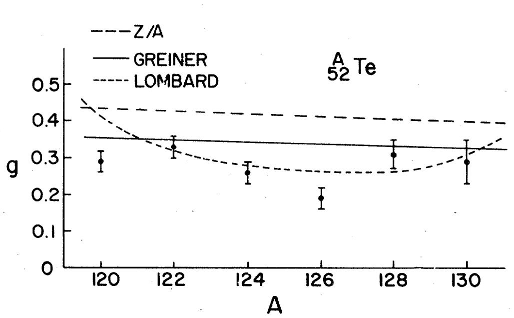

FIG. 2. g factors of the 2_1^+ states of Te isotopes. The dashed line represents the collective model estimate of $g = Z/A$. The solid line reflects the Greiner estimate. The dotted line corresponds to the Lombard quasiparticle calculation.

DISCUSSION

A plot of the g factors obtained for the different isotopes is shown in Fig. 2. The striking feature of the data is the minimum at ^{126}Te. This result suggests the presence of a mixture of collective and shell effects. The crude collective model prediction of Z/A overestimates the g factors. The Greiner formula,[15]

TABLE III. Comparison of the experimental g factors of the first 2^+ excited states of Te isotopes with theoretical estimates.

Isotope	$g_{2\,\text{expt}}^{+}$	$\frac{Z}{A}$	Greiner (Ref. 15)	Lombard (Ref. 16)
^{120}Te	0.29(3)	0.433	0.356	0.41
^{122}Te	0.33(3)	0.426	0.350	0.32
^{124}Te	0.26(3)	0.419	0.346	0.28
^{126}Te	0.19(3)	0.413	0.340	0.26
^{128}Te	0.31(4)	0.406	0.334	0.26
^{130}Te	0.29(6)	0.400	0.328	0.31

TABLE IV. Comparison of the measured g factors of the 2_1^+ excited states of Pd and Cd isotopes with the predictions of the quasiparticle model and the fitted g factors to the first order IBA model. N_ν and N_π are the numbers of neutron and proton bosons, respectively.

Nucleus	N_π	N_ν	$g_{2\,\mathrm{expt}}^{+}$ [a]	g factor $g_{2\,\mathrm{qp}}$ [b]	g_{IBA} [c]
^{102}Pd	2	3	0.41(4)	0.48	0.453
^{104}Pd	2	4	0.46(4)	0.50	0.422
^{106}Pd	2	5	0.398(21)	0.53	0.391
^{108}Pd	2	6	0.36(3)	0.57	0.360
^{110}Pd	2	7	0.31(3)	0.58	0.329
^{106}Cd	1	4	0.40(10)	0.41	0.389
^{108}Cd	1	5	0.34(9)	0.44	0.358
^{110}Cd	1	6	0.285(55)	0.47	0.327
^{112}Cd	1	7	0.32(8)	0.48	0.296
^{114}Cd	1	8	0.29(7)	0.47	0.265
^{116}Cd	1	7	0.30(7)	0.45	0.296

[a] Using $B(v,Z)=97\,Z^{1.1}(v/v_0)^{0.45}\mu_B N_p$. See Reference 2.
[b] Reference 16.
[c] $g=0.48-0.031N_\nu+0.033N_\pi$.

$$g=\frac{Z}{A}(1-\tfrac{4}{3}f)\,, \tag{2}$$

where

$$f=\frac{N}{A}\left[\frac{\beta_0(n)}{\beta_0(p)}-1\right],$$

$\beta_0(n)$ and $\beta_0(p)$ are the deformation parameters for neutrons and protons, respectively, and

$$\frac{\beta_0(n)}{\beta_0(p)}\approx 1.2$$

is represented by the solid line in Fig. 2.

Quasiparticle calculations have been carried out on the vibrational states of doubly even spherical nuclei within the framework of the BCS theory.

TABLE V. Comparison of the measured g factors of the 2_1^+ excited states of Te and Ba isotopes with the fitted g factors to the first order IBA model. N_ν and N_π are the numbers of neutron and proton bosons, respectively.

Nucleus	N_π	N_ν	$g_{2\,\mathrm{expt}}^{+}$ [a]	g factor g_{IBA} [b]	Ref.
^{120}Te	1	7	0.29(3)	0.213	
^{122}Te	1	6	0.33(3)	0.244	
^{124}Te	1	5	0.26(3)	0.275	This
^{126}Te	1	4	0.19(3)	0.306	work
^{128}Te	1	3	0.31(4)	0.337	
^{130}Te	1	2	0.29(6)	0.368	
^{130}Ba	3	4	0.35(3)	0.326	
^{132}Ba	3	3	0.34(3)	0.357	2
^{134}Ba	3	2	0.43(5)	0.388	
^{136}Ba	3	1	0.35(5)	0.419	

[a] Using $B(v,Z)=97Z^{1.1}(v/v_0)^{0.45}\mu_B N_p$.
[b] $g=0.42-0.031N_\nu+0.01N_\pi$.

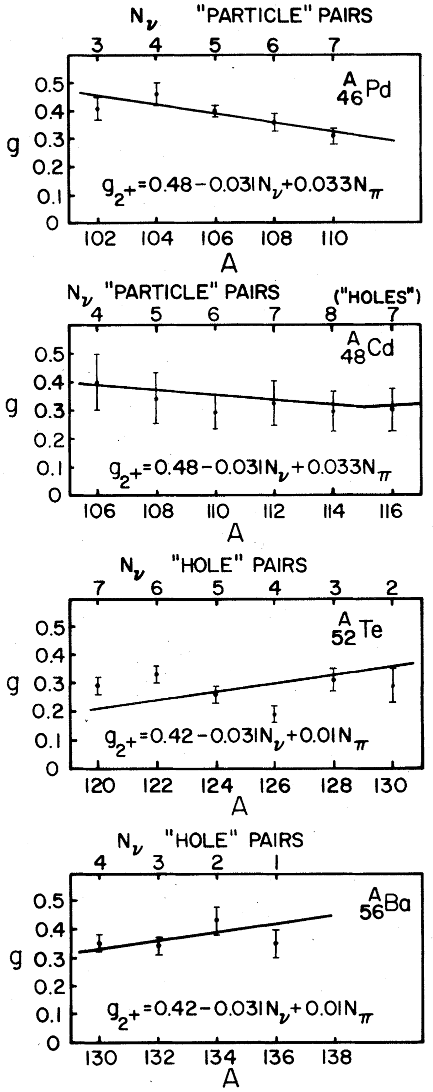

FIG. 3. g factors of the 2_1^+ states of Pd, Cd, Te, and Ba isotopes. The solid lines represent the best fits to Eq. (3).

The residual forces consist of a short-range pairing force acting only between neutron pairs coupled to spin zero and proton pairs coupled to spin zero. In addition to the short range pairing force, a long range quadrupole or octupole force is assumed, acting between neutron-neutron pairs, proton-proton pairs, and neutron-proton pairs. These assumptions, as well as the inclusion of particle-hole type core excitations, were used by Lombard[16] in the quasiparticle calculations of the g factors of the 2_1^+ states of even Pd, Cd, and Te nuclei. The results of the above calculations are presented in Tables III and IV. The Lombard calculation reproduces the overall trend in the data with a noticeable minimum around ^{126}Te, but grossly overestimates the magnitude and the trend of the magnetic moments of Pd and Cd isotopes.

Within the framework of the IBA model, in the SU(5) or vibrational limit, the g factors of the 2_1^+ states of even-even nuclei are given by the expression[17]

$$g_{2^+} = A + B_\nu N_\nu + B_\pi N_\pi , \qquad (3)$$

where A, B_ν, and B_π are constants and N_ν and N_π represent the number of neutron and proton bosons. We will consider the two pairs of nuclei Pd-Cd and Te-Ba. Since Pd and Cd contain neutron bosons that belong to the same major shell as those of Te and Ba, a simultaneous fit of the above equation to the Pd and Cd data produces a constant B_ν which can be used in the analysis of the Te and Ba data. Because the proton bosons of Pd and Cd are in a major shell that is different from that occupied by the proton bosons of Te and Ba, the constants A and B_π are expected to be different for the two cases.

A reanalysis of the data presented in Table IV from a previous experiment[2] on Pd and Cd nuclei yields the best fit to expression (3):

$$g = 0.48 - 0.031N_\nu + 0.033N_\pi ,$$

with a reduced chi square of 0.48. Using this value of $B_\nu = -0.031$, the Te and Ba data, which are presented in Table V, were simultaneously fitted to Eq. (3). The best fit to the data yields

$$g = 0.42 - 0.031N_\nu + 0.01N_\pi ,$$

with a reduced chi square of 6.0. The g factors arising from the fit of the data to Eq. (3) for Pd and Cd, and Te and Ba, are summarized in Tables IV and V, respectively. These values are plotted in Fig. 3.

It is clear from the simultaneous fit to the Te and Ba data that the IBA formula [Eq. (3)] cannot be fitted with the same measure of success as in the case of Pd and Cd. On the other hand, the precision of these data is sufficient to attempt to calculate higher order terms and to carry out microscopic calculations within the IBA framework in order to explain the deviations of the data from the general trends predicted by the theory.[18]

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[1]N. K. B. Shu, D. Melnik, J. M. Brennan, W. Semmler, and N. Benczer-Koller, Phys. Rev. C 21, 1828 (1980).
[2]J. M. Brennan, M. Hass, N. K. B. Shu, and N. Benczer-Koller, Phys. Rev. C 21, 574 (1980).
[3]G. M. Heestand, R. R. Borchers, B. Herskind, L. Grodzins, R. Kalish, and D. E. Murnick, Nucl. Phys. A133, 310 (1969).
[4]*Table of Isotopes 7th ed.*, edited by C. M. Lederer and V. S. Shirley (Wiley, New York, 1978), pp. 574—647.
[5]M. Hass, J. M. Brennan, H. T. King, and T. K. Saylor, Phys. Rev. C 14, 2119 (1976).
[6]J. M. Brennan, N. Benczer-Koller, M. Hass, and H. T. King, Phys. Rev. C 16, 899 (1977).
[7]J. M. Brennan, N. Benczer-Koller, M. Hass, and H. T. King, Hyp. Int. 4, 268 (1978).
[8]N. Benczer-Koller, M. Hass, and J. Sak, Annu. Rev. Nucl. Part. Sci. 30, 53 (1980).
[9]S. K. Bhattacherjee, J. D. Bowman, and E. N. Kaufmann, Phys. Lett. 24B, 65 (1967).
[10]K. Johansson, E. Karlsson, and R. W. Sommerfeldt, Phys. Lett. 22, 297 (1966).
[11]K. Auerback, B. Harns, K. Siepe, G. Wittkemper, and H. J. Korner, Phys. Lett. 22, 299 (1966).
[12]J. Murray, T. A. McMath, and J. A. Cameron, Can. J. Phys. 45, 1821 (1967).
[13]J. Murray, T. A. McMath, W. H. Brooker, and J. A. Cameron, Can. J. Phys. 45, 1600 (1967).
[14]E. Bozck, R. Broda, J. Golezewski, A. Z. Hrynkiewicz, R. Kulessa, S. Ogaza, M. Rybicka, and W. Walus in *Hyperfine Structure and Nuclear Radiation,* edited by E. Matthias and D. A. Shirley (North-Holland, Amsterdam, 1968), p. 158.
[15]W. Greiner, Nucl. Phys. 80, 417 (1966).
[16]R. J. Lombard, Nucl. Phys. A114, 449 (1968).
[17]A. Arima and F. Iachello, Ann. Phys. (N.Y.) 99, 253 (1976).
[18]F. Iachello (private communication).