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g factors of the 80 and 1094 keV states of ^{168}Er

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The g factors of the first excited and 1.094 MeV states of ^{168}Er have been obtained by the time integral and time differential perturbed angular correlation methods using two large volume Ge(Li) detectors. The results are found to be $g(2+)=0.31\pm0.03$ for the first excited state and $g(4-)=0.24\pm0.01$ for the 1.094 MeV state. These values are compared to the experimental results reported previously and to theoretical predictions.

[RADIOACTIVITY ^{168}Er level; measured $\gamma\gamma$ coin., $\gamma\gamma(\theta,t)$, deduced $T_{1/2}$, relaxation constants; measured $\gamma\gamma(\theta,H)$, $\gamma\gamma(\theta,H,t)$. TIPAC, TDPAC methods, deduced g.]

I. INTRODUCTION

^{168}Er is one of the typical deformed even-even nuclei, and excited states of this nucleus are described fairly well by the rotation-vibration model.

Besides the usual ground-state rotational band, three other bands have been identified in the spectrum, having $K\pi=2+$, 4−, and 3−, respectively. The 1.094 MeV level has been identified as the band head of a $K\pi=4-$ rotational band and may be represented by a configuration involving two neutrons in the Nilsson orbits (633 $\frac{7}{2}^+$) and (521 $\frac{1}{2}^-$).[1,2]

This observation is supported mainly by reaction studies,[3,4] but there is only one measurement of the g factor for this level that has reasonably small experimental errors.[5] Recently, two neutron resonance measurements have been reported, but these have large experimental errors.[6,7]

In general, the spin rotation method on gamma radiation from radioisotope decay can be carried out with rather small experimental errors compared with the results of the neutron resonance method. However, it is fairly difficult to measure the g factor of the 1.094 MeV level populated in the ^{168}Tm decay, as the strong 448–198 keV cascade has a very small anisotropy.

In the present work, two large volume Ge(Li) detectors were used, and the time differential spin rotation measurement has been performed in HI solution for the 448-830 keV cascade whose anisotropy was expected to be larger, by about a factor of 7 than that of the 448-198 keV cascade. The time integral rotated angular correlation measurement for the 816-80 keV cascade has also been carried out, and the g factor of the first excited state was evaluated.

These results were compared with others obtained so far.[8-11] Furthermore, the results from the time differential perturbed angular correlation measurement have been examined in order to determine the relaxation time in the HI solution.

The time integral rotated angular correlation and time differential spin rotation measurements were carried out at the Research Laboratory of Nuclear Science, Tohoku University, while the time differential perturbed angular correlation was measured at the Faculty of Science, Niigata University.

II. EXPERIMENTS

A. Source preparation

A source of about 30 μCi of the 93 day ^{168}Tm isotope was produced by the electron linac at the Research Laboratory of Nuclear Science, Tohoku University. A Tm target was bombarded with 60 MeV photons for 48 hours.

The measurements were carried out about two months after irradiation, in order to let the ^{167}Tm ($T_{1/2}=9.6$ d) activity decay. The source needed for the time integral measurement was dissolved in HNO_3 solution, while the source used for the time differential measurements was dissolved in HI solution. The liquid solutions were then placed in plastic source holders which had holes with 0.4 cm inner diameter and 0.7 cm length. The source to detector distance was 6.8 cm.

B. Experimental apparatus and measurements

Two large volume Ge(Li) detectors were used for the time integral angular correlation and the time differential spin rotation measurements. One detector was a true coaxial type, 80 cm^3 in volume, having a resolution of 2.2 keV [full width at half maximum (FWHM) at 1.33 MeV]; the other was a single ended coaxial type, 70 cm^3 in volume, having a resolution of 2.4 keV (FWHM at 1.33 MeV).

Coincidence data were taken with a fast-slow coincidence system utilizing constant fraction timing. The resulting data were corrected for accidental coincidence and for finite solid angle of the detectors. The finite solid angle corrections were calculated with a high speed computer by the Monte Carlo method for each energy and source-detector distance.

An external magnetic field directed either up or down with respect to the plane of the gamma rays was applied to the source, which was placed in the gap of the pole pieces of the magnet.

For the time integral angular correlation measurement, the coincidence counting rates for the 816-80 keV cascade were accumulated automatically at seven angles from 90–225° with respect to the symmetry axis of the two detectors. The magnitude of the external magnetic field, 7300 ±100 Gauss, was maintained constant throughout the time period of data accumulation.

The energy was taken from a timing single channel analyzer with a window set at 816 ±3 keV, and the time to pulse height converter was adjusted to provide a resolving time of about 60 nsec. The measurements were carried out in 10 runs of 8192 sec duration for each angle and for each field direction, and about 20 000 counts were obtained at 90°. The data were then least square fitted to derive $\Delta\theta_2$, $\Delta\theta_4$, b_{22}, and b_{44} values which were defined by equations (1) and (2),[12-14]

$$W(\theta,B)=1+\frac{b_{22}}{[1+(2\omega_B\tau)^2]^{1/2}}\cos 2(\theta-\Delta\theta_2)+\frac{b_{44}}{[1+(4\omega_B\tau)^2]^{1/2}}\cos 4(\theta-\Delta\theta_4)\ , \qquad (1)$$

$$\tan(N\Delta\theta_N)=N\omega_B\tau\ , \qquad (2)$$

where ω_B and τ are the Larmor precession frequency and the mean life of the intermediate state, respectively.

On the other hand, for the time differential spin rotation measurements, the two detectors were separated by constant angle 135°, and the total coincidence counting rates of seven days for each field direction were obtained for the 448-830 keV cascade. An external magnetic field of 8900 ±100 G was applied in this case. Let the coincidence rates be $W(t,\ B+,\ 135°)$, $W(t,\ B-,\ 135°)$ for the up and down directions of the magnetic field, respectively; a ratio $C(t,\ B,\ 135°)$ was defined the usual way be Eq. (3)[13,14]:

$$C(t,B,\ 135°)=\frac{2[W(t,B+,135°)-W(t,B-,135°)]}{W(t,B+,135°)+W(t,B-,135°)}\ . \qquad (3)$$

For the two Ge(Li) detectors system, the prompt time distribution was measured by taking two pairs of energy bands selected with ^{22}Na source. One pair involved the two photopeaks of the positron annihilation 511 keV γ rays and the other was taken by selecting the photopeak of the positron annihilation 511 keV γ ray in the 70 cm^3 Ge(Li) detector, and the 99.0 ±1.5 keV region of its Compton continuum in the 80 cm^3 Ge(Li) detector. In the former case, a resolving time of 9.2 ±0.2 nsec was obtained, and it was assumed to be roughly equal to the resolving time for the 448-830 keV cascade case. In the latter case, a time resolution of 16.2 ±0.5 nsec was obtained.

For the relaxation time measurement, a 35 cm^3 Ge(Li) detector for the 448 keV transition and a 3.8 cm×0.64 cm NaI(Tl) crystal for the 99 keV transition were used.

The coincidence counting rates for the 448-99 keV cascade were taken at 90° and 180°, with respect to the symmetry axis of the two detectors, and the measurements were carried out in 7 runs of two days for each angle. Let the coincidence rates be $W(t,90°)$, $W(t,180°)$ for the 90° and 180° angle settings, respectively; a ratio $\overline{A}(t)$ was defined by Eq. (4):

$$\overline{A}(t)=\frac{2[W(t,180°)-W(t,90°)]}{W(t,90°)+W(t,180°)}\ . \qquad (4)$$

A prompt time distribution was measured with a ^{60}Co source. The resolving time in this case was 6.0 ±0.5 nsec.

III. RESULTS

Figure 1 shows the partial level scheme of ^{168}Er in which the thick arrows are related to several transitions measured in this experiment.[15]

The single spectra measured with the 80 cm^3 Ge(Li) detector and with the NaI(Tl) crystal are shown in Figs. 2 and 3, respectively. Again, only the energy values which are related to present experiments are indicated with arrows.

The time integral angular correlations are shown in Fig. 4. The angular coefficients A_{22} and A_{44} for the 816-80 keV cascade have been measured by several authors. The values

$$A_{22}=-0.157\pm0.008,$$

$$A_{44}=-0.09\pm0.02\ ,$$

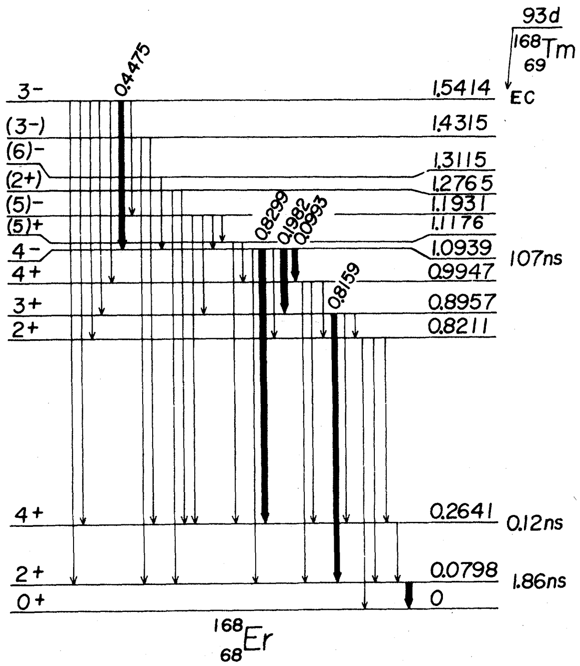

FIG. 1. Partial level scheme of ^{168}Er taken from Table of Isotopes (Ref. 15).

have been obtained by Behar *et al.* recently.[16]

Because the A_{44} value is not negligibly small, it is necessary to take into account the $k=4$ term in the polynomial expansion for the data analysis and to use explicitly Eqs. (1) and (2). The fitted values for Eq. (1) were as follows:

$\Delta\theta_2 = 0.195 \pm 0.015$ rad ,

$\Delta\theta_4 = 0.176 \pm 0.042$ rad ,

$b_{22} = -0.105 \pm 0.004$ (not corrected for solid angle),

$b_{44} = -0.022 \pm 0.005$ (not corrected for solid angle).

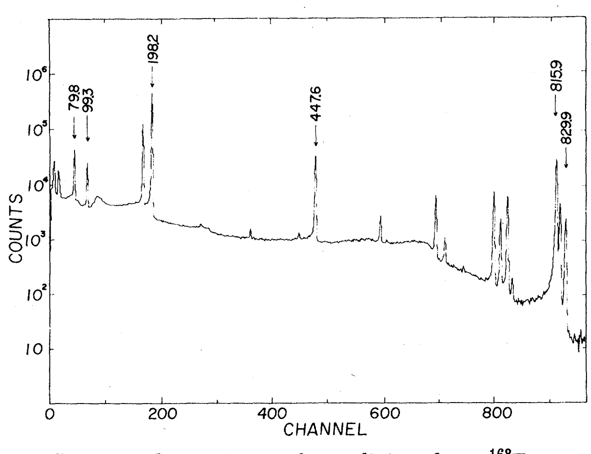

FIG. 2. Single spectrum of γ radiation from ^{168}Tm decay obtained with the 80 cm^3 Ge(Li) detector.

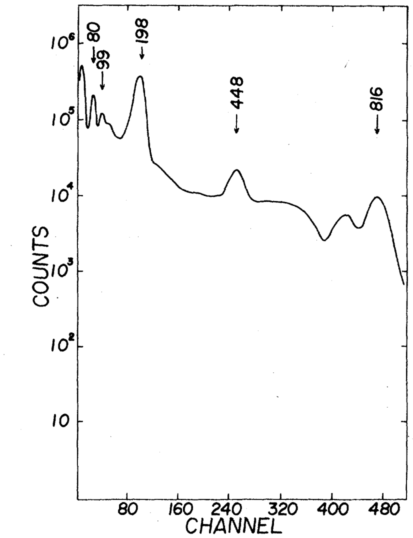

FIG. 3. Single spectrum of γ radiation from ^{168}Tm decay obtained with an NaI(Tl) detector of 3.8 cm diameter by 0.64 cm long.

Using Eq. (2), $\omega_B\tau$ was calculated:

$\omega_B\tau = 0.206 \pm 0.016$ rad (from $\Delta\theta_2$) ,

$\omega_B\tau = 0.21 \pm 0.05$ rad (from $\Delta\theta_4$) .

The mean life $\tau = 2.68$ nsec was taken from the Table of Isotopes.[15] A paramagnetic correction factor 6.97 (20°C) (Ref. 17) was used to obtain the *g* factor of the first excited state:

$g(2+) = 0.31 \pm 0.03.$

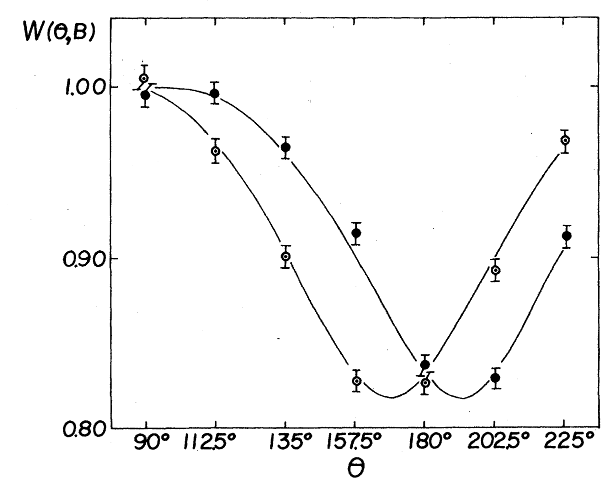

FIG. 4. Time integral angular correlation for the 816-80 keV cascade obtained with two Ge(Li) detectors. The open and closed circles indicate the up and down magnetic field directions, respectively. No correction is made for finite solid angle in this figure.

This result is shown in Table I and is compared with the measured values by several authors; each experimental method is also indicated.

Comparing experimentally obtained b_{22} and b_{44} values with A_{22} and A_{44} values, and taking into account the solid angle corrections, the attenuation coefficients G_{22}, G_{44} and the relaxation constants λ_2, λ_4 can be assigned.

If we adopt the values by Behar *et al.* for A_{22} and A_{44} coefficients,

$$G_{22} = 0.90^{+0.03}_{-0.04}, \quad G_{44} = 0.70^{+0.15}_{-0.16},$$

$$\lambda_2 = (4.3 \pm 1.6)\times 10^7 \text{ sec}^{-1}$$

and

$$\lambda_4 = (1.6^{+1.6}_{-1.0})\times 10^8 \text{ sec}^{-1}$$

are obtained.

From these results, it is inferred that the magnetic interaction is predominant in the HNO_3 solution.[18]

The prompt distribution curve obtained with the two Ge(Li) detectors system is shown in Fig. 5, and the delayed curve of 1.094 MeV level for the intense 448-198 keV cascade is shown in Fig. 6. From this delayed curve, we assign the half-life $T_{1/2} = 112.5 \pm 1.0$ nsec, which agrees with previous results.[5,19]

Sufficiently long relaxation time is needed in order to observe clearly the spin rotation effect by the time differential method. Until recently, several reports pointed out the long relaxation time in the HF solution in which minimum extra perturbations are seen.[16,20] So we tried to measure with the source in the HF solution, but since HF acid has very small solubility for Tm metal, we could not have sufficiently intense source activity.

In several relaxation time measurements with various kinds of solutions, we found that the relaxation time in the HI solution, which has a large solubility for Tm metal, was as long as in the HF solution. The time dependence behavior of the anisotropy $\bar{A}(t)$ for the 448-99 keV cascade in the HI solution is shown in Fig. 7. Since the coefficient A_{44} is negligible small in this cascade, it is sufficient to consider only the attenuation coefficient $G_{22}(t)$ for the attenuation. $G_{22}(t)$ would be expressed by relaxation constant λ_2 as follows:

$$G_{22}(t) = e^{-\lambda_2 t} .$$

TABLE I. The results of *g*-factor measurements for the first excited state by several authors and present experiments. Experimental methods for each measurement are shown also.

Level energy (keV)	*g* factor	Method	Reference
	0.31 ±0.03	IPAC[a]	Present
	0.27 ±0.03	IPAC[a]	8
79.8	0.333±0.0008	ME[b]	9
	0.305±0.010	RIGV[c]	10
	0.348±0.029	CETD[d]	11

[a] IPAC: Time-integral perturbed (rotated) angular correlation.
[b] ME: Mössbauer effect.
[c] RIGV: Recoil into gas and/or vacuum.
[d] CETD: Time-differential perturbed angular distribution of γ rays following Coulomb excitation.

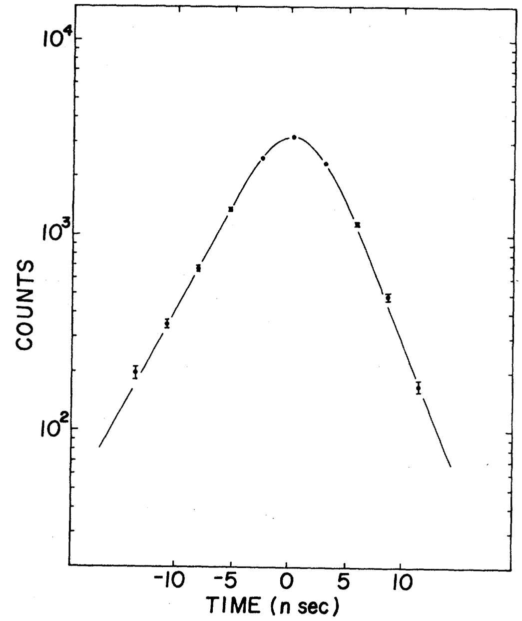

FIG. 5. Prompt time distribution for the 511-511 keV positron annihilation γ rays obtained with two Ge(Li) detectors and an ^{22}Na source.

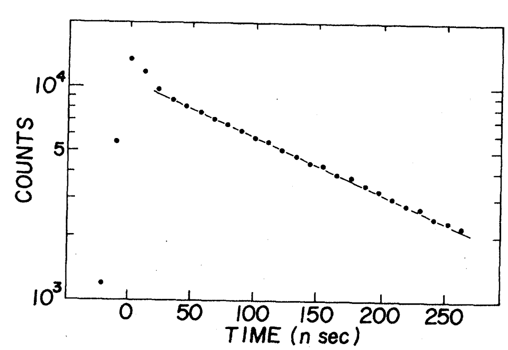

FIG. 6. Delayed time coincidence spectrum for the 448-198 keV cascade obtained with two Ge(Li) detectors.

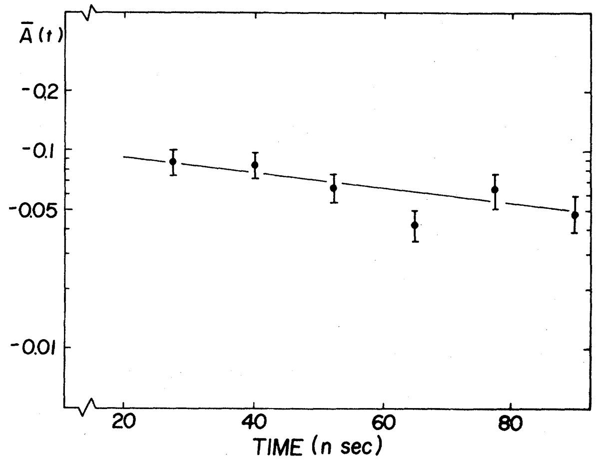

FIG. 7. Time differential perturbed angular correlation for the 448-99 keV cascade obtained with the 35 cm^3 Ge(Li) detector and the NaI(Tl) detector. No correction is made for finite solid angle in this figure.

The best fit obtained from the curve in Fig. 7 gives

$$\lambda_2 = (0.81 \pm 0.25)\times 10^7 \text{ sec}^{-1} .$$

This result corresponds to the value (0.75 ±0.10) $\times 10^7$ obtained in HF solution by Behar *et al.*

The spin rotation measurement for the 448-830 keV cascade by the time differential method is shown in Fig. 8. The spin rotation effect is clearly seen. Since the two Ge(Li) system was utilized, a narrow energy region for the two γ transitions could be selected, and, moreover, since the resolving time was approximately as short as for large Ge(Li) detectors, it is assumed that this measurement was not much affected by the competing γ-γ cascades.

The mixing ratios δ of the 448 and 830 keV transitions have been reported recently to be $-0.06 \geq \delta \geq -0.17$ and $0.01 \geq \delta \geq -0.09$ by Behar *et al.*, and using these values, the angular coefficient A_{22} is evaluated to be $-0.098 \leq A_{22} \leq 0.002$. Moreover, Behar *et al.* have assigned the coefficient $A_{22} = -0.07 \pm 0.01$ for the 448-99 keV cascade and the mixing ratio $\delta = -0.06 \pm 0.05$ for the 99 keV transition. If these values are taken into account, the A_2 value is calculated to be $0.18 \geq A_2 \geq 0.12$ for the 448 keV transition and then, the coefficient A_{22} for the 448-830 keV cascade is evaluated as $-0.051 \geq A_{22} \geq 0.088$. Our result is approximately consistent with this value.

It is expected that the coefficient A_{44} is negligibly small in this cascade and the time dependence behavior would be expressed by Eq. (5):

$$C(t, B, 135^\circ) = \frac{12A_{22}\sin 2\omega_B t}{8 + 2A_{22}} . \quad (5)$$

From the best fit of the data to Eq. (5), the precession frequency was obtained in an external applied magnetic field:

$$\omega_B = (7.3 \pm 0.3)\times 10^7 \text{ sec}^{-1} .$$

This value yields $g(4-) = 0.24 \pm 0.01$, and the sign is assigned to be positive from the observation of the direction of the spin rotation with respect to the applied field direction and of the sign of the A_{22} coefficient. This result is shown in Table II and is compared again to the values measured up to now.

IV. DISCUSSION

The g factor for the first excited state of the present experiment agrees with the previous data shown in Table I, and particularly agrees with the results of the RIGV (recoil into gas and/or vacuum) and ME (Mössbauer effect) methods. We think that our result is better than previous results by the IPAC [time-integral perturbed (rotated) angular correlation] method, because we measured with two Ge(Li) detectors and the data analysis was done by solving explicitly the relevant equations; the error in the $\Delta\theta_2$ assignment due to the

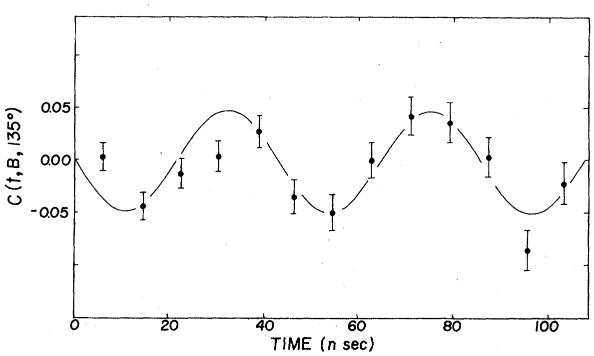

FIG. 8. Time differential spin rotation behavior for the 448-830 keV cascade obtained with two Ge(Li) detectors. No correction is made for finite solid angle in this figure.

TABLE II. The results of g-factor measurements for the 1.094 MeV state by several authors and present experiments. Experimental methods for each measurement are shown also.

Level energy (keV)	g factor	Method	Reference
	0.24± 0.01	DPAC[a]	Present
1093.9	0.45 ± 0.02	DPAC[a]	5
	−0.11 ± 0.18	NRES[b]	6
	0.22 ± 0.10	NRES[b]	7

[a] DPAC: Time-differential perturbed (spin rotation) angular correlation.

[b] NRES: Neutron resonance energy shift.

perturbation effect by internal fields,[13] and to the contribution from the $k=4$ term in the polynomial expansion, is very small.

On the other hand, it is found that there are considerable differences in the results for the g factor of the 1.094 MeV state, as shown in Table II. Our result is consistent with the data by Alfimenkov *et al.*, who utilized a NRES method, but is inconsistent with the data by Kim *et al.*, who used the ^{168}Tm decay.

The 1.094 MeV level has been assigned to be $I=4$ and identified as the band head of a $K\pi=4-$ rotational band as mentioned before, and the (d,p) reaction studies suggest this level to be represented by a configuration involving two quasineutrons in Nilsson orbits having $\Omega=(633\ \frac{7}{2}^+)+(521\ \frac{1}{2}^-)$. The g factor for this configuration can be obtained from so-called additive theory which is given by Eq. (6),[21-23]

$$g(I)=\tfrac{1}{2}(g_1+g_2)+\frac{j_1(j_1+1)-j_2(j_2+1)}{2I(I+1)}(g_1-g_2)\ , \quad (6)$$

where $g(I)$ is the g factor of a state I, which is a two particle configuration with the spins j_1 and j_2 and the g factors g_1 and g_2, respectively. The value of the g factor is thus calculated to be $g(4-)=-0.013$ using $g[^{167}\mathrm{Er},\ (633\ \frac{7}{2}^+)_n]=-0.162$ and $g[^{169}\mathrm{Er},\ (521\ \frac{1}{2}^-)_n]=1.03$, which were obtained experimentally for the neighboring odd neutron nuclei. It appears that the resulting g cannot be interpreted with the above configuration completely, and therefore one should take into account the two quasiprotons state, which is reasonably assigned to be $(523\ \frac{7}{2}^-)_p$ and $(411\ \frac{1}{2}^+)_p$. Then the g factor of the 1.094 MeV state can be explained by a mixture of about 30% of the quasiprotons state configuration, with $g[^{165}\mathrm{Ho},\ (523\ \frac{7}{2}^-)_p]=1.19$ and $g[^{169}\mathrm{Tm},\ (411\ \frac{1}{2}^+)_p]=-0.643$ which were obtained experimentally in neighboring proton odd mass nuclei.

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[1]A. Bohr and B. R. Mottelson, *Nuclear Structure* (Benjamin, Reading, Mass., 1975), Vol. II.
[2]W. Michaelis, H. Ottmar, and F. Weller, Nucl. Phys. A150, 161 (1970).
[3]L. M. Bollinger and G. E. Thomas, Phys. Rev. C 2, 1851 (1970).
[4]R. A. Harlan and R. K. Sheline, Phys. Rev. 160, 1005 (1967).
[5]B. T. Kim, W. K. Chu, and J. C. Glass, Phys. Rev. C 8, 1920 (1973).
[6]K. H. Beckurts and G. Brunhart, Phys. Rev. C 1, 726 (1970).
[7]U. P. Alfimenkov *et al.*, Yad. Fiz. 17, 13 (1973) [Sov. J. Nucl. Phys. 17, 6 (1973)].
[8]E. Bodenstedt, H. J. Korner, E. Gerdau, J. Radeloff, L. Mayer, R. Auerbach, J. Braunsfurth, and G. Mielken, Z. Phys. 170, 355 (1962).
[9]E. Münck, Z. Phys. 208, 184 (1968).
[10]I. Ben-zvi, M. B. Goldberg, G. Goldring, K. H. Speidel, and A. Sprinzak, Nucl. Phys. A151, 401 (1970).
[11]J. D. Kurfess and R. P. Scharenberg, Phys. Rev. 161, 1185 (1967).
[12]E. Bodenstedt, in *The Electromagnetic Interaction in Nuclear Spectroscopy*, edited by W. D. Hamilton (North-Holland, Amsterdam, 1975), p. 738.
[13]E. Bodenstedt, in *Perturbed Angular Correlations*, edited by E. Karlsson, E. Matthias, and K. Siegbahn (North-Holland, Amsterdam, 1964), p. 217.
[14]H. Frauenfelder and R. M. Steffen, in *Alpha–Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland, Amsterdam, 1974), Vol. 2, p. 1153.
[15]*Table of Isotopes, 7th edition*, edited by C. M. Lederer and V. S. Shirley (Wiley, Interscience, New York, 1978).
[16]M. Behar, L. M. Quinones, and Z. W. Gravowski, Z. Phys. 274, 359 (1975).
[17]C. Günther and I. Lindgen, in *Perturbed Angular Correlations*, edited by E. Karlsson, E. Matthias, and K. Siegbahn (North-Holland, Amsterdam, 1964), p. 357.
[18]H. F. Wagner, M. Popp, and M. Forker, Z. Phys. 248, 195 (1971).
[19]C. Günther and D. R. Parsignault, Phys. Rev. 153, 1297 (1967).
[20]F. C. Zawislak, D. E. Brandao, A. Vasquez, and F. P. Livi, Phys. Lett. 7, 337 (1963).
[21]E. Bodenstedt, Hyp. Int. 2, 1 (1976).
[22]P. J. Brussaard and P. W. M. Glaudemans, *Shell Model Applications in Nuclear Spectroscopy* (North-Holland, Amsterdam, 1977), p. 256.
[23]E. Ejiri, G. B. Hagemann, and T. Hammer, in *Proceedings of the International Conference on Nuclear Moments and Nuclear Structure*, edited by H. Horie and K. Sugimoto (Physical Society of Japan, Tokyo, 1972), p. 428.