Parity Mixing and Nuclear Structure in the Decays from Oriented $^{153,159}Gd$ and ^{161}Tb†

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(Received 9 August 1971)

Measurement of the angular distribution of the 363-keV γ radiation following the decay of ^{159}Gd oriented in $GdFe_2$ at low temperatures has yielded a vanishing value of the parity-nonconserving forward-backward asymmetry, indicating in this transition no large effect resulting from the parity-violating weak nucleon-nucleon interaction. Vanishing asymmetries were observed for other strongly hindered transitions in ^{159}Tb and in ^{161}Dy. The 0–90° anisotropy of the 363-keV angular distribution has yielded a value for the magnetic moment of the ^{159}Gd ground state of $\mu = (-0.44 \pm 0.03)\mu_N$. The magnitude of the hyperfine field of Tb in $GdFe_2$ has been estimated to be 370 ± 80 kG, based on observation of the 0–90° anisotropy of γ transitions in ^{161}Dy. The multipole characters of various β and γ transitions following the decay of oriented $^{153,159}Gd$ and ^{161}Tb have been deduced.

I. INTRODUCTION

Recent investigations of the forward-backward asymmetry in the γ radiation from polarized nuclei[1] and of the circular polarization of γ radiation from unpolarized nuclei[2-4] have demonstrated small, but definitely nonvanishing parity admixtures in nuclear states. These admixtures help to substantiate the Feynman-Gell-Mann current-current theory of weak interactions.[5,6] Comprehensive reviews of earlier parity experiments are found in the literature.[7-8]

Previous investigation[9] of the angular distribution of the 363-keV γ radiation following the β decay of oriented ^{159}Gd suggested an observable forward-backward asymmetry, but these measurements suffered from a relatively large statistical error. Later circular polarization measurements[4] indicated that a smaller asymmetry would be expected. The present investigation was undertaken to reduce the experimental uncertainty in the asymmetry measurements by a factor of 5.

In addition to the 363-keV γ ray of primary interest, the angular distributions of the 58-, 226-, and 348-keV transitions of ^{159}Tb were also measured. Since ^{153}Gd and ^{161}Tb (produced following the 4-min decay of ^{161}Gd), as well as ^{159}Gd, result from the neutron activation of natural gadolinium, it proved convenient to investigate the angular distributions of the 96- and 103-keV transitions in ^{153}Eu and the 49-, 57-, and 75-keV transitions in ^{161}Dy. Various pieces of nuclear-structure information can be extracted from these other measurements, notably γ-ray multipole mixing ratios, angular momentum multipolarities of various (unobserved) β radiations, and the hyperfine energy splitting of the parent state.

II. LEVEL SCHEMES

The partial decay schemes of $^{153,159}Gd$ and ^{161}Tb to levels of ^{153}Eu, ^{159}Tb, and ^{161}Dy, respectively, are illustrated in Figs. 1–3,[10] which include the

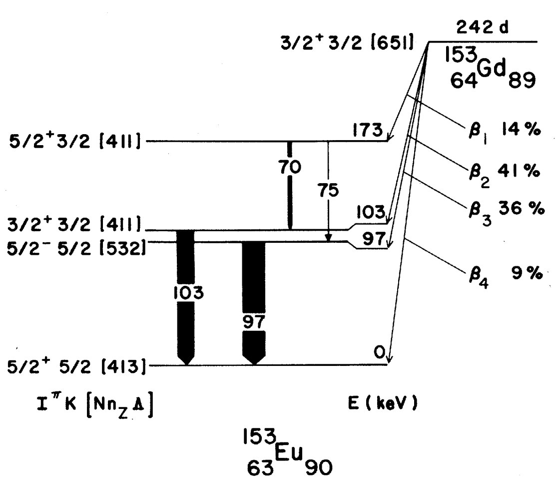

FIG. 1. Partial decay scheme of ^{153}Gd.

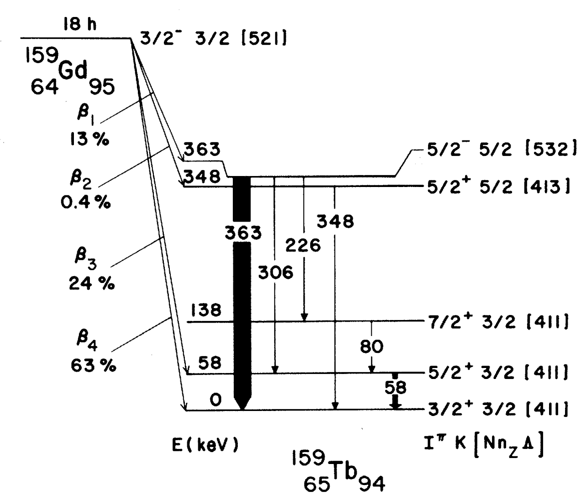

FIG. 2. Partial decay scheme of ^{159}Gd.

Nilsson assignments for the levels involved in the present work. The details of the ^{153}Eu level scheme, populated by the electron-capture decay of ^{153}Gd, have been established[11–13] through investigation of γ and conversion-electron spectroscopy[12–14] and through γ-γ directional correlations.[11] The β decay of ^{159}Gd to levels in ^{159}Tb and the radiations of ^{159}Tb have been investigated by γ and conversion-electron spectroscopy,[15,16] Coulomb excitation,[17] γ-ray coincidence studies,[18] nuclear resonance fluorescence,[19] and γ-γ directional correlations.[20] The low-energy γ transitions following the β decay of ^{161}Tb to levels in ^{161}Dy have been investigated through studies of the γ rays,[21,22] conversion electrons,[23] and through γ-γ directional correlations.[24,25]

III. EXPERIMENTAL

Nuclear polarization was achieved through a combination of ultralow temperatures and high magnetic fields. A ^{3}He-^{4}He dilution refrigerator was used to produce temperatures around 18 mK, and the sample used, $GdFe_2$, was selected to have a large hyperfine field (+453 kG) at the Gd nuclei.[26] A much smaller field, about 2 kG, was used to establish the hyperfine field direction. The apparatus has been described in detail in a previous work.[27]

The $GdFe_2$ samples were shaped in the form of thin elongated disks with approximate dimensions 0.4 mm thick, 2 mm wide, and 6 mm long. These samples were shown by x-ray analysis to be single-phase polycrystals of pure $GdFe_2$. They were neutron activated in the Los Alamos Omega West Reactor with an integrated flux of 2×10^{17} neutrons/cm^2. Following the irradiation, the samples were annealed at 800°C for one-half an hour.

The angular distributions of the γ rays were measured by intermittently rotating the external magnetic field among 0, 90, and 180° counting angles. Most of the data were taken at the 0 and 180° positions, since the parity mixing, determined by the forward-backward asymmetry, requires greater statistical accuracy than the information derived from the normal polar-equitorial anisotropy. Data from two stationary 40-cm^3 Ge(Li) γ-ray detectors were collected for about 15 min between field rotations. The data were stored in two multichannel analyzers and printed out whenever the field direction was changed. Figure 4 shows a typical γ-ray spectrum.

The radiation intensity W as a function of the angle θ relative to the direction of nuclear orientation can be written[28]

$$W(\theta)=\sum_k B_k U_k A_k Q_k P_k(\cos\theta)\,. \qquad (1)$$

The expansion is in terms of Legendre polynomials, P_k. The B_k give the orientation of the initial state, the U_k show the depolarization due to preliminary decays, the A_k describe the γ ray in question, and the Q_k correct for the finite solid angle of the detector.[29] Equation (1) is normalized so that $B_0=U_0=A_0=Q_0=1$.

In the absence of parity mixing, only even-k terms appear in Eq. (1), and at the temperatures reached in the present work all terms with $k\geqslant 3$ could be neglected. The parity mixing appears as a nonvanishing $k=1$ term. The actual data analysis proceeded along the same lines as described

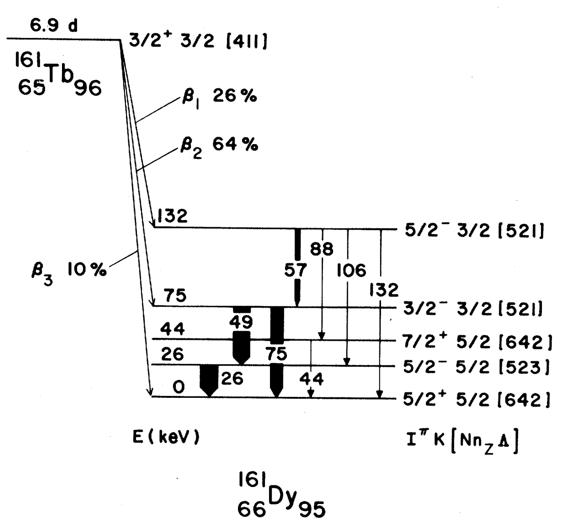

FIG. 3. Partial decay scheme of ^{161}Tb.

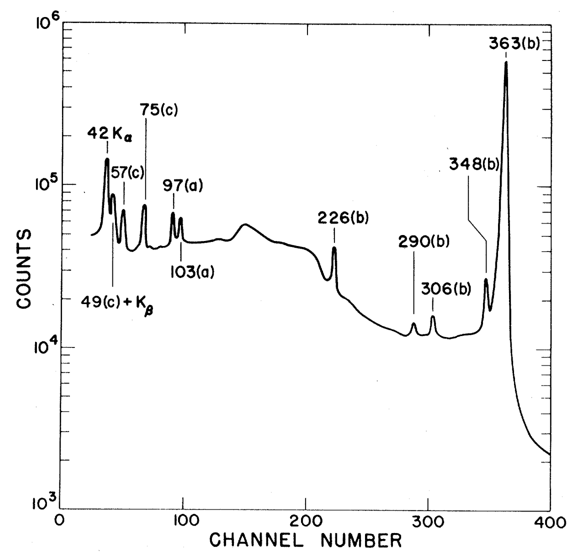

FIG. 4. Ge(Li) detector γ-ray spectrum of neutron-activated Gd: (a) ^{153}Gd, (b) ^{159}Gd, and (c) ^{161}Tb.

in Ref. 27, in which the asymmetry for a given point was computed by comparing the counting rate for that point with a logarithmic interpolation of the field-reversed point before and after the given point. The logarithmic interpolation procedure is necessary because of the length of the counting periods (15–20 min) relative to the half-life of the sample (18 h).

IV. RESULTS

A. Parity Impurities

The results derived for the coefficients of the P_1 term in the angular distribution are presented in Table I. These results have been corrected for a small asymmetry in the angular distribution from unpolarized samples at 1°K or at 4°K; this asymmetry (probably due to slight motion of the source) amounted to a correction of $(1.6 \pm 0.9) \times 10^{-4}$ for sample I and $(1 \pm 1) \times 10^{-4}$ for sample II. The orientation parameters B_1 were derived from the values of B_2 deduced from the measured 0–90° anisotropy as discussed below. The sign of B_1 was determined from the sign of the magnetic moment assumed in Ref. 9. The average of all measurements of the parity-violating asymmetry A_1 shows a vanishing value, in good agreement with the results based on measurements of the circular polarization of radiation from unpolarized sources.[4] It can be concluded that the parity-violating weak interaction produces no laboratory effect on the 363-keV γ transition of ^{159}Tb within the limits of the present experiment.

The computation of the forward-backward asymmetry $\mathcal{A} = [W(0°) - W(180°)]/W(0°)$ for the strongly hindered 226- and 348-keV γ transition in ^{159}Tb and the 49- and 75-keV transitions in ^{161}Dy likewise yielded vanishing values, indicating the absence of any observable parity-violating effect. The values measured were $\mathcal{A}$ (^{159}Tb, 348 keV) $= +0.0017 \pm 0.0050$, $\mathcal{A}$ (^{159}Tb, 226 keV) $= -0.0012 \pm 0.0040$, $\mathcal{A}$ (^{161}Dy, 49 keV) $= -0.0030 \pm 0.0032$, $\mathcal{A}$ (^{161}Dy, 75 keV) $= -0.0002 \pm 0.0020$.

B. Nuclear Structure

^{153}Eu

97 keV. The 97-keV radiation has been determined to be of $E1$ multipolarity by measurement of its internal-conversion coefficient.[13] Assuming the hyperfine splitting of the ^{153}Gd to be similar to that of ^{159}Gd, the B_2 for ^{153}Gd will probably be within a factor of 2 of that of the ^{159}Gd as derived below. With the A_2 coefficient for a pure $E1$ ($\frac{5}{2}^- - \frac{5}{2}^+$) transition, we therefore estimate $U_2(\beta_2) = 0.21 \pm 0.18$, based on the measured value presented in Table II. Since $U_2(\frac{3}{2}^+ - \frac{5}{2}^- \beta) = 0.748 |\alpha_1|^2 - 0.107 |\alpha_2|^2$ (where $|\alpha_L|^2$ is the amplitude of the Lth multipole component in the β radiation field, normalized such that $\sum_L |\alpha_L|^2 = 1$), we estimate, under the above assumption, $|\alpha_2(\beta_2)|^2 = 0.63 \pm 0.28$, indicating most of the β_2 transitions carry two units of angular momentum. Although the β transition violates the Nilsson selection rule[30] for a $\Delta K = 1$ transition (Nilsson asymptotic selection rules require $\Delta n_Z = 0$, while we have $\Delta n_Z = 2$ for β_2), the

TABLE I. Parity-nonconserving forward-backward asymmetry of the ^{159}Tb 363-keV γ ray.

Reference	Experimental asymmetry [a] $B_1 U_1 A_1$ (units of 10^{-4})	Gd polarization [a] ($-0.74 B_1$)	Parity-violating angular distribution coefficient A_1 (units of 10^{-4})
Present work, sample I	$+0.7 \pm 1.7$	0.135	4 ± 10
Present work, sample II	3.9 ± 3.0	0.15	21 ± 16
	-1.2 ± 1.7	0.19	-5 ± 7
	-1.3 ± 2	0.23	-5 ± 7
		Average of present work	-3.0 ± 4.3
Previous nuclear orientation results [b]	$+2.7 \pm 1.8$	0.07	31 ± 21
		Average of nuclear orientation work	-1.6 ± 4.2
Circular polarization results [c]			-1 ± 5

[a] Defined with respect to the direction of nuclear polarization, opposite to the direction of the applied field.
[b] Reference 9.
[c] Reference 4.

small expected deformation of this nucleus casts doubt on the validity of the asympototic selection rules. However, the large fraction of the β decays which carry two units of angular momentum suggests that the Nilsson selection rules may indeed have some influence on the β radiation field.

103 keV. Results of measurements of the 70–103-keV γ-γ directional correlation[11] showed a vanishing anisotropy. Since both γ rays are expected to be of $M1$ character with small $E2$ admixtures, it is impossible from the directional-correlation data alone to determine whether the vanishing anisotropy is due to the B_k of the 70-keV radiation of the A_k of the 103-keV radiation. Since the present work measures the same A_k(103 keV) as does the γ-γ correlation, the nonvanishing of the $B_2 U_2 A_2$ result of the present work implies a vanishing B_2(70 keV) in the directional-correlation results,[11] from which we derive the $E2/M1$ mixing ratio

$$\delta(70\text{ keV}) = +0.085 \pm 0.006\,.$$

The γ-ray mixing ratios are defined according to the phase convention of Krane and Steffen,[31] in which the interference term in the expression for A_k is written with a positive sign and the corresponding term in B_k with a negative sign. From the $B_2 U_2 A_2$ value of the 103-keV transition, using the above estimate for B_2, and estimating a U_2 value from the branching intensities with the multipole character of β_1 taken to be $(50 \pm 50)\%$ $L=1$, we estimate $A_2(103\text{ keV}) = 0.42 \pm 0.16$ from which estimate we obtain the $E2/M1$ mixing ratio of the 103-keV transition, $\delta(103\text{ keV}) = 0.27 \pm 0.13$. Although the value of A_2 yields two values of δ, the second value $(+11^{+\infty}_{-5})$ can be excluded based on internal-conversion results.[13]

TABLE II. 0–90° anisotropy of γ radiation from oriented ^{153,159}Gd and ^{161}Tb.

Isotope	Energy (keV)	$B_2 U_2 A_2$
^{153}Eu	97	-0.0027 ± 0.0018
	103	$+0.0091 \pm 0.0021$
^{159}Tb	226	$+0.0096 \pm 0.0018$
	348	-0.0013 ± 0.0015
	363	$+0.0051 \pm 0.0003$
^{161}Dy	49 [a]	$+0.0165 \pm 0.0023$
	57 [b]	$+0.150 \pm 0.018$
	75	$+0.0244 \pm 0.0015$

[a] Derived from compound line containing 42% K_β x ray.
[b] Derived from compound line consisting of 25% of the 57-keV transition in ^{161}Dy and 75% of the 58-keV transition in ^{159}Tb.

^{159}*Tb*

226 keV. From the value of B_2 derived below from the analysis of the 363-keV line, and from the the U_2 for a pure Gamow-Teller $(\frac{3}{2}^- - \frac{5}{2}^-)$ β transition, we derive

$$A_2 = +0.36 \pm 0.07\,,$$

from which we obtain the $M2/E1$ mixing ratio

$$\delta(226\text{ keV}) = 0.17 \pm 0.05\,.$$

The other value of δ obtained from A_2 $(\delta = +40^{+\infty}_{-25})$ can be excluded based on systematics of $E1$ transitions.

348 keV. The vanishing value of the product $U_2 A_2$ leads to either (or both) of the following interpretations: (1) $U_2 = 0$, in which case $|\alpha_2(\beta_2)|^2 = 0.87$; (2) $A_2 = 0$, implying $\delta(348\text{ keV}) = +0.2$ or -10. The β transition β_2 (for which $\Delta\Lambda = 2$) violates the Nilsson asymptotic selection rule[30] $\Delta\Lambda = 0, 1$ for first-forbidden transitions, and hence we would expect the larger multipolarities to dominate. In addition the 348-keV γ transition (also $\Delta\Lambda = 2$) violates the selection rule for $M1$ transitions, and we would expect a substantial $E2$ admixture. However, $|\delta| = 10$ is somewhat large for such a transition, and $\delta = 0.2$ is perhaps somewhat small. Hence we conclude that the vanishing anisotropy is probably due to a vanishing U_2 term, which yields, assuming A_2 is not small, $|\alpha_2(\beta_2)|^2 = 0.87 \pm 0.13$.

363 keV. The A_2 coefficient of the 363-keV transition is known from angular distribution measurements following nuclear resonance fluorescence[19] to be $A_2 = 0.243 \pm 0.030$, corresponding to an $M2/E1$ mixing ratio $\delta = +(0.06^{+0.01}_{-0.02})$. Using this value along with the U_2 coefficient for the β transition feeding the 363-keV level, we obtain

$$B_2 = 0.028 \pm 0.003\,.$$

This corresponds to a hyperfine energy splitting of

$$\frac{|\Delta|}{T} = \frac{\mu H}{I k_B T} = 0.24 \pm 0.01\,.$$

From previous experiments,[27] we know $T = 20 \pm 1$ mK, and thus

$$|\Delta| = 4.8 \pm 0.3\text{ mK}\,,$$

from which we derive (assuming $H = +453$ kG[26])

$$\mu = (-0.44 \pm 0.03)\mu_N\,.$$

Although the B_2 values are independent of the sign of μ, the negative sign is indicated based on the negative moments of ^{161}Dy and ^{157}Gd.[32] This result differs from the earlier result of Ref. 9 $[\mu = (-0.22 \pm 0.05)\mu_N]$; however, it is felt that the earlier result is uncertain because of the possibility of a reduced average hyperfine field in the unannealed samples used in Ref. 9, or of the possibility of faulty resistance thermometry.

^{161}Dy

49 keV. The value presented in Table II for the 49-keV radiation is based on a measured value of 0.0087 ± 0.0012 corrected for the presence of the Gd K_β x ray, the distribution of which is assumed to be isotropic. Since the 75-keV (discussed below) and 49-keV transitions come from the same level, the ratio of the anisotropies of the two transitions is identical to the ratio of their A_2 coefficients. From the A_2(75 keV) value derived below (based on an estimated U_2 value for transitions populating the 75-keV level), we estimate $A_2(49\text{ keV}) = 0.11 \pm 0.07$ from which we compute

$$\delta(49\text{ keV}) = -0.01 \pm 0.06 .$$

The alternate value of $\delta = +5$ is unlikely based on conversion-electron measurements[23] which indicate a predominately $M1$ multipolarity for the 49-keV radiation.

57 keV. From the measured P_2 coefficient of $+0.0362 \pm 0.0017$, the value presented in Table II was derived by considering the presence of a 75% contribution due to the 58-keV transition in ^{159}Tb. From directional correlation data,[25] $\delta = 0.22 \pm 0.02$, for which $A_2(57\text{ keV}) = -0.053$. This value is not consistent with the large, positive anisotropy observed in the present work. From internal-conversion data,[23] $\delta^2 = 0.04$, and to obtain a positive anistropy we take $\delta = -0.2$, for which $A_2 = 0.73$. Assuming that most $(75 \pm 25)\%$ of the β decays to the 132-keV level carry one unit of angular momentum, we obtain $U_2 = 0.54 \pm 0.21$. From these estimated values of U_2 and A_2 we obtain $B_2 = 0.29 \pm 0.10$, corresponding to a hyperfine splitting energy (at $T = 20 \pm 1$ mK) of $\Delta = 18 \pm 4$ mK. Assuming $\mu \simeq 2\mu_N$ (in agreement with values reported[32] for ^{157}Tb and ^{159}Tb), the hyperfine field of Tb in $GdFe_2$ has a magnitude $H = 370 \pm 80$ kG.

75 keV. Based on the branching intensities[10] for the transitions feeding the 75-keV level and assuming the character of β_1 to be $(80 \pm 20)\%$ $L = 1$ and that of β_2 to be $(60 \pm 20)\%$ $L = 0$ and $(20 \pm 20)\%$ $L = 1$, we estimate the value $U_2 = 0.44 \pm 0.22$. From the above estimate for B_2, we obtain $A_2 = 0.19 \pm 0.12$, for which $\delta(75\text{ keV}) = +0.08 \pm 0.10$. While a pure $E1$ multipolarity is permitted, a small $M2$ contribution is allowed by the measured δ. Such an $M2$ admixture should not be surprising in view of the large retardation (10^5) of the 75-keV $E1$ transition.[33]

V. DISCUSSION

The 363-keV transition in ^{159}Tb has a relatively large (10^5) retardation[33] for a K-allowed $E1$ transition. This retardation is due to the violation of the Nilsson asymptotic selection rules, which require $\Delta n_z = 0$, while in actuality $\Delta n_z = 2$. (This selection rule would not inhibit the emission of $M2$ radiation, and hence the relatively large 6% $M2$ amplitude.[19])

Defining the relevant mixing ratios as

$$\delta = \frac{\langle \| M2 \| \rangle}{\langle \| E1 \| \rangle}, \tag{2a}$$

$$\epsilon = \frac{\langle \| \tilde{M}1 \| \rangle}{\langle \| E1 \| \rangle}, \tag{2b}$$

$$\tilde{\delta} = \frac{\langle \| \tilde{E}2 \| \rangle}{\langle \| \tilde{M}1 \| \rangle}; \tag{2c}$$

the circular polarization P_γ of the 363-keV radiation is given by

$$P_\gamma = \frac{2\epsilon}{1 + \epsilon^2 + \delta^2 + \epsilon^2\tilde{\delta}^2}(1 + \delta\tilde{\delta}) \approx 2\epsilon(1 + 0.06\tilde{\delta}) , \tag{3}$$

and the A_1 term measured in the present work is given by

$$A_1 = \frac{2\epsilon}{1 + \epsilon^2 + \delta^2 + \epsilon^2\tilde{\delta}^2}[-1.03 + 0.52(\delta + \tilde{\delta}) - 0.54\delta\tilde{\delta}]$$

$$\approx -2\epsilon(1 - 0.49\tilde{\delta}) . \tag{4}$$

In obtaining Eqs. (3) and (4) we have used the result $\delta = 0.06$ from resonance fluorescence measurements.[19]

The vanishing value measured[4] for P_γ, which is not particularly sensitive to $\tilde{\delta}$, indicates a vanishingly small value for ϵ; that is, there is little or no $\tilde{M}1$ radiation admixed with the regular $E1$. The present result for A_1, which is an order of magnitude more sensitive to $\tilde{\delta}$, indicates a similar vanishingly small value for the product $\epsilon\tilde{\delta}$; that is, there is likewise little or no $\tilde{E}2$ admixed with the regular $E1$.

The absence of $\tilde{M}1$ or $\tilde{E}2$ admixtures in the 363-keV radiation field indicates the lack of an observable parity-nonconserving effect in the case of ^{159}Tb. These results are in qualitative agreement with predictions by Vogel[34] who estimates $\epsilon \le 2 \times 10^{-4}$ and $\epsilon\tilde{\delta} \le 2 \times 10^{-5}$.

†Work performed under the auspices of the U. S. Atomic Energy Commission.

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[1]K. S. Krane, C. E. Olsen, J. R. Sites, and W. A. Steyert, Phys. Rev. Letters 26, 1579 (1971).

[2]J. C. Vanderleeden and F. Boehm, Phys. Rev. C 2, 748 (1970).

[3]B. Jenschke and P. Bock, Phys. Letters 31B, 65 (1970).

[4]E. D. Lipson, F. Boehm, and J. C. Vanderleeden, Phys. Letters 35B, 307 (1971).

[5]R. P. Feynman and M. Gell-Mann, Phys. Rev. 109, 193 (1958).

[6]M. Gell-Mann, Rev. Mod. Phys. 31, 834 (1959).

[7]W. D. Hamilton, Progr. Nucl. Phys. 10, 1 (1969).

[8]E. M. Henley, Ann. Rev. Nucl. Sci. 19, 367 (1969).

[9]W. P. Pratt, Jr., R. I. Schermer, J. R. Sites, and W. A. Steyert Phys. Rev. C 2, 1499 (1970).

[10]C. M. Lederer, J. M. Hollander, and I. Perlman, *Table of Isotopes* (Wiley, New York, 1967).

[11]R. E. Sund and M. L. Wiedenbeck, Phys. Rev. 120, 1792 (1960).

[12]P. Alexander, Phys. Rev. 134, B499 (1964).

[13]P. Boyer, P. Chedin, and J. Oms, Nucl. Phys. A99, 213 (1967).

[14]R. L. Graham, G. T. Ewan, and J. S. Geiger, Bull. Am. Phys. Soc. 5, 21 (1960).

[15]L. Persson, Arkiv Fysik 25, 307 (1963).

[16]J. C. Hill and M. L. Wiedenbeck, Nucl. Phys. A111, 457 (1968).

[17]D. Ashery, A. E. Blaugrund, and R. Kalish, Nucl. Phys. 76, 336 (1966).

[18]R. A. Brown, K. I. Roulston, G. T. Ewan, and G. I. Andersson, Can. J. Phys. 47, 1017 (1969).

[19]R. S. Raghaven, Phys. Rev. 143, 947 (1966).

[20]B. N. Subba Rao, Nucl. Phys. 36, 342 (1962).

[21]P. Gregers Hansen, O. Nathan, O. B. Nielsen, and R. K. Sheline, Nucl. Phys. 6, 630 (1958).

[22]R. T. Brockmeier and J. D. Rogers, Nucl. Phys. 67, 428 (1965).

[23]R. L. Graham, J. S. Geiger, and G. T. Ewan, Bull. Am. Phys. Soc. 6, 72 (1961).

[24]B. N. Subba Rao, Nuovo Cimento 23, 477 (1962).

[25]B. N. Subba Rao, Nucl. Phys. 72, 414 (1965).

[26]R. E. Gegenwarth, J. I. Budnick, S. Skalski, and J. H. Wernick, Phys. Rev. Letters 18, 9 (1967).

[27]K. S. Krane, C. E. Olsen, J. R. Sites, and W. A. Steyert, Phys. Rev. C 4, 1906 (1971).

[28]R. M. Steffen, Los Alamos Scientific Laboratory Report No. LA-4565-MS, 1971 (unpublished); S. R. de Groot, H. A. Tolhoek, and W. J. Huiskamp, in *Alpha-, Beta-, and Gamma-Ray Spectroscopy,* edited by K. Siegbahn (North-Holland, Amsterdam, 1965), p. 1199.

[29]D. C. Camp and A. L. Van Lehn, Nucl. Instr. Methods 76, 192 (1969). The Q_k for odd k are discussed by K. S. Krane (to be published).

[30]B. R. Mottelson and S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. Skrifter 1, No. 8 (1959).

[31]K. S. Krane and R. M. Steffen, Phys. Rev. C 2, 724 (1970).

[32]V. S. Shirley, in *Hyperfine Structure and Nuclear Radiations,* edited by E. Matthias and D. A. Shirley (North-Holland, Amsterdam, 1968), p. 985.

[33]K. E. G. Löbner and S. G. Malmskog, Nucl. Phys. 80, 505 (1966).

[34]P. Vogel, California Institute of Technology Report No. CALT-63-155, 1971 (unpublished).