PHYSICAL REVIEW VOLUME 128, NUMBER 4 NOVEMBER 15, 1962

Nuclear Matrix Elements in the First-Forbidden Beta Decay of the Eu^{152} Ground State*

P. ALEXANDER† AND R. M. STEFFEN
Department of Physics, Purdue University, Lafayette, Indiana
(Received June 28, 1962)

The degree of circular polarization $P_c(\theta_{\beta\gamma})$ and the directional correlation $W(\theta_{\beta\gamma})=1+A_2(W)P_2(\cos\theta_{\beta\gamma})$ were measured in the 3^-(1.49-MeV β^-) $\rightarrow 2^+$(0.344-MeV γ) $\rightarrow 0^+$ β-γ cascade leading from the ground state of Eu^{152} to the Sm^{152} ground state. The angle $\theta_{\beta\gamma}$ is the angle between the β and γ momentum vectors. Representative values of $P_c(\theta_{\beta\gamma})$ measured at $\bar{W}=3.20$ (in units mc^2) for some average angles $\bar{\theta}_{\beta\gamma}$ are: $P_c(90°)=-0.01\pm0.09$, $P_c(130°)=+0.33\pm0.07$, $P_c(157°)=0.33\pm0.07$, $P_c(171°)=0.24\pm0.10$. Some representative values of the directional correlation coefficient $A_2(W)$ are: $A_2(2.8)=-0.335\pm0.006$, $A_2(3.15)=-0.363\pm0.006$, $A_2(3.4)=-0.381\pm0.005$, $A_2(3.7)=-0.388\pm0.004$. The data were analyzed on an electronic digital computer on the basis of the Kotani parameters Y, u, x, and z. Information obtained about the nuclear matrix parameters may be summarized as follows: $Y=0.70\pm0.20$, $x=0.125\pm0.06$, $u=0.125\pm0.06$, $z=1.0$. Taken jointly with the ft value of the 1.49-MeV β transition these parameters yield the nuclear matrix elements: $\int B_{ij}/R=\pm(2.9\pm0.4)\times10^{-3}$, $\int \mathbf{r}/R=\pm(4.3\pm2.3)\times10^{-4}$, $\int i\boldsymbol{\sigma}\times\mathbf{r}/R=\pm(3.6\pm1.9)\times10^{-4}$, $\int i\boldsymbol{\alpha}=\pm(2.5\pm1.1)\times10^{-4}$, where R is the nuclear radius of Eu^{152} in units of $\hbar/mc$. These results reveal the importance of $\int B_{ij}$ relative to the other nuclear matrix elements which contribute to the decay. The experimental value of the matrix element ratio $\int i\boldsymbol{\alpha}/\int \mathbf{r}$ agrees with the prediction of the conserved vector current theory of beta decay.

1. INTRODUCTION

THE majority of first-forbidden nonunique beta spectra exhibit what may approximately be termed an allowed (or statistical) shape. This behavior was first explained by Konopinski and Uhlenbeck[1] on the basis of the so-called ξ approximation. A number of first-forbidden nonunique beta spectra, however, clearly show deviations from the statistical shape.[2] Interest has since focused on these cases. These beta transitions are especially interesting because only in these cases is it possible to determine the individual nuclear matrix elements which contribute to the beta decay.[3–5] First-forbidden beta transitions whose spectral shapes deviate from an allowed shape are, in general, characterized by large ft values. When these transitions are followed by a gamma decay, the beta-gamma directional correlation exhibits a rather large anisotropy.

It has been shown[6–7] that a first-forbidden beta spectrum of a medium heavy beta emitter may exhibit deviations from the predictions of the ξ approximation for two reasons: (1) a cancellation of certain otherwise large nuclear matrix elements occurs or (2) a selection rule effect exists which causes the tensor-type nuclear matrix element $\int B_{ij}$ to be enhanced relative to the other matrix elements. Most beta transitions which show measurable deviations from the ξ approximation follow the scheme $3^-(\beta)\rightarrow 2^+(\gamma)\rightarrow 0^+$. In all of the $3^-\rightarrow 2^+\rightarrow 0^+$ decays so far investigated, a suppression of the nuclear matrix elements, of tensor rank $\lambda=1$ ($\int \mathbf{r}$, $\int i\boldsymbol{\alpha}$, $\int i\boldsymbol{\sigma}\times\mathbf{r}$) relative to the $\int B_{ij}$ matrix element of tensor rank $\lambda=2$, seems to be responsible for the observed deviations. The nuclear matrix element of rank $\lambda=2$ ($\int B_{ij}$) describes that component of the lepton field which carries away two units of angular momentum.

Employing the equations of Kotani,[7] it is possible to extract the values of the nuclear matrix elements from a knowledge of (1) the angular dependence of the beta-gamma circular polarization correlation $P_c(\theta)$, (2) the energy dependence of the beta-gamma directional correlation coefficient $A_2(W)$, (3) the beta spectrum shape factor $C(W)$, (4) the ft value of the beta transition. In this paper measurements of the angular dependence of the circular polarization of the gamma radiation following the 1.49-MeV first-forbidden beta transition of the Eu^{152} ground state ($T_{1/2}=12.45$ yr) are reported. In addition the beta-gamma-directional correlation involving the same beta transition was determined as function of the beta energy.

The dual decay of the ground state of Eu^{152} to Gd^{152} and to Sm^{152} (Fig. 1) has been investigated by many authors.[8] Accurate measurements of the beta and the electron-capture branching ratios and of the maximum energies of the beta transitions, which are important for the computation of the ft values, have been reported by Nathan and Hultberg[9] and by Schneider.[10]

There are a number of published values for the Eu^{152}

* Work supported by the U. S. Atomic Energy Commission.
† Present address: California Institute of Technology, Pasadena, California.
[1] E. J. Konopinski and G. E. Uhlenbeck, Phys. Rev. **60**, 308 (1941).
[2] L. M. Langer and D. R. Smith, Phys. Rev. **119**, 1308 (1960).
[3] R. M. Steffen, Phys. Rev. **124**, 145 (1961).
[4] P. Alexander and R. M. Steffen, Phys. Rev. **124**, 150 (1961).
[5] G. Hartwig and H. Schopper, Phys. Rev. Letters **4**, 293 (1960).
[6] T. Kotani and M. Ross, Progr. Theoret. Phys. (Kyoto) **20**, 643 (1958).
[7] T. Kotani, Phys. Rev. **114**, 795 (1959).
[8] *Nuclear Data Sheets*, National Academy of Sciences, National Research Council (U. S. Government Printing Office, Washington, D. C.).
[9] O. Nathan and S. Hultberg, Nuclear Phys. **10**, 118 (1959).
[10] W. Schneider, Nuclear Phys. **21**, 55 (1960).

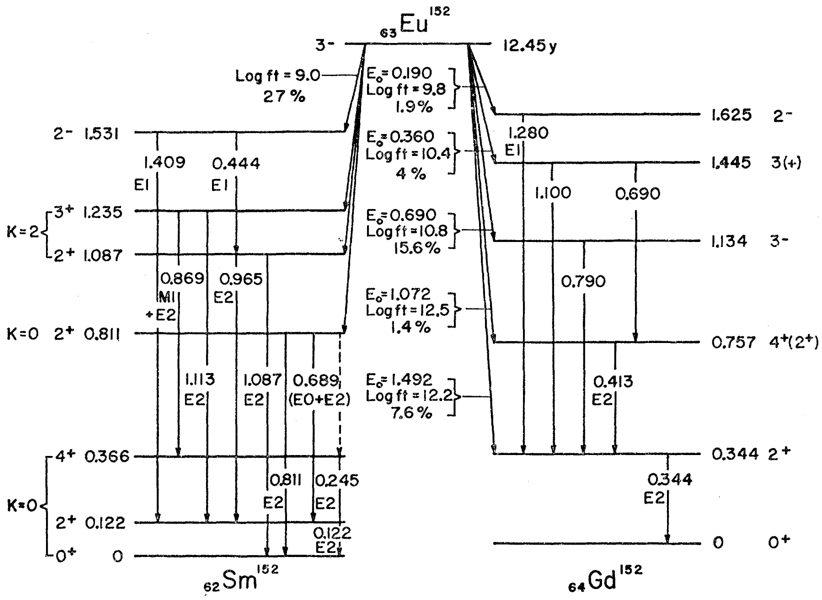

FIG. 1. Decay of the 12.45-yr Eu^{152} ground state. (Energies in MeV.)

beta-gamma directional correlation.[11–14] Unfortunately, the reported measurements do not agree within the quoted error limits. For this reason, we felt it necessary to embark on a new measurement of the Eu^{152} beta-gamma directional correlation. A preliminary measurement of the $3^- \rightarrow 2^+ \rightarrow 0^+$ beta-gamma circular polarization correlation of Eu^{152} has been reported.[15] The spectral shape factor of the highest energy beta group in Eu^{152} has been measured by Langer and Smith.[2]

2. EXPERIMENTAL METHODS AND RESULTS

The sources of Eu^{152} were prepared from EuO_3 enriched to 92% in Eu^{151}, which was irradiated with slow neutrons in the Argonne CP 5 reactor. The EuO_3, was dissolved in HCl and deposited on 1-mil and $\frac{1}{4}$-mil Mylar foils, respectively, for use in the beta-gamma circular polarization correlation and the beta-gamma directional correlation measurements.

The circular polarization of the 0.344 MeV Eu^{152} gamma ray was measured by the method of Compton scattering from the polarized electrons in the large electromagnet described previously.[4] The polarization correlation $P_c(\theta)$ was measured simultaneously at four different "table" angles θ (see reference 4). The beta and gamma detectors were as previously described, except that the thickness of the Pilot B disks mounted on the beta detectors was changed to 0.31 in. An IBM card punch replaced the digital printer which previously was used as an output device for the four-channel fast-slow coincidence system (Fig. 2). The four fast coincidence circuits were operated at an average resolving time of 11 nsec.

Using the methods previously described, the gamma single-channel analyzer was set to accept scattered photons in the energy range from 0.140 MeV to 0.280 MeV. The four beta single-channel analyzers were adjusted to accept beta particles in the range from 1.01 MeV to 1.49 MeV corresponding to an average beta energy $\bar{W}=3.20$, in units mc^2. Every 15 min the magnetic field was reversed and the digital information, stored in the 4 coincidence and 5 single count scalers, was punched on an IBM card. The measurements were made continuously for a period of five months. From the corrected beta-gamma coincidence rates $N^+(\theta)$ and $N^-(\theta)$, where $N^+(\theta)$ and $N^-(\theta)$ represent the data taken with the magnetic induction in the (+) and (−) direction, respectively, the quantity

$$\delta(\theta)=(N^+(\theta)-N^-(\theta))/(N^+(\theta)+N^-(\theta))$$

was computed (for details, see reference 4). The quantity $\delta(\theta)$ was measured at table angles θ of 90°, 110°, 120°, 130°, 140°, 150°, 160°, and 180° using magnet aperture A of Fig. 4 of reference 4; at 117°, 147°, 208°, 227°, using magnet aperture B; and at 132°, 162°, 208°, 228° using magnet aperture C. The reason for using different magnet apertures, and the geometrical shape of the apertures are explained in reference 4. The data were corrected for the presence of genuine gamma-gamma coincidences and for chance coincidences, including higher order corrections involving the finite resolving time of the slow triple coincidence circuit used in the fast-slow coincidence arrangement.[16]

[11] J. W. Sunier, P. Debrunner, and P. Scherrer, Nuclear Phys. **19**, 62 (1960).
[12] H. J. Fischbeck and R. G. Wilkinson, Phys. Rev. **120**, 1762 (1960).
[13] S. K. Bhattacherjee and S. K. Mitra, Nuovo cimento **16**, 175 (1960).
[14] H. Dulaney, C. H. Braden, and L. D. Wyly, Phys. Rev. **117**, 1092 (1960).
[15] J. Berthier, R. Lombard, and J. W. Sunier, Compt. rend. **252**, 257 (1961).
[16] H. Paul, Nuclear Instr. **9**, 131 (1960).

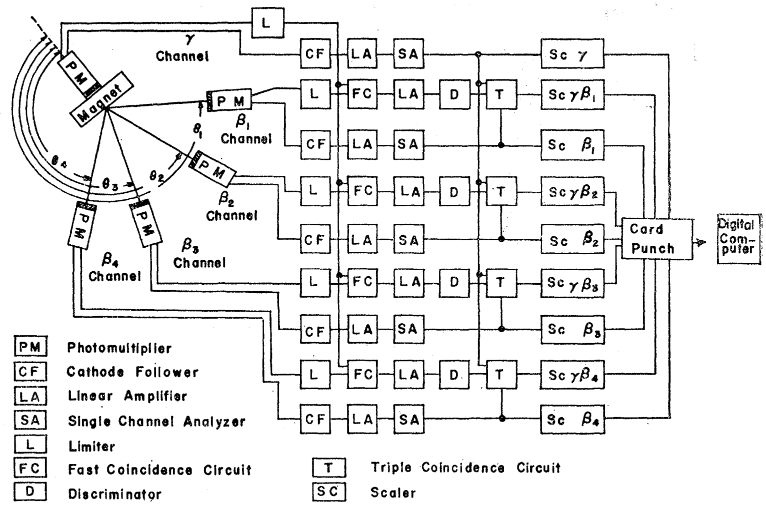

FIG. 2. Block diagram of electronic system for measurement of the beta-gamma circular polarization correlation.

The degree of circular polarization $P_c(\theta)$ of the gamma rays following the 1.49 MeV beta decay of Eu^{152} was then computed from the known polarization efficiency $\bar{E}(h\nu)$ of the analyzer

$$P_c(\theta)=\delta(\theta)/\bar{E}(h\nu).$$

The results are shown in Fig. 3. The agreement with the similar results of reference 15 is satisfactory. Recently, Bhattacherjee and co-workers[17] measured the energy dependence of the circular polarization $P_c(W)$ of the gamma radiation following the beta decay of Eu^{152}. Our value of P_c at $\bar{\theta}=160°$ is in good agreement with the value reported by Bhattacherjee[17] for $\bar{W}=3.2$.

The beta-gamma directional correlation of Eu^{152} was measured with the detector arrangement and vacuum chamber which were described previously.[18] Using the multichannel coincidence electronics, the beta-gamma directional correlation of the 3^-(1.49 MeV β)2^+(0.344 MeV γ)0^+ cascade and of the competing 3^-(1.05 MeV β)4^+(0.419 MeV γ)2^+ cascade were determined simultaneously. This method of measurement permitted correction of the $3^-(\beta)2^+(\gamma)0^+$ data for the presence of the $3^-(\beta)4^+(\gamma$, unobserved$)2^+(\gamma)0^+$ triple correlation in the same manner as discussed in reference 18.

In view of the fact that the spin of the second excited state of Gd^{152} is not definitely established (probably $I=4^+$, possibly $I=2^+$), this correction introduces an uncertainty of the experimental points of $A_2(W)$ for $W<W(\beta_2)=3.04$. This uncertainty is included in the error flags of the experimental points. Thus, the error limits for $W<3.04$ are somewhat larger than the errors of the points for $W>3.04$, although the statistical errors are essentially the same for all points.

The experimentally observed anisotropy factor $A_2(W)$ of the 3^-(1.49 MeV β)2^+(0.344 MeV γ)0^+ beta-gamma directional correlation of Eu^{152} is shown in Fig. 4.

[17] S. K. Bhattacherjee (private communication).
[18] R. M. Steffen, Phys. Rev. **123**, 1787 (1961).

The directional correlation data agree reasonably well with the measurements of Fischbeck and Wilkinson,[12] but disagree with the results reported by the Zurich group[11] and by the Indian group.[13,19]

3. EVALUATION OF DATA

For a first-forbidden beta transition ($\Delta I=\pm1$) the degree of circular polarization $P_c(\theta_{\beta\gamma})$ of gamma radiation observed at an angle $\theta_{\beta\gamma}$ with respect to the emission direction of a preceding beta particle is given by

$$P_c(\theta_{\beta\gamma})=\frac{A_1(W)P_1(\cos\theta_{\beta\gamma})+A_3(W)P_3(\cos\theta_{\beta\gamma})}{C(W)[1+A_2(W)P_2(\cos\theta_{\beta\gamma})]}.$$

The coefficients $A_i(W)$ and the shape factor $C(W)$ are functions of the beta energy W and of the matrix

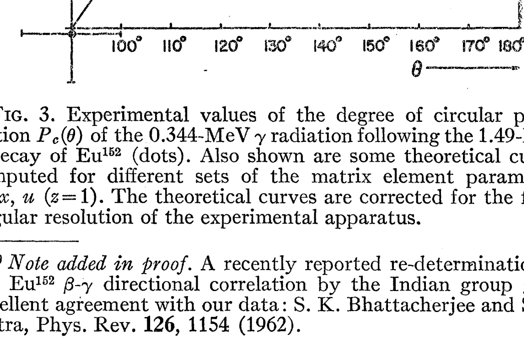

FIG. 3. Experimental values of the degree of circular polarization $P_c(\theta)$ of the 0.344-MeV γ radiation following the 1.49-MeV β decay of Eu^{152} (dots). Also shown are some theoretical curves computed for different sets of the matrix element parameters Y, x, u ($z=1$). The theoretical curves are corrected for the finite angular resolution of the experimental apparatus.

[19] *Note added in proof.* A recently reported re-determination of the Eu^{152} β-γ directional correlation by the Indian group gives excellent agreement with our data: S. K. Bhattacherjee and S. K. Mitra, Phys. Rev. **126**, 1154 (1962).

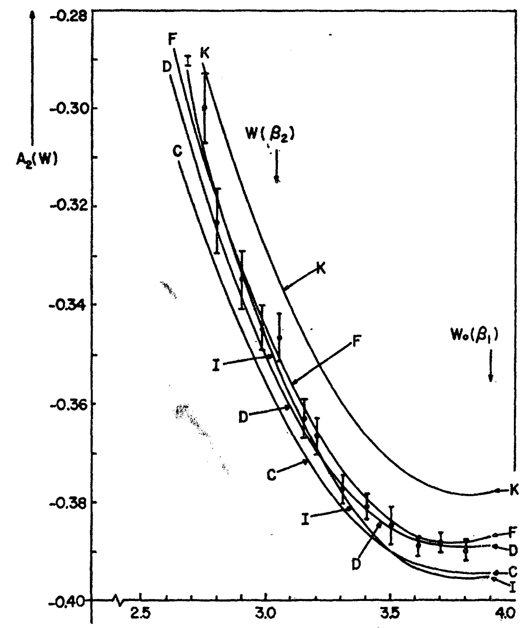

FIG. 4. Experimental values of the anisotropy factor $A_2(W)$ of the $3^-(1.49\text{ MeV},\beta)2^+(0.344\text{ MeV},\gamma)0^+$ beta-gamma directional correlation of Eu^{152}. W is in units mc^2. Also shown are some theoretical curves computed for different sets of the matrix element parameters Y, x, and u ($z=1$). The theoretical curves are corrected for the finite energy resolution of the experimental apparatus (including backscattering at the scintillator).

element parameters Y, x, u, and z[7]:

$$Y=\frac{1}{s}C_V\int i\alpha-\xi(u+x),\quad \xi=\alpha Z/2R,$$

$$x=-\frac{1}{s}C_V\int \mathbf{r},$$

$$u=\frac{1}{s}C_A\int i\boldsymbol{\sigma}\times\mathbf{r},$$

$$z=\frac{1}{s}C_A\int B_{ij}.$$

These parameters are dimensionless numbers and represent the contributions of the various matrix elements to the beta transition as compared to a standard matrix element s. For the evaluation of the Eu^{152} data we chose as standard matrix element $s=C_A\int B_{ij}$, i.e., $z=1$. The total transition probability for the beta decay is proportional to $|s|^2$. Thus the value of $|s|^2$ is determined by the (corrected) f_ct value of the beta transition

$$|s|^2=(\pi^3(\ln 2)/f_ct),$$

where

$$f_c=\int_1^{W_0}F_0(Z,W)pW(W_0-W)^2C(W)dW.$$

TABLE I. Matrix element parameters Y, x, u ($z=1$), compatible with experimental results for the 1.49-MeV beta transition of Eu^{152}.[a]

	Y	x	u	$C(W)$	$A_2(W)$	$P_c(\theta)$
A	0.35	−0.05	−0.04	+	0	−
B	0.40	0.01	0.01	+	−	+
C	0.50	0.04	0.04	+	−	+
D	0.60	0.09	0.09	+	++	+
E	0.65	0.09	0.10	++	++	++
F	0.70	0.125	0.125	++	++	++
G	0.70	0.23	−0.06	+	−	+
H	0.75	0.150	0.175	+	+	+
I	0.80	0.175	0.150	+	0	++
J	0.85	0.20	0.175	−	0	+
K	0.90	0.20	0.20	−	−	+

[a] Very good fit of data is indicated by ++; satisfactory fit of data is indicated by +; poor fit of data is indicated by 0; no fit of data is indicated by −.

In order to compute $C(W)$, the parameters Y, x, and u must be known first. Expressions for $A_i(W,Y,x,u)$ and for $C(W,Y,x,u)$ are given by Kotani,[7] and in more compact form, in reference 4. Numerical results for a wide choice of parameters have been tabulated by Alexander and Steffen.[20]

The beta-gamma directional correlation involving a first-forbidden beta transition is

$$W(\theta_{\beta\gamma})=1+A_2(W)P_2(\cos\theta_{\beta\gamma}).$$

The evaluation of the data in terms of the parameters Y, x, and u was done by an electronic computer (IBM 704). The computer was presented with the equations for $P_c(\theta_{\beta\gamma})$, $A_2(W)$, and $C(W)$ and was instructed to compute these functions for 10^6 different combinations of the matrix parameters Y, x, and u within the ranges $-10\leqslant Y\leqslant 10$, $-5\leqslant x\leqslant +5$, and $-5\leqslant u\leqslant +5$. The computer then compared the result of its calculations with the experimental data, and only those (Y,x,u) sets were accepted which gave satisfactory agreement with the experimental data within limits of error. The error limits given to the computer were much larger than the actual ones in order to estimate the magnitude of variations of Y, x, and u which would give a fit to the data somewhat outside the error limits. The experimental values of $C(W)$ were taken from reference 2.

The results of this analysis are summarized in Table I together with an indication of the "goodness" of the fit.

In Fig. 3 and Fig. 4 some computed curves for $P_c(\theta)$ and $A_2(W)$ are indicated, together with the experimental points. The labels of the curves are explained in Table I. The data presented in Table I may be summarized as

$$Y=0.70\pm0.20,$$
$$x=0.125\pm0.060,$$
$$u=0.125\pm0.060.$$

[20] P. Alexander and R. M. Steffen, U. S. Atomic Energy Commission Report, TID-13666, 1961 (Office of Technical Services, Department of Commerce, Washington 25, D. C.).

Dulaney, Braden, and Wyly[21] evaluated their experimental results[14] of the beta-gamma directional correlation of Eu^{152} and the beta-gamma circular polarization correlation measurements of Berthier *et al.*[15] by a graphical method. Our values of Y, x, and u agree within the rather large limits given by these authors: $0.5 \leqslant Y \leqslant 1.5$, $-0.1 \leqslant u \leqslant 0.1$, $-0.02 \leqslant x \leqslant 0.6$, $z=1$.

The set G of the matrix element parameters which was proposed by Berthier *et al.*[15] does not agree with our directional correlation data.

The ft value of the 1.49-MeV beta transition of Eu^{152} is $ft=10^{12.2\pm0.2}$. The correction for the nonstatistical shape of the spectrum, gives the value $f_ct=10^{11.9}$ sec, or in natural units ($\hbar=m_0=c=1$), $f_ct=6.2\times10^{32}$. From this value the "standard" matrix element may be computed

$$|s|^2=\left(C_A\int B_{ij}\right)^2=(\pi^3(\ln 2)/f_ct).$$

With $C_A=-1.2C_V$ and $C_V=(3.00\pm0.02)\times10^{-12}\hbar^3/m_0{}^2c$ one obtains for the value of the tensor-type matrix element

$$\int B_{ij}=\pm(5.2\pm0.7)\times10^{-5}\hbar/m_0c.$$

With the experimentally determined values of Y, x, and u the vector-type matrix elements, which contribute to the first-forbidden beta transition, can be computed:

$$\int i\boldsymbol{\alpha}=\pm(2.5\pm1.1)\times10^{-4},$$

$$\int \mathbf{r}=\pm(7.7\pm4.2)\times10^{-6}\hbar/m_0c,$$

$$\int i\boldsymbol{\sigma}\times\mathbf{r}=\pm(6.4\pm3.5)\times10^{-6}\hbar/m_0c.$$

In order to have a more significant comparison of the various matrix elements, the matrix elements containing r are divided by the nuclear radius of Eu^{152}, $R=1.8\times10^{-2}\hbar/m_0c$. The final result is

$$\int B_{ij}/R=\pm(2.9\pm0.4)\times10^{-3},$$

$$\int i\boldsymbol{\alpha}=\pm(2.5\pm1.1)\times10^{-4},$$

$$\int \mathbf{r}/R=\pm(4.3\pm2.3)\times10^{-4},$$

$$\int i\boldsymbol{\sigma}\times\mathbf{r}/R=\pm(3.6\pm1.9)\times10^{-4}.$$

[21] H. Dulaney, C. H. Braden, and L. D. Wyly, Phys. Rev. **125**, 1620 (1962).

4. DISCUSSION

As compared to the majority of nonunique first-forbidden beta transitions with ft values ranging from 10^6 to 10^7, the vector-type matrix elements of the 1.49-MeV beta transition of Eu^{152} are smaller by about a factor of 300. The tensor-type matrix elements $\int B_{ij}$ in ordinary unique first-forbidden transitions ($\log ft \simeq 8.5$) are of the order: $\int B_{ij}\simeq 0.2R$. In comparison, the $\int B_{ij}$ matrix element in the Eu^{152} beta-transition is smaller by about a factor of 70. Thus the $\int B_{ij}$ matrix element is much less inhibited than the vector-type matrix elements in the Eu^{152} beta transition. This relative dominance of the $\int B_{ij}$ matrix element explains the large deviation of the Eu^{152} beta transition from the ξ approximation.[7]

The strong inhibition of the vector-type matrix elements, which describe the components of the lepton field which carry away one unit of angular momentum, and the less pronounced inhibition of the tensor-type $\int B_{ij}$ matrix element which is responsible for the emission of a lepton field of two units of angular momentum must be due to some "selection rule" effect.

At first one might be tempted to attribute the reduction of the $Eu^{152}\rightarrow Gd^{152}$ β-matrix elements to the K-selection rule[7,22] (K forbiddeness) which is operative in deformed nuclei. The level structure of Gd^{152}, however, is characteristic of vibrational states of a spherical nucleus and the equilibrium shape of the Gd^{152} nucleus is almost certainly spherical. Thus there seems to be no significance in assigning K quantum numbers to the lower excited states of Gd^{152}. On the other hand, the level structure of the other neighbor of Eu^{152}, Sm^{152}, is typical of a deformed nucleus and K quantum numbers may be assigned to the various levels (see Fig. 1). These facts indicate that the nuclei Sm^{152}, Eu^{152}, Gd^{152} are in a transition region where the nature of the nuclear levels changes rapidly from one nucleus to the next and a poor overlap of the wave functions in the beta matrix elements is to be expected. The experimental fact that the tensor type $\int B_{ij}$ matrix element is much less inhibited than the vector type matrix elements $\int i\boldsymbol{\alpha}$, $\int \mathbf{r}$, and $\int i\boldsymbol{\sigma}\times\mathbf{r}$, however, cannot be explained in such a simple way. More detailed knowledge of the structure of the Eu^{152} ground state and of the first excited state of Gd^{152} is essential to arrive at an understanding of the "selection rule" which is operative in the beta decay of the Eu^{152} ground state.

Note added in proof. If the validity of the conserved vector current hypothesis[23] is assumed, a relationship between the "current type" matrix element $\int i\boldsymbol{\alpha}$ and the "charge distribution type" matrix element $\int \mathbf{r}$ can

[22] G. Alaga, K. Alder, A. Bohr, and B. R. Mottelson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **29**, No. 9 (1955).

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

be established.[24,25] This relationship, which is the beta-decay analog to the SIEGERT theorem[26,27] in electrodynamics, can be expressed as

$$\int i\boldsymbol{\alpha} = \left(W_0 - \Delta M + \frac{7}{6}\frac{\alpha Z}{R}\right)\int \mathbf{r},$$

where ΔM is the neutron-proton mass difference in units mc^2 and $\alpha Z/R = 2\xi$. On the basis of this expression the predicted value of the matrix element ratio is

$$\int i\boldsymbol{\alpha} \Big/ \int \mathbf{r} = +29.$$

The experimental value

$$\int i\boldsymbol{\alpha} \Big/ \int \mathbf{r} = +32_{-17}^{+60}$$

agrees very well with this prediction of the conserved vector current hypothesis.

ACKNOWLEDGMENT

The authors wish to convey their appreciation to J. Alberghini who helped to record the directional correlation data and to R. M. Singru who assisted in the circular polarization correlation measurements.

[24] J. I. Fujita, Phys. Rev. **126**, 202 (1962).
[25] J. Eichler, Z. Physik (to be published).
[26] A. J. F. Siegert, Phys. Rev. **52**, 787 (1937).
[27] R. G. Sachs and N. Austern, Phys. Rev. **81**, 705 (1951).

PHYSICAL REVIEW VOLUME 128, NUMBER 4 NOVEMBER 15, 1962

Search for H^5

ROBERT J. CENCE AND CHARLES N. WADDELL*
Lawrence Radiation Laboratory, University of California, Berkeley, California
(Received July 12, 1962)

Following the suggestion that H^5 might be stable against nucleon emission, a search was made for delayed neutrons resulting from the reaction $Li^7(\gamma,2p)H^5$. The targets were bombarded with a 340-MeV bremsstrahlung beam and the delayed neutrons detected in a shielded paraffin-moderated array of BF_3 counters. Counts were scaled in 14 delay channels of variable width and variable initial delay. Separated isotopes of Li^7 and Li^6 were used as targets. As H^5 cannot be produced from the bombardment of Li^6, counts observed during the bombardment of Li^6 were used to measure the background. After background subtraction, the data fall uniformly about zero and show no apparent lifetime. Assuming a 10-msec half-life, an upper limit for the activation cross section is $\sigma_A \leq 3\times10^{-32}$ cm^2. A comparison of this with the yield expected from the extrapolation of the measured yields of the reactions $B^{11}(\gamma,2p)Li^9$ and $F^{19}(\gamma,2p)N^{17}$ indicates that the upper limit for the activation cross section is of the order of 1% of the expected yield. Hence it appears unlikely that H^5 is stable against particle emission.

INTRODUCTION

In this paper we present the results of an experiment previously reported,[1] and confirm the results of an independent experiment reported by Tautfest.[2] Following the suggestion by Blanchard and Winter that H^5 might be stable against nucleon emission,[3] we attempted to produce it by means of the reaction

$$\gamma + Li^7 \rightarrow H^5 + 2p,\ Q \approx -30 \text{ MeV}. \qquad (1)$$

If H^5 does exist, it will decay to He^5 by β^- emission ($\approx$19 MeV) with a minimum half-life of about 10 msec.[2,3] Since all states of He^5 are unstable against neutron emission, H^5 would be a delayed-neutron emitter.

* Present address: University of Southern California, Los Angeles, California.
[1] Conference on Photonuclear Reactions, held at Case Institute, Cleveland, 1958 (unpublished).
[2] G. W. Tautfest, Phys. Rev. **111**, 1162 (1958).
[3] C. H. Blanchard and R. G. Winter, Phys. Rev. **107**, 774 (1957).

APPARATUS AND EXPERIMENTAL PROCEDURE

Neutrons were detected in a paraffin-moderated array of enriched BF_3 proportional counters. The efficiency of the detector was determined to be 0.83% by calibration with a mock fission source. The moderator was enclosed in a cadmium container to reduce the thermal neutron background, and the detector was enclosed in a 4-ft-thick shield of blocks containing a mixture of boric acid powder and paraffin.

The targets were combarded by γ rays from the Berkeley 340-MeV synchrotron. The bremsstrahlung beam was collimated by a lead collimator and then cleared of charged particles by passage through a magnetic field. Additional shielding was added to reduce the neutron background produced in the synchrotron and in the lead collimator. To minimize the number of neutrons produced by the photon beam, a thin-walled ionization chamber was used to monitor the number of photons passing through the targets. This chamber was