THE
PHYSICAL REVIEW

A journal of experimental and theoretical physics established by E. L. Nichols in 1893

SECOND SERIES, VOL. 139, NO. 1B 12 JULY 1965

Study of Second Excited 2^+ States of Some Even-Even Nuclei by Beta-Gamma Angular Correlations*

R. S. RAGHAVAN,† Z. W. GRABOWSKI, AND R. M. STEFFEN
Department of Physics, Purdue University, Lafayette, Indiana

(Received 25 January 1965)

Beta-gamma directional correlations of several first-forbidden β transitions leading to second excited states of even-even nuclei (β_2 transitions) have been studied. The energy-dependence of the β directional correlation factor $A_2(\beta)$ in the β-γ correlation function $W(\theta)=1+A_2(\beta)A_2(\gamma)P_2(\cos\theta)$ has been measured for the β_2 transitions of As^{76}, Sb^{122}, I^{126}, Sb^{124}, and La^{140}, and the reduced β coefficient $R_2(W)=A_2(\beta)/(\lambda_2p^2/W)$ was determined. In all cases $R_2(W)$ was found to be very different from $R_1(W)$, the reduced β factor describing the β_1 transition to the first excited state of the daughter nucleus. The results indicate that the relative magnitudes of the nuclear β-matrix elements in the β_1 transition and in the β_2 transition are significantly different, although the ft values are very similar. The implication of these experimental results for the structure of first and second excited states of even-even spherical nuclei is discussed.

I. INTRODUCTION

THE developments in theory and experiment that followed the discovery of nonconservation of parity have led to considerable clarification of the laws of beta-decay interactions which are now considered to be well-known. This situation has naturally led nuclear spectroscopists to examine whether β-decay measurements could be used to elicit information on the structure of excited states of nuclei in the same manner as gamma-ray measurements have been used to study excited nuclear states. Although analyses of beta-decay systematics, such as logft value classifications,[1] have been well-known and quoted in arguments for or against specific nuclear models, more quantitative data, e.g., in the form of individual β-matrix elements, have only recently become available after the discovery of parity violation made new types of experiments possible.

Data on allowed β decay have been used to gain information on isospin impurity admixtures of nuclear states.[2] The analysis of some experimental results on first-forbidden β transitions allowed interesting conclusions about a number of 2^+ first excited states of even-even nuclei.[3] In a number of cases, it was possible to extract values of the β-matrix elements that contribute to first-forbidden transitions from a combination of shape measurements and β–γ angular-correlation experiments. This method has been successfully applied to the β decays of Sb^{124}, Eu^{152}, Eu^{154}, and La^{140} and with less complete results to some other β emitters.[4]

Recently, attempts have been made to calculate the β-matrix elements of first-forbidden transitions on the basis of the quasiparticle model.[5] These theoretical considerations indicate that the collective modes introduce particle-hole correlations which lead to cancellations. This effect provides an explanation of the experimental results for the magnitude of the $\langle iB_{ij}\rangle$ matrix element which is usually found to be orders of magnitude smaller than the expected value $\langle iB_{ij}\rangle/R\approx 1$ (R=nuclear radius in units $\hbar=m=c=1$). The small experimental values of the vector-type matrix elements ($\langle\boldsymbol{\alpha}\rangle$, $\langle i\mathbf{r}\rangle$, $\langle\boldsymbol{\sigma}\times\mathbf{r}\rangle$) and of the scalar-type matrix elements ($\langle\gamma_5\rangle$ and $\langle i\boldsymbol{\sigma}\cdot\mathbf{r}\rangle$) are easily understood on the basis of the shell model. In fact, in most first-forbidden β tran-

---

* Work supported by the U. S. Atomic Energy Commission under Contract AT(11-1)1420.

† Present address: Bartol Research Foundation, Swarthmore, Pennsylvania.

[1] R. W. King and D. C. Peaslee, Phys. Rev. **94**, 1284 (1954).

[2] S. D. Bloom, L. G. Mann, and J. A. Miskel, Phys. Rev. **125**, 2021 (1962).

[3] Z. Matumoto, M. Yamada, I. T. Wang, and M. Morita, Phys. Rev. **129**, 1308 (1963).

[4] For a summary, see H. Frauenfelder and R. M. Steffen, *Alpha-, Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1964), Chap. XIXA.

[5] L. S. Kisslinger and C. S. Wu, Phys. Rev. **136**, B1254 (1964).

Copyright © 1965 by The American Physical Society.

sitions, the transforming nucleon stays in the same major shell and the vector- and scalar-type matrix elements are j-forbidden in the shell model.

It is of particular interest to study the contributions of the $\langle iB_{ij}\rangle$ matrix elements and to compare the results with the quasiparticle theory. So far, only β transitions leading to first excited 2^+ states of the even-even parent nuclei have been systematically studied. It is the purpose of this paper to present data on β transitions leading to *second* excited states of even-even nuclei.

The determination of the individual matrix elements in first-forbidden β transitions is, at present, only possible if special circumstances prevail. Most first-forbidden β transitions are characterized by the so-called Coulomb or ξ approximation, which gives a good description of the experimental data, if the maximum kinetic energy of the β particles W_0-1 is much smaller than the Coulomb energy $\xi=\alpha Z/2R$ ($\alpha=e^2/\hbar c\simeq 1/137$, $R=$nuclear radius in units $\hbar=m=c=1$), and if the tensor-type β-matrix element $\langle iB_{ij}\rangle$ is not unusually large compared to the vector- and scalar-type matrix elements.[6–9] The Coulomb approximation results in an energy-independent shape factor S of the β spectrum:

$$S=V_0^2+Y_1^2, \tag{1}$$

where the parameter V_0 and Y_1 are linear combinations of the scalar-type and vector-type matrix elements, respectively[10]:

$$\begin{aligned} V_0&=C_A\langle\gamma_5\rangle+\xi C_A\langle i\boldsymbol{\sigma}\cdot\mathbf{r}\rangle\,,\\ Y_1&=-C_V\langle\boldsymbol{\alpha}\rangle+\xi C_V\langle i\mathbf{r}\rangle-\xi C_A\langle\boldsymbol{\sigma}\times\mathbf{r}\rangle\,. \end{aligned} \tag{2}$$

The directional correlation involving a first-forbidden β transition $I_i\rightarrow I$ followed by a γ transition $I\rightarrow I_f$ is of the form

$$W(\theta)=1+A_{22}P_2(\cos\theta)\,. \tag{3}$$

The directional-correlation coefficient A_{22} can be separated into a β factor $A_2(\beta)$ and a γ factor $A_2(\gamma)$

$$A_{22}=A_2(\beta)A_2(\gamma)\,. \tag{4}$$

The γ factor $A_2(\gamma)$ for a pure 2^L multipole gamma transition is simply[4]

$$A_2(\gamma)=F_2(LLI_fI)\,. \tag{5}$$

The $F_2(LL'I'I)$ are geometrical angular-momentum coefficients. Tables of these coefficients have been published in many places.[4,11,12] If the β transition is followed by a mixed $M1+E2$ γ transition with the (amplitude) mixing ratio $\delta=\langle I_f\|E2\|I\rangle/\langle I_f\|M1\|I\rangle$, the γ coefficient is

$$\begin{aligned} A_2(\gamma)=[F_2(11I_fI)-2\delta F_2(12I_fI)\\ +\delta^2F_2(22I_fI)]/(1+\delta^2)\,. \end{aligned} \tag{6}$$

The sign of δ that is determined from a γ–γ directional correlation experiment, where the mixed transition is the first one in the γ–γ cascade, is opposite to the sign of the δ in the β–γ correlation experiment, where the mixed γ transition is the second radiation in the β–γ cascade. The β factor $A_2(\beta)$ is given by

$$\begin{aligned} A_2(\beta)=(F_2(02I_iI)b_2(0,2)+F_2(11I_iI)b_2(1,1)\\ +F_2(12I_iI)b_2(1,2)+F_2(22I_iI)b_2(2,2))S(W)^{-1}\,, \end{aligned}$$

where the β-particle parameters $b_2(LL')$ are in the Coulomb approximation[12–14]:

$$\begin{aligned} b_2(0,2)&=-(2/75)^{1/2}V_0C_A\langle iB_{ij}\rangle\lambda_2p^2/W\,,\\ b_2(1,1)&=\tfrac{2}{3}Y_1[2C_V\langle i\mathbf{r}\rangle+C_A\langle\boldsymbol{\sigma}\times\mathbf{r}\rangle]\lambda_2p^2/W\,,\\ b_2(1,2)&=(2/15)^{1/2}Y_1C_A\langle iB_{ij}\rangle\lambda_2p^2/W\,,\\ b_2(2,2)&\approx 0\,. \end{aligned} \tag{8}$$

The factor λ_2 contains Coulomb corrections of order $\alpha ZW/p$ and is of order unity. It varies very little with energy for $p>1$. Tables of λ_2 can be found in Ref. 7. The energy-dependence of $A_2(\beta)$ is thus determined by the factor p^2/W.

It is convenient to introduce the reduced β coefficient that is characteristic of the β transition

$$R(W)=(A_2(\beta)/\lambda_2p^2)W\,. \tag{9}$$

If the Coulomb approximation describes the β transition well, $R(W)$ is constant. In the following, the experimental determination of $R(W)$ for the first-forbidden transitions of As^{76}, Sb^{122}, Sb^{124}, I^{126}, and La^{140}, leading to the first and second excited states of their respective daughter nuclei, will be discussed and compared. All these daughter nuclei are even-even nuclei and their level structures are reasonably consistent with the predictions of the vibrational model of spherical nuclei.

II. EXPERIMENTAL APPARATUS AND PROCEDURE

The beta-gamma directional correlation measurements were performed with a vacuum-chamber scintillation-counter arrangement that has been described before.[15] A 3-in.×3-in. NaI(Tl) crystal was used to detect the gamma-rays, while beta-particles were detected by Pilot B plastic discs whose thickness was chosen in each case to be somewhat greater than the range of the most energetic electrons to be investigated.

---

[6] E. J. Konopinski and G. E. Uhlenbeck, Phys. Rev. **69**, 308 (1941).

[7] T. Kotani and M. Ross, Phys. Rev. **113**, 622 (1959).

[8] T. Kotani and M. Ross, Progr. Theoret. Phys. (Kyoto) **20**, 643 (1958).

[9] E. J. Konopinski and M. E. Rose, *Alpha-, Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1964), Chap. XVII.

[10] We use the notation of Refs. 4 and 9. Note that $\langle i\mathbf{r}\rangle=R\langle i\hat{\mathbf{r}}\rangle$, etc. Also, Y(Konopinski)$=-Y$(Kotani)$=-Y$(Frauenfelder and Steffen).

[11] M. Ferentz and N. Rosenzweig, Argonne National Laboratory Report 5324 (unpublished).

[12] K. Alder, B. Stech, and A. Winther, Phys. Rev. **107**, 728 (1957).

[13] M. Morita and R. K. Morita, Phys. Rev. **109**, 2048 (1958).

[14] T. Kotani, Phys. Rev. **114**, 795 (1959).

[15] R. M. Steffen, Phys. Rev. **123**, 1787 (1961).

The multichannel coincidence electronics consisted of four β-energy channels and two γ-energy channels and was capable of measuring simultaneously the coincidence events of four β-energy groups with two different γ transitions. The resolving time (τ) of the eight fast-coincidence circuits was about 15 nsec.

The coincidence counting rate $C'(\theta)$ was recorded at several angles θ and was corrected for chance coincidences, γ–γ coincidences, coincidences caused by competing β–γ cascades, if any, beta-bremsstrahlung coincidences, and coincidences resulting from the compton quanta of higher energy gamma radiation. From the corrected coincidence counting rate $C(\theta)$, the "experimental" anisotropy factor $A_{22}''(W)$ was determined. Application of the finite solid-angle correction[4] to $A_{22}''(W)$ yielded the point-counter anisotropy factor $A_{22}'(W)$ which, after correcting for backscattering effects in the plastic β detector represents the "true" anisotropy factor $A_{22}(W)$. The latter correction was unsignificant in all cases considered. Corrections for the finite thickness of the sources were considered and found to be negligibly small for the β energies involved in the measurements.

Most radioactive isotopes (As^{76}, Sb^{124}, La^{140}) were obtained from Oak Ridge National Laboratory. Sources of Sb^{122} were prepared by irradiating enriched (98.9%)Sb^{121} in the ORNL reactor. Sources of I^{126} were produced by a (p,n) reaction from Te^{126} in a cyclotron. The β–γ correlation sources were prepared either by evaporating a drop of solution on a 1.2 mg/cm² Mylar film, yielding sources of about 400 μg/cm² or, for low β-energy sources (e.g., Sb^{122}), by vacuum evaporation onto an aluminized Mylar film of 0.8 mg/cm² thickness, giving sources of less than 100 μg/cm² average thickness.

From $A_{22}(W)$, the reduced β coefficient $R(W)$ was then computed from

$$R(W)=(A_{22}(W)/A_2(\gamma))(W/\lambda_2 p^2)\,.$$

In most cases, $A_2(\gamma)=F_2(LLI_fI)=F_2(2202)=-0.598$.

III. EXPERIMENTAL RESULTS

A. First-Forbidden $\Delta I=0$ β Transitions

As^{76}

The decay scheme of As^{76} is fairly well established (Fig. 1). The spin of As^{76} has been determined by radio frequency orientation.[16] The spin assignments to the first three excited states of Se^{76} have been verified by γ–γ angular correlation measurements.[17] The decay of As^{76} is fairly complex for reliable β–γ directional correlation measurements. However, the 559- and 1216-keV gamma lines, which are of interest for the measurement of the β_1–γ_1 and β_2–γ_3 correlation are prominent and well resolved in the scintillation-counter spectrum. The complexity of the decay scheme does not present any difficulties if β particles of energy greater than the end point of the β_3 spectrum are accepted. The experimental results of the β–γ directional correlation measurements on As^{76} are summarized in Table I. The reduced β coefficients $R_1(W)$, describing the β_1–γ_1 directional correlation involving the first excited state of Se^{76} and $R_2(W)$, describing the β_2–γ_3 directional correlation involving the second excited state of Se^{76}, are presented in Fig. 2. The β_1–γ_1 directional correlation has also been studied by Fischbeck and Newsome.[18] The $R_1(W)$ values calculated from their data have been included in Fig. 2. The agreement between the two measurements is very

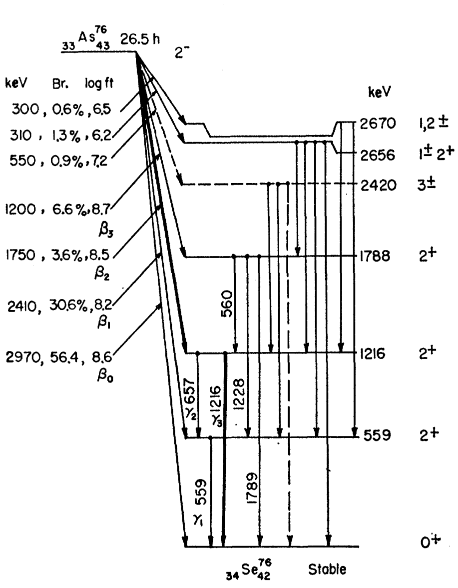

FIG. 1. Decay scheme of As^{76}.

TABLE I. β–γ directional correlation results for As^{76}.

β energy (keV)	W	$A_{22}(W)$	$R(W)$
	2^-(2410-keV β_1)2^+(559-keV γ_1)0^+ correlation		
1570	4.07	+0.0845±0.0065	−0.039 ±0.003
1750	4.43	+0.087 ±0.007	−0.037 ±0.003
1850	4.62	+0.097 ±0.007	−0.039 ±0.003
1920	4.76	+0.0975±0.005	−0.038 ±0.002
2020	4.95	+0.105 ±0.008	−0.039 ±0.003
2140	5.19	+0.113 ±0.008	−0.040 ±0.003
2225	5.35	+0.108 ±0.012	−0.037 ±0.004
2270	5.44	+0.120 ±0.015	−0.040 ±0.005
2310	5.52	+0.112 ±0.015	−0.037 ±0.005
	2^-(1750-keV β_2)2^+(1216-keV γ_3)0^+ correlation		
1275	3.49	−0.0101±0.0097	+0.0055±0.0053
1325	3.59	−0.0144±0.0100	+0.0076±0.0053
1375	3.69	−0.0185±0.0120	+0.0095±0.0061
1425	3.79	−0.0114±0.0147	+0.0057±0.0074
1575	4.08	−0.0179±0.0285	+0.0082±0.0130

---

[16] F. M. Pipkin and J. W. Culvahouse, Phys. Rev. **109**, 1423 (1958).

[17] Z. W. Grabowski, S. Gustafson, and I. Marklund, Arkiv Fysik **17**, 411 (1960).

[18] H. J. Fischbeck and R. W. Newsome, Phys. Rev. **129**, 2231 (1963).

good. Our results of $R_2(W)$ indicate a small, but definitely nonvanishing value of $R_2(W)$. This is not inconsistent with some data quoted by Fischbeck and Newsome,[18] who find $R_2(W)\simeq 0$ within their limits of error. Grenacs and de Raedt[19] also find an isotropic β_2–γ_3 directional correlation in an integral measurement. All data indicate a significant difference between $R_1(W)$ and $R_2(W)$ for the As^{76} β–γ directional correlations.

Sb^{122}

The decay of Sb^{122} has been well studied and is relatively simple (Fig. 3). The spin of Sb^{122} has been determined by radio frequency orientation measurements.[20] The spin assignments to the excited states of Te^{122} have been verified by γ–γ directional correlation measurements.[21–23] The 686-keV γ radiation is a mixed $M1+E2$ transition with $\delta=\langle 2\|E2\|2\rangle/\langle 2\|M1\|2\rangle=3.4\pm0.5$.[21–23] Previous β–γ angular-correlation measurements have been restricted to the β_1–γ_1 cascade only.[15,24,25] These measurements have shown that the β_1 transition is well described by the Coulomb approximation.

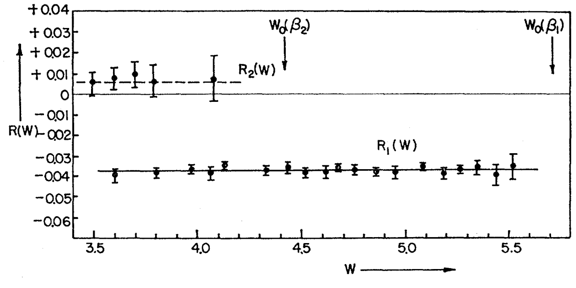

FIG. 2. Reduced β coefficients $R_1(W)$ and $R_2(W)$ for the As^{76} β transitions.

The β_1–γ_1 directional correlation was measured concurrently with the β_2–γ_2 and β_2–γ_3 directional correlation in our multichannel arrangement. The experimental results of the β–γ anisotropy factor $A_{22}(W)$ are listed in Table II. The reduced β coefficient $R_1(W)$ is plotted in Fig. 4. The agreement with the results reported by Steffen[15] is excellent.

Our main attention was devoted to the measurement of $R_2(W)$ involving the β transition to the second excited state of Te^{122}. The branching ratio of the 740-keV β_2 group is only 4% and special attention must be paid to the effects of the interfering main β–γ cascade. The factor $R_2(W)$ may be determined in two ways: by measuring the directional correlation of either the β_2–γ_2 cascade or of the β_2–γ_3 cascade. Although the β_2–γ_3 cascade involving the cross-over gamma-transition results in a much smaller coincidence counting rate than the β_2–γ_2 cascade, the interfering effects are practically negligible in the β_2–γ_3 measurement. In the measurement of the β_2–γ_2 directional correlation, the contributions of the γ_2–γ_1 directional correlations are significant. After all corrections were applied the results of $R_2(W)$ obtained by the two methods were in satisfactory agreement. The experimental values of $R_2(W)$ for the 740-keV β transition to the second excited state of Te^{122} are plotted in Fig. 4.

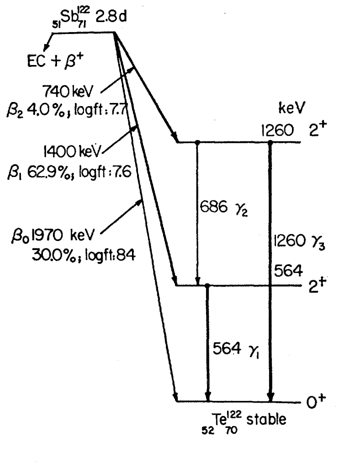

FIG. 3. Decay scheme of Sb^{122}.

The data indicate strongly that $R_2(W)$ is not independent of W and thus the β_2 transition does not follow the Coulomb approximation. However, an energy-independent reduced β coefficient $R_2(W)$ cannot be entirely excluded on the basis of the experimental errors of the $R_2(W)$ values.

As a byproduct of these measurements, the $E2$–$M1$ mixing ratio of the 686-keV γ transition was determined: $\delta=+3.0\pm1.0$. This value is in good agreement with the value $\delta=+3.4\pm0.5$, obtained in γ–γ directional correlation experiments.

I^{126}

The decay scheme of I^{126} is shown in Fig. 5. The spin of I^{126} has been measured directly by the atomic beam

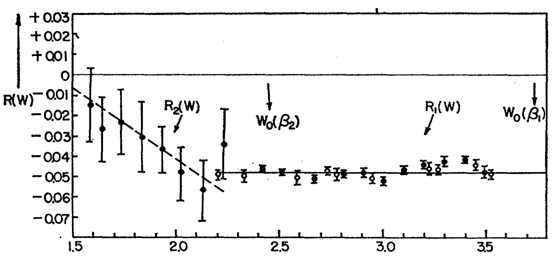

FIG. 4. Reduced β coefficients $R_1(W)$ and $R_2(W)$ for the Sb^{122} β transitions.

---

[19] J. Grenacs and J. de Raedt, J. Phys. Radium **24**, 925 (1963).

[20] F. M. Pipkin, Phys. Rev. **112**, 935 (1958).

[21] R. M. Steffen, *Proceedings of 1954 Glasgow Conference on Nuclear and Meson Physics* (Pergamon Press, Inc., London 1955), p. 206.

[22] M. J. Glaubmann, Phys. Rev. **98**, 645 (1955).

[23] T. Lindquist and I. Marklund, Nucl. Phys. **4**, 189 (1957).

[24] J. Deutsch and P. Lipnik, J. Phys. Radium **21**, 806 (1960).

[25] Z. W. Grabowski, R. S. Raghavan, and R. M. Steffen, Nucl. Phys. (to be published).

TABLE II. β–γ directional correlation results for Sb^{122}.

β energy (keV)	W	$A_{22}(W)$	$R(W)$
	2^-(1400-keV β_1)2^+(564-keV γ_1)0^+ correlation		
725	2.42	$+0.048\ \pm0.002$	-0.0466 ± 0.002
775	2.52	$+0.053\ \pm0.002$	-0.0483 ± 0.002
825	2.61	$+0.070\ \pm0.002$	-0.0608 ± 0.002
875	2.71	$+0.052\ \pm0.002$	-0.0430 ± 0.0016
925	2.81	$+0.062\ \pm0.002$	-0.0489 ± 0.0016
975	2.91	$+0.064\ \pm0.002$	-0.0482 ± 0.0016
1025	3.01	$+0.072\ \pm0.002$	-0.0524 ± 0.0017
1075	3.10	$+0.068\ \pm0.003$	-0.0471 ± 0.0018
1125	3.20	$+0.067\ \pm0.003$	-0.0450 ± 0.002
1175	3.30	$+0.066\ \pm0.004$	-0.0428 ± 0.0024
1225	3.40	$+0.067\ \pm0.004$	-0.0417 ± 0.0024
1275	3.50	$+0.077\ \pm0.005$	-0.0478 ± 0.0028
	2^-(740-keV β_2)2^+(1260-keV γ_3)0^+ correlation		
275	1.54	$+0.0067\pm0.0081$	-0.0149 ± 0.0179
325	1.64	$+0.0142\pm0.0086$	-0.0272 ± 0.0164
375	1.73	$+0.0138\pm0.0094$	-0.0235 ± 0.0160
425	1.83	$+0.0206\pm0.0114$	-0.0314 ± 0.0174
475	1.93	$+0.0262\pm0.0081$	-0.0364 ± 0.0113
525	2.03	$+0.0383\pm0.0100$	-0.0489 ± 0.0128
575	2.13	$+0.0481\pm0.0124$	-0.0569 ± 0.0146
625	2.22	$+0.0201\pm0.0101$	-0.0335 ± 0.0169

method.[26] The spin assignments to the first two excited states of Xe^{126} have been verified by γ–γ directional correlation measurements.[27,28] The 480-keV γ transition is an almost pure $E2$ transition with $|\delta| = |\langle 2\|E2\|2\rangle / \langle 2\|M1\|2\rangle| > 5$. Since positrons are emitted in the dual decay of I^{126}, special precautions must be taken to avoid the interfering effects of the strong correlation of the annihilation radiation. For this reason, the β–γ coincidences (together with the unavoidable γ–γ coincidences) were measured at seven angles and the β–γ directional correlation factors $A_{22}(W)$ were determined by a least square fit after the points near $\theta = 180°$ were corrected for the presence of the annihilation radiation.

Previous measurements of the β–γ directional correlation in I^{126} were restricted to the β_1–γ_1 directional correlation.[29,30] However, these experiments indicated widely differing values. In order to resolve these discrepancies, the measurement of the β_1–γ_1 directional correlation was first undertaken. The experimental values of $A_{22}(W)$ are summarized in Table III.

TABLE III. β–γ directional correlation results for I^{126}.

β energy (keV)	W	$A_{22}(W)$	$R(W)$
	2^-(865-keV β_1)2^+(386-keV γ_1)0^+ correlation		
425	1.83	$+0.058\pm0.002$	-0.090 ± 0.003
475	1.93	$+0.065\pm0.003$	-0.092 ± 0.004
525	2.03	$+0.072\pm0.003$	-0.092 ± 0.004
575	2.12	$+0.070\pm0.003$	-0.084 ± 0.004
600	2.17	$+0.085\pm0.004$	-0.099 ± 0.005
625	2.22	$+0.093\pm0.003$	-0.105 ± 0.004
662	2.30	$+0.078\pm0.005$	-0.083 ± 0.005
725	2.42	$+0.059\pm0.006$	-0.058 ± 0.006
775	2.52	$+0.086\pm0.008$	-0.080 ± 0.008
	2^-(385-keV β_2)2^+(860-keV γ_3)0^+ correlation		
280	1.55	-0.005 ± 0.009	$+0.011\pm0.020$

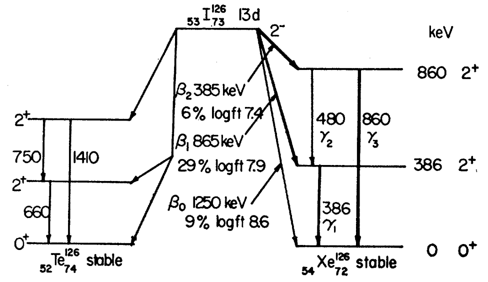

FIG. 5. Decay scheme of I^{126}.

The measured energy-dependence of $R_1(W)$ is illustrated in Fig. 6, the data points being shown as open circles and a solid line. Within the limits of experimental error, it may be seen that the $R_1(W)$ is independent of, or very slowly varying with, energy. These data are in general agreement with recent measurements of Simms.[30]

An attempt was made to measure the differential β–γ directional correlation of the β_2–γ_3 cascade. The cross-over γ_3 transition of 860 keV was included in the gamma channel gate while the β channels accepted β particles from 200 to 400 keV at intervals of 50 keV. For all these energies, the β_2–γ_3 correlation showed a vanishing anisotropy within experimental error (3%). Therefore, an integral measurement was performed accepting all beta particles from 200 to 400 keV. The isotropy of the correlation was confirmed with better statistics. The experimental point for the β_2–γ_3 directional correlations is indicated in Fig. 6 as a single point at the average β energy.

B. First-Forbidden $\Delta I = \pm 1$ β Transitions

Sb^{124}

The decay of Sb^{124} is fairly complex (Fig. 7). Although some uncertainty about the position and spin of the

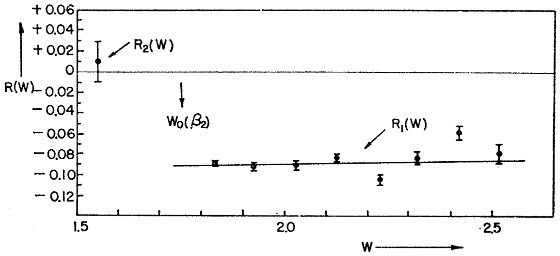

FIG. 6. Reduced β coefficients $R_1(W)$ and $R_2(W)$ for the I^{126} β transitions.

---

[26] H. L. Garwin and E. Lipworth, Nucl. Phys. **19**, 140 (1960).

[27] M. Sakai, H. Ikegami, T. Yamazaki, and K. Sugiyama, J. Phys. Soc. Japan **14**, 983 (1959).

[28] I. Asplund, L. G. Stromberg, and T. Wiedling, Arkiv Fysik **18**, 65 (1960).

[29] H. Stevenson and M. Deutsch, Phys. Rev. **84**, 1071 (1951).

[30] P. C. Simms (private communication).

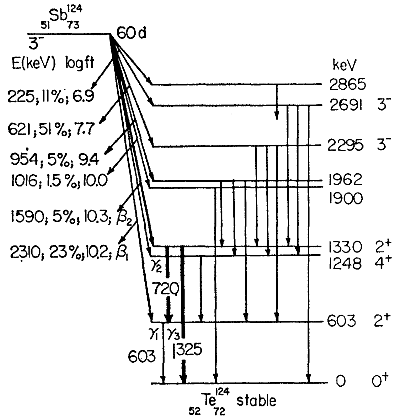

FIG. 7. Decay scheme of Sb^{124}.

higher excited states of Te^{124} exists, the first three excited states are well established. Paul,[31] and more recently Glaubmann and Oberholtzer,[32] have provided evidence for the existence of a level at 1248 keV. Beta-gamma scintillation-coincidence spectrometry measurements confirmed the existence of this level. Using a 2-mm Li-drifted Ge solid-state detector, we could clearly identify the stop-over 645-keV gamma line. The intensity of this line was found to be about 70% of the intensity of the 720-keV line, in agreement with the results reported in Ref. 32. No evidence for a cross-over gamma ray of 1248 keV was observed in the Ge-detector spectrum. The spin assignment to the three first excited states of Te^{124} were made on the basis of γ–γ angular correlation experiments[32] and the second and third excited states are identified as members of the two-phonon vibrational triplet.

The directional correlation of the β_1–γ_1 cascade is one of the most thoroughly investigated.[33–37] In fact, the 2310-keV β_1 transition was the first β transition whose individual β-matrix elements could be determined by a combination of angular correlation and shape measurements.[33–40] The experimental $R_1(W)$ values of Steffen[33] for the 2310-keV β_1 transition are plotted in Fig. 8 as a function of the β energy. The fact that $R_1(W)$ is strongly energy-dependent shows that the β_1 transition of Sb^{124} deviates from the Coulomb approximation.

The reduced β factor $R_2(W)$ of the 1590 keV β transition can be determined from a measurement of either the β_2–γ_3 correlation or the β_2–γ_2 correlation. The β_2–γ_3 directional correlation can be observed without any interference from cascades that involve the 1248-keV 4^+ level. The β–γ coincidence counting rate, however, is very small, due to the small β_2- and γ_3-branching ratios. On the other hand, although the coincidence counting rate in the measurement of the β_2–γ_2 correlation is much more favorable, the contributions from competing β–γ cascades must be taken into account. Table IV summarizes the observed $A_{22}(W)$ values of the β_2-γ directional correlations of Sb^{124}. The $R_2(W)$ values for the 1590-keV β_2 transition determined as a weighted average of the results obtained with the two methods described above are shown in Fig. 8. The computation of $R_2(W)$ from the β_2–γ_2 correlation requires the knowledge of the $E2$–$M1$ mixing ratio δ of the 720-keV γ transition. We obtain satisfactory agreement between the two $R_2(W)$ measurements, if we accept the value $\delta=1.0\pm0.2$ of Paul,[31] which is consistent with the value $\delta^2=1.0\pm0.2$, reported by Lindquist and Marklund.[41] We cannot obtain agreement with the mixing ratio $\delta=4.0\pm0.6$ that has been reported by Glaubmann and Oberholtzer.[32]

TABLE IV. β–γ directional correlation results for Sb^{124}.

β energy (keV)	W	$A_{22}(W)$	$R_2(W)$
3^-(1590-keV β_2)2^+(1325-keV γ_3)0^+ correlation			
1150	3.25	-0.193 ± 0.010	$+0.141\pm0.007$
1250	3.45	-0.227 ± 0.014	$+0.130\pm0.008$
1350	3.64	-0.230 ± 0.027	$+0.121\pm0.015$
1450	3.84	-0.252 ± 0.052	$+0.142\pm0.030$
3^-(1590-keV β_2)2^+(720-keV γ_2)2^+ correlation			
1150	3.25	$+0.176\pm0.003$	$+0.148\pm0.006$
1250	3.45	$+0.159\pm0.003$	$+0.125\pm0.006$
1350	3.64	$+0.161\pm0.003$	$+0.118\pm0.006$
1450	3.84	$+0.206\pm0.005$	$+0.143\pm0.010$

La^{140}

The decay of La^{140} is illustrated in Fig. 9. The spins of the two first excited states of Ce^{140} are well established by γ–γ directional correlation experiments.[42] The 2083

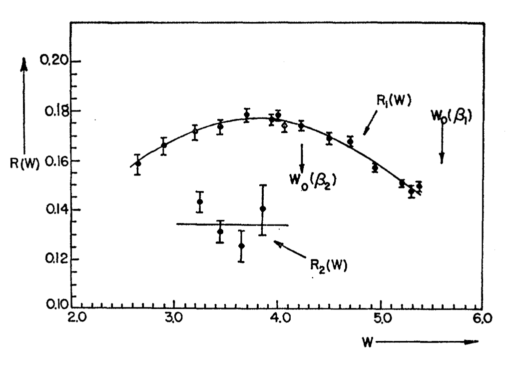

FIG. 8. Reduced β coefficients $R_1(W)$ and $R_2(W)$ for the Sb^{124} β transitions.

---

[31] H. Paul, Phys. Rev. **121**, 1175 (1961).

[32] M. J. Glaubmann and J. D. Oberholtzer, Phys. Rev. **135**, B1313 (1964).

[33] R. M. Steffen, Phys. Rev. Letters **4**, 290 (1960).

[34] R. M. Steffen, Phys. Rev. **124**, 145 (1961).

[35] H. J. Fischbeck and M. L. Wiedenbeck, Bull. Am. Phys. Soc. **6**, 238 (1961).

[36] R. F. Petry, K. S. R. Sastry, and R. G. Wilkinson (unpublished).

[37] J. W. Sunier, Helv. Phys. Acta **36**, 429 (1963).

[38] G. Hartwig and H. Schopper, Phys. Rev. Letters **4**, 293 (1960).

[39] P. Alexander and R. M. Steffen, Phys. Rev. **124**, 1175 (1961).

[40] G. Hartwig, Z. Physik **161**, 221 (1961).

[41] T. Linquist and I. Marklund, Nucl. Phys. **4**, 189 (1957).

[42] W. H. Kelly and M. L. Wiedenbeck, Phys. Rev. **102**, 1130 (1956).

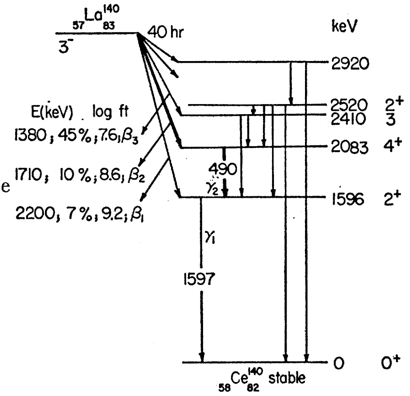

FIG. 9. Decay scheme of La^{140}.

keV 4^+ state has been the object of a number of studies since its lifetime is unusually long ($\tau = 0.5 \times 10^{-9} s$).[43] The measured g factor of this state, $g = 1.11 \pm 0.04$, agrees reasonably well with the result of a quasiparticle calculation for a vibrational collective state for a spherical nucleus $g_{QP} = 0.95$.[44] It should be emphasized, however, that this 4^+ state of Ce^{140} can also be interpreted in the shell model as a $[g_{7/2}d_{5/2}]_4$ proton configuration.

The β_1–γ_1 angular correlation of La^{140}, involving the first excited state of Ce^{140}, has been studied before[45,46] and attempts have been made to determine the individual matrix elements that contribute to this β transition.[47,48] The reduced β coefficient $R_1(W)$, as measured by Alberghini and Steffen,[45] is shown in Fig. 10. Although, within limits of error, $R_1(W)$ is independent of W, the β_1 transition does not follow the Coulomb approximation. This fact is evidenced by the nonstatistical shape of the β_1 spectrum[49] and by the β_1–γ_1 circular polarization correlation.[48] The large ft value and the deviations from the Coulomb approximation seem to be caused by a cancellation effect of the vector-type matrix elements, rather than by a selection-rule effect that favors the B_{ij} tensor matrix element.[48]

The β_2–γ_2 directional correlation involving the second excited 4^+ state of Ce^{140} was measured in the β-energy range from 1400 to 1600 keV. The observed correlation was corrected (a) for the contributions of β–γ coincidences caused by the compton quanta of the 1600-keV gamma radiation and (b) for the contributions of γ–γ coincidences. The latter contribution was large (50–60% of the total coincidence rate). The experimental data of $A_{22}(W)$ for the β_2–γ_2 directional correlation are listed in Table V. The errors of the $A_{22}(W)$ values are mainly caused by the γ–γ corrections. Figure 10 shows the reduced β coefficient $R_2(W)$ computed from these data. Also included in Fig. 10 are the values of $R_2(W)$, computed from the data reported by Newsome and Fischbeck.[47] It should be mentioned that the lifetime of the 2083-keV state of Ce^{140} is long enough to make extranuclear perturbations of the β_2–γ_2 directional correlation possible. The existence of such an extranuclear perturbation, however, would imply an even more pronounced difference between $R_1(W)$ and $R_2(W)$.

TABLE V. β–γ directional correlation results for La^{140}.

β energy (keV)	W	$A_{22}(W)$	$R_2(W)$
	3^-(1710-keV β_2)4^+(490-keV γ_2)2^+ correlation		
1350[a]	3.64	$+0.177 \pm 0.018$	-0.135 ± 0.014[a]
1425	3.79	$+0.243 \pm 0.018$	-0.177 ± 0.014
1450[a]	3.84	$+0.194 \pm 0.025$	-0.139 ± 0.018[a]
1475	3.89	$+0.227 \pm 0.035$	-0.160 ± 0.025
1550[a]	4.03	$+0.216 \pm 0.030$	-0.146 ± 0.025[a]
1550	4.03	$+0.272 \pm 0.025$	-0.184 ± 0.015

[a] Data of Ref. 47.

IV. SUMMARY OF RESULTS AND DISCUSSION

The reduced β coefficient $R_1(W)$ for the β transitions to the first excited 2^+ states of the even-even spherical nuclei Se^{76}, Te^{122}, and Xe^{126} is energy-independent. In fact, there is good evidence that all three β transitions satisfy the Coulomb approximation. The reduced β coefficients for the corresponding β transitions to the second excited 2^+ states of the same nuclei is in all cases markedly different from $R_1(W)$. In the cases of As^{76} and I^{126}, the β_2 decay seems to follow the Coulomb approximation, whereas the β_2 transition of Sb^{122} seems to deviate from the Coulomb approximation. The data for the various β transitions are summarized in Table VI. The striking feature is the experimental fact that $R_1(W)$ is very different from $R_2(W)$—$R_1(W)$, in general, being larger than $R_2(W)$—although the ft values of β_1 and β_2 are nearly the same in all three cases.

The β_1 transition of Sb^{124}, leading to the first excited 2^+ state of Te^{124}, has an unusually large ft value. The

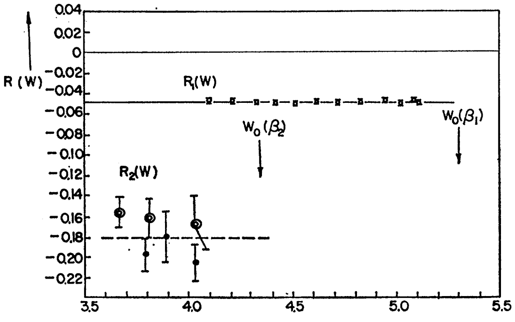

FIG. 10. Reduced β coefficients $R_1(W)$ and $R_2(W)$ for the La^{140} β transitions.

---

[43] W. M. Currie, Nucl. Phys. **37**, 574 (1962).

[44] K. Alder and R. M. Steffen, Ann. Rev. Nucl. Sci. **14**, 403 (1964).

[45] J. E. Alberghini and R. M. Steffen, Phys. Letters **7**, 85 (1963).

[46] S. K. Bhattacherjee and S. K. Mitra, Phys. Rev. **131**, 2611 (1963).

[47] R. W. Newsome and H. J. Fischbeck, Phys. Rev. **133**, B273 (1964).

[48] R. M. Singru, P. C. Simms, and R. M. Steffen, Nucl. Phys. (to be published).

[49] L. M. Langer and D. R. Smith, Phys. Rev. **119**, 1308 (1960).

TABLE VI. Comparison of data for first-forbidden β transitions to first and second excited states of daughter nuclei.

β emitter		log *ft*	$R(W)$	
$\Delta I=0$				
As^{76}	β_1	8.2	-0.038 ± 0.002	independent of W
	β_2	8.5	0.007 ± 0.003	independent of W
Sb^{122}	β_1	7.6	-0.049 ± 0.002	independent of W
	β_2	7.7	-0.01 to -0.05	indication of strong W-dependence
I^{126}	β_1	7.9	-0.090 ± 0.007	independent of W
	β_2	7.4	0.01 ± 0.02	approximately independent of W
$\Delta I=\pm 1$				
Sb^{124}	β_1	10.2	$+0.15$ to $+0.18$	varies with W
	β_2	10.2	$+0.135\pm 0.02$	consistent with constant $R(W)$
La^{140}	β_1	9.2	-0.052 ± 0.002	independent of W
	β_2	8.6	-0.18 ± 0.03	consistent with constant $R(W)$

shape of the β_1 spectrum[49] and the angular correlation show strong deviations from the Coulomb approximation, resulting from the very strong contribution of the B_{ij} component. These facts are well understood on the basis of the available shell-model orbitals for the transforming nucleon, which cause a strong inhibition of the vector-type matrix elements and thus favor the B_{ij} matrix element. The β_2 transition, leading to the second excited 2^+ state of Te^{124} has almost the same *ft* value as the β_1 transition. The reduced β factors $R(W)$ for the two transitions, however, are significantly different.

The β_1 transition of La^{140}, leading to the first excited 2^+ state of Ce^{140} does not satisfy the Coulomb approximation. The observed data are satisfactorily explained on the basis of a mutual cancellation of the vector-type matrix elements which causes a relative dominance of the B_{ij} component. The *ft* value of the β_2 transition to the second excited state of Ce^{140} is considerably smaller than the *ft* value of the β_1 transition, indicating that the cancellation effects are less complete. This is in accordance with the large difference between $R_1(W)$ and $R_2(W)$. It should be kept in mind, however, that $R_1(W)$ and $R_2(W)$ cannot be directly compared with each other, because the angular momenta of the final states of these two β transitions are different and, therefore, the F coefficients in Eq. (7) are not the same.

The experimental results presented in this paper indicate that the relative contributions of the nuclear matrix elements in first-forbidden β transitions leading from the ground state of an odd-odd nucleus to first and second excited states of even-even spherical nuclei are significantly different. In terms of the quasiparticle model, the first excited states (one-phonon states in terms of quadrupole vibrational modes) are linear combinations of two-quasiparticle states, whereas the second excited states (two-phonon states in terms of vibrational modes) are linear combinations of zero- and four-quasiparticle states. In the quasiparticle representation the beta-decay operators, expressed in terms of quasiparticle creation and destruction operators lead to several terms representing various quasiparticle and quasihole transitions.[5] Since the quasiparticle description of the two-phonon state is quite different from the quasiparticle description of the one-phonon state, the various parts of the β-decay operator contribute differently to the two β transitions. Hence, the β matrix elements in the β transitions to the two excited vibrational states are expected to give different relative contributions, in qualitative agreement with experiment.