Beta-Gamma Directional Correlation in Sb^{125}†

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The directional correlation of the first-forbidden 0.437-MeV beta group and the 0.176-MeV gamma ray in the decay of Sb^{125} has been measured at four beta energies between 0.255 and 0.405 MeV. A large anisotropic gamma-gamma coincidence background was eliminated by increasing the distance from source to beta detector while focusing the beta rays with a pair of quadrupole magnets. The beta-energy dependence of the directional correlation indicates a spin assignment of $\frac{9}{2}$ for the 0.321-MeV state in Te^{125}. Analysis of the relative magnitudes of the principal nuclear matrix elements gives possible values for parameter Λ in agreement with the prediction 2.34 based on the conserved-vector-current theory.

INTRODUCTION

THE decay scheme of Sb^{125} has been extensively investigated with results in good agreement for the low-lying states of the daughter Te^{125}.[1–5] The spins of the ground state and the first two excited states have been established along with the multipolarity of the connecting gamma transitions. The successive spin and parity assignments are shown in Fig. 1.[6] Narcisi measured the K conversion coefficient and conversion ratios for the 0.176-MeV gamma transition connecting the second and third excited states.[5] Narcisi interpreted his data to require that the 0.176-MeV gamma transition be a mixture of $M1$ and $E2$ radiation. The presence of $M1$ radiation limits the spin of the 0.321-MeV state in Te^{125} to be 13/2, 11/2, or $\frac{9}{2}$. A logft value of 9.3 for the 0.437-MeV beta group which populates the 0.321-MeV state indicates a first-forbidden beta transition. Therefore, the spin and parity of the 0.321-MeV state must be either 9/12− or 11/2− in view of the $\frac{7}{2}+$ ground state of Sb^{125}.[6] Narcisi chose the assignment $\frac{9}{2}-$.[5] On the other hand, the measurements of Inamura *et al.*[7] indicated the assignment 11/2−. The present report concerns the measurement of the directional correlation of the 0.437-MeV beta group and the 0.176-MeV gamma ray. A preliminary report of these results has been given.[8] The experimental data are related to the spin of the 0.321-MeV state in Te^{125}. In order to investigate possible restrictions imposed on the principal nuclear matrix elements that may be expected to govern this transition, the approximate formulation of the theory given by Morita and Morita[9] is employed for analysis of the limited data available on this beta decay.

The experimental setup consisted of a fixed beta detector and a gamma detector movable about the radioactive source so that the angle between the trajectories of the observed beta and gamma radiations was variable from 90° to 270°. A 1.5-in.-diam by 1-in.-thick NaI(Tl) scintillation crystal was used for gamma detection, and a 1.5-in.-diam by 2-mm-thick anthracene scintillation crystal was used for beta detection. The two detectors fed into single-channel pulse-height analyzers and a fast-slow coincidence circuit set for a resolving time of about 55 nsec.

The initial coincidence studies revealed a highly asymmetric gamma-gamma coincidence background due to Compton scattering of gamma rays of energy about 0.600 MeV. A Compton event in the beta detector followed by detection of the scattered gamma ray in the gamma detector produced absorbed energies in the range of the beta-gamma transition energies under investigation. No shielding technique was found to be adequate to eliminate this effect when the radiation detectors were set to detect beta rays and gamma rays emitted at a relative angle of 180°. The gamma-gamma background was eliminated by increasing the source-to-

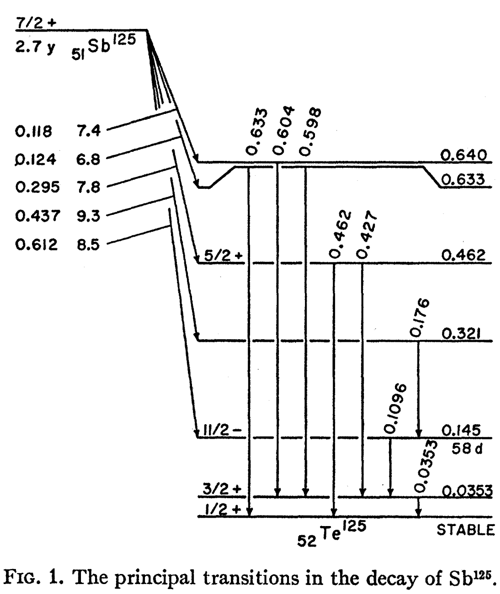

FIG. 1. The principal transitions in the decay of Sb^{125}.

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[1] K. Siegbahn and W. Forsling, Arkiv Fysik **1**, 505 (1950).
[2] J. Moreau, Arkiv Fysik **7**, 391 (1954).
[3] N. H. Lazar, Phys. Rev. **102**, 1058 (1956).
[4] G. Chandra and V. R. Pandharipande, Nucl. Phys. **46**, 119 (1963).
[5] R. S. Narcisi, Harvard Technical Report No. 2–9, 1959 (unpublished).
[6] *Nuclear Data Sheets*, compiled by K. Way, *et al.* (Printing and Publishing Office, National Academy of Sciences—National Research Council, Washington 25, D. C.).
[7] T. Inamura, T. Iwashita, Y. Ikedoto, and S. Kageyama, J. Phys. Soc. Japan **19**, 239 (1964).
[8] J. L. DuBard, Bull. Am. Phys. Soc. **11**, 530 (1966).
[9] M. Morita and R. S. Morita, Phys. Rev. **109**, 2048 (1958).

detector distance for the beta rays while the beta counting rate was maintained by magnetically focusing the beta rays.

BETA FOCUSING

Beta rays were focused into the beta detector by a pair of quadrupole magnets manufactured by Spectromagnetic Industries. The aperture between pole faces was 2 in. and the length of the pole faces was 4 in. The two magnets were mounted on aluminum supports with a separation of 7 in. between centers. The radioactive source holder was fitted onto the end of an evacuated 2-in.-o.d. aluminum pipe which extended through the aperture of the magnetic lens into a housing for the beta detector.

Focusing properties of the magnetic lens were studied experimentally using conversion electrons from the decay of Cs^{137} and Sn^{113}. Magnetizing currents in the two quadrupoles were varied to maximize the electron counting rate for various combinations of object and image distances. In addition, photographs of the distribution of electron intensity over the area of the scintillation crystal were taken for various combinations of object and image distances. The experimental data, together with the requirement for an object distance large enough to permit proper positioning of the gamma detector, led to the choice of an object distance of 4 cm and an image distance of 25.6 cm measured from the respective faces of the lens. The total source-to-detector distance was 60 cm. The resulting electron distribution over the area of the scintillation crystal was confined to a band about 0.5-cm wide. The remaining area of the scintillation crystal was masked with a thick, Lucite-lined, lead shield to further eliminate gamma rays. The effective solid angle subtended by the beta detector was determined by comparing the counting rate with that for a simple geometry. The effective source-to-detector distance for a 1.5-in.-diam scintillation crystal was found to be about 23 cm.

With the geometry of the beta-focusing system fixed, a calibration plot of focusing currents in the two quadrupole magnets versus beta energy was obtained using Cs^{137}, Sn^{113}, and Hg^{203} conversion-electron sources. The calibration plots were found to be linear. The focusing currents were such that the magnetic field at the pole faces was in the range 80 to 200 G.

EXPERIMENTAL PROCEDURE AND RESULTS

Sb^{125} was obtained as a chloride in hydrochloric acid solution from the Oak Ridge National Laboratory. A source was prepared by evaporating successive drops of the solution on a 0.25-mil clear Mylar sheet glued over the face of a shallow Lucite cylinder. The crystalline residue was lightly coated wlth a clear plastic spray. The other face of the Lucite cylinder was also covered with Mylar, so that the source was completely encapsulated except for a small pump-out hole. The source was electrically grounded through an aquadag path.

The gamma detector was necessarily positioned very close to the quadrupole magnets. A 4-in.-long Lucite light piper was inserted between the NaI crystal and the face of the photomultiplier tube to displace the photomultiplier tube from the highest magnetic field region. The tube was then magnetically shielded with a 7-in.-long cylinder of Mumetal. A 2-mm-thick lead sheet was used to form a cylindrical shield around the NaI crystal and a conical shield around the solid angle subtended by the NaI crystal in order to eliminate gamma radiation scattered by the magnets.

The directional correlation of the allowed 0.295-MeV beta group in the decay of Sb^{125} and the 0.427–0.462 MeV gamma rays was measured as a check of instrumental asymmetries. With the pulse-height analyzer set to accept beta rays in the energy range 0.235–0.275 MeV, the anisotropy was found to be 0.002 ± 0.012. The gamma-gamma coincidence background was measured at beta pulse-height analyzer settings over the range of observed beta energies. A $\frac{3}{16}$-in.-thick Lucite disk was inserted in the source end of the vacuum chamber to absorb all beta rays, and the magnets were demagnetized to avoid focusing any energetic electrons produced in the Lucite. The average ratio of the real-plus-accidental gamma-gamma coincidence counting rate to the real beta-gamma coincidence counting rate was less than 0.3% for every experiment. Therefore, the gamma-gamma coincidence background was considered negligible.

The directional correlation of the 0.437-MeV beta group and the 0.176-MeV gamma ray was measured at four beta energies between 0.255 and 0.405 MeV. This energy range was limited at the low end by the presence of another beta group in coincidence with the 0.176-MeV gamma ray. The accidental coincidence counting rate was measured periodically by inserting a 0.4-μsec time delay in the beta channel. This counting rate was checked by removing and shielding the gamma detector from the Sb^{125} source and then introducing a second

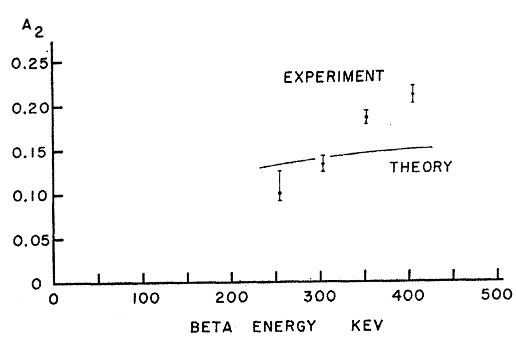

FIG. 2. The experimental directional correlation A_2 coefficients at beta energies 0.255, 0.305, 0.355, and 0.405 MeV, and the theoretical beta energy dependence of the directional correlation A_2 coefficient for the hypothesis of intermediate state spin 11/2.

TABLE I. Sb^{125} directional correlation data for the 0.437-MeV beta group and the 0.176-MeV gamma rays. ΔW represents the beta energy range accepted by the pulse-height analyzer; N_π represents the total number of real coincidence counts in the 180-deg counting position; and R represents the ratio of real-to-accidental coincidence counting rates.

ΔW (MeV)	N_π	R	A_2
0.235–0.275	28 200	5.5	0.088±0.005
	13 700		0.109±0.007
	34 300		0.106±0.004
0.285–0.325	14 100	6	0.140±0.007
	19 600		0.126±0.005
0.335–0.375	21 800	5	0.182±0.005
	21 400		0.189±0.005
0.385–0.425	13 300	2	0.235±0.008
	14 500		0.189±0.007

Sb^{125} source to the gamma detector so as to reproduce the original gamma counting rate. The results of the directional correlation measurements are given in Table I. The calculated A_2 coefficients of the second-order Legendre polynomial in the directional correlation are plotted in Fig. 2, where the experimental points represent the average of the individual measurements at each beta energy. The calculations included normalization of the coincidence counting rate to the product of the beta and gamma counting rates and correction for the finite angular resolution of the detectors according to the method of Rose[10] and the calculations of Stanford and Rivers.[11] The quoted errors represent probable statistical errors except for the lowest energy point. The A_2 coefficient for the directional correlation is observed to increase rapidly and monotonically with energy.

The gamma spectrum in coincidence with the 0.437- and 0.295-MeV beta groups was observed with the beta pulse-height analyzer set to accept beta rays in the energy range 0.235 to 0.275 MeV. This was the beta energy range used for the lowest beta-energy measurement of the A_2 coefficient. The coincidence spectrum showed that some gamma counts corresponding to an energy of 0.176 MeV in the Compton distribution from the 0.427- and 0.462-MeV gamma transitions, were observed in coincidence with beta counts in the energy range 0.235 to 0.275 MeV from the allowed 0.295-MeV beta transition. It was estimated that these coincidences possibly could contribute up to 8% of the area under the coincidence spectrum peak at gamma energy 0.176 MeV. These coincidences from an allowed beta transition would have an isotropic directional correlation with the result that the lowest beta energy measurement of the A_2 coefficient possibly could be too small by as much as 12%, as indicated by the extended error bar in Fig. 2 for the lowest energy point.

[10] M. E. Rose, Phys. Rev. **91**, 610 (1953).
[11] A. L. Stanford and W. K. Rivers, Rev. Sci. Instr. **30**, 719 (1959).

SPIN OF THE 0.321-MeV STATE

The 0.437-MeV beta transition incolves a nuclear-spin change of two units under the assumption of spin 11/2 for the 0.321-MeV state in Te^{125}. In this case, the beta transition is unique, and the beta energy dependence of the A_2 coefficient may be calculated without ambiguity. Figure 2 includes a graph of the theoretical A_2 coefficient versus beta energy, for the unique beta transition, calculated from the formulas of Kotani.[12] The formulas of Morita and Morita,[9] using the electron functions of Bhalla and Rose,[13] gave results negligibly different from these. The theoretical A_2 coefficient was adjusted arbitrarily to the value 0.140 at beta energy 0.305 MeV. This adjustment may be achieved in principle by varying the unknown gamma multipole mixing ratio. The experimental and theoretical A_2 coefficients are observed to have a much different dependence on the beta energy. This disagreement indicates that the spin of the 0.321-MeV state in Te^{125} is not 11/2.

For the 0.176-MeV gamma transition, Narcisi measured a K conversion coefficient of 0.156 and a K to L conversion ratio greater than 5.45.[5] The conversion coefficient tables of Sliv and Band give a K conversion coefficient of 0.18 and a K to L conversion ratio of 4.67 for a pure $E2$ gamma transition of energy 0.176 MeV.[14] Consideration of the magnitude of error commonly encountered in conversion-coefficient measurements and allowance for some margin of error due to approximations made in the theoretical calculations indicate that a pure $E2$ multipole assignment for the 0.176-MeV gamma ray cannot be ruled out. If this transition is pure $E2$, then the spin of the 0.321-MeV state in Te^{125} can be $\frac{7}{2}$, in which case, the absence of any spin change in the 0.437-MeV beta transition complicates the analysis of this transition to the point that any fruitful interpretation does not seem feasible. It is assumed, in accord with Narcisi[5] and the evaluation of the Nuclear Data Group,[6] that the 0.176-MeV gamma transition indeed involves some $M1$ radiation. Then the 0.321-MeV state in Te^{125} must be a $\frac{9}{2}-$ state. The most feasible experiment to establish the relative intensities of the $M1$ and $E2$ components of the 0.176-MeV transition appears to be a measurement of the ratios of the L-subshell internal conversion coefficients.

NUCLEAR MATRIX ELEMENT RATIOS

Four first-forbidden beta-decay nuclear matrix elements may be operative for the 0.437-MeV beta transition. These are $\int \boldsymbol{\sigma}\times\mathbf{r}$, $\int \boldsymbol{\alpha}$, $\int \mathbf{r}$, and $\int B_{ij}$. Matrix element $\int \boldsymbol{\alpha}$ is related to $\int \mathbf{r}$ through the parameter Λ

[12] T. Kotani, Phys. Rev. **114**, 795 (1959).
[13] C. P. Bhalla and M. E. Rose, Oak Ridge National Laboratory Report No. ORNL-3207, 1961 (unpublished).
[14] L. A. Sliv and I. M. Band, *Gamma-Rays* (Academy of Sciences of the USSR, Moscow-Leningrad, 1961).

defined by Ahrens and Feenberg.[15]

$$\Lambda \frac{\alpha Z}{2R} \int \mathbf{r} = -i \int \boldsymbol{\alpha}.$$

It is convenient to define two other parameters, x and u, in notation adapted from Kotani[12]:

$$x = -\frac{C_V}{C_A} \frac{\int \mathbf{r}}{\int B_{ij}}, \quad u = \frac{i \int \boldsymbol{\sigma} \times \mathbf{r}}{\int B_{ij}}.$$

The theoretical directional correlation A_2 coefficient may be expressed in terms of the three independent nuclear matrix-element parameters Λ, x, and u, and the gamma multipole mixing ratio δ. The ratio of the A_2 coefficients at two different beta energies is independent of δ.

Using the ratio of the experimental A_2 coefficients at beta energies 0.368 and 0.287 MeV and a range of independent variables Λ and x, a fourth-order equation in parameter u was solved algebraically using a digital computer. The formulas of Morita and Morita[9] for the A_2 coefficient were programmed using both the electron functions of Bhalla and Rose[13] and the approximation $(\alpha Z)^2 \ll 1$ which results in the formulas of Kotani[12] with his Coulomb corrections λ_i equated to unity. The ratio of the A_2 coefficients at beta energies 0.368 and 0.287 MeV, corresponding to normalized beta momenta of 1.4 and 1.2, was taken from a straight line drawn between these energies to best fit the experimental data of Fig. 2. A greater ratio and a lesser ratio, determined by consideration of the experimental error limits, were also used in separate computer calculations. For each solution for parameter u, a quadratic equation in the mixing ratio was solved using an experimental value for the A_2 coefficient at beta energy 0.287 MeV.

Results of the computer calculations are given in the three parts of Fig. 3. All combinations of x and Λ which were investigated gave two real solutions for u. Only one solution for u, at most, gave real solutions for the mixing ratio. The three parts of Fig. 3 show regions of the $x\Lambda$ plane in which real solutions for the mixing ratio were obtained. The behavior of parameter u is indicated by the slope of the cross hatching as specified in the key. Region C contains negative values of both u and δ; regions A and B contain positive values of both u and δ. Figure 3 shows solutions obtained using the electron functions of Bhalla and Rose.[13] Use of the approximation $(\alpha Z)^2 \ll 1$ resulted in similar regions of solutions. In general, region B was displaced upward in the Λ direction by about 0.4, and region C was wider and extended to larger negative values of x. Parameter Λ was investigated in the range from 0 to 5 and parameter x in the range from -10 to $+10$.

Both parameters x and u are bounded away from

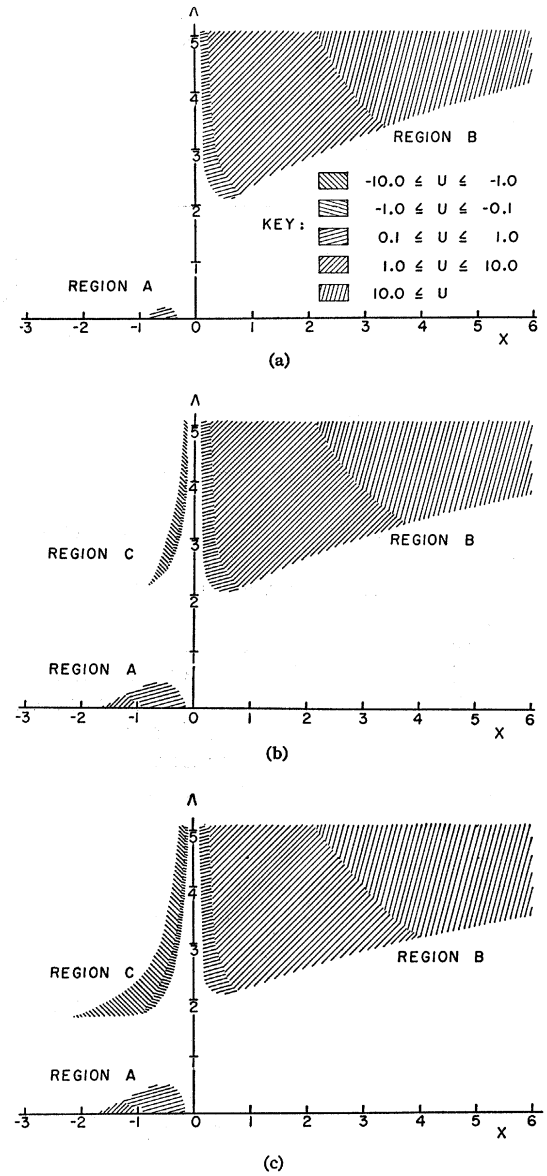

FIG. 3. Nuclear matrix-element parameters Λ, x, and u, consistent with the experimental beta-energy dependence of the A_2 coefficient. Parts (a), (b), and (c) give results for three different ratios, within experimental error limits, of the A_2 coefficients at beta energies $W_1=0.368$ MeV and $W_2=0.287$ MeV. (a) $A_2(W_1)/A_2(W_2)=1.786$, $A_2(W_2)=0.112$. (b) $A_2(W_1)/A_2(W_2)=1.559$, $A_2(W_2)=0.127$. (c) $A_2(W_1)/A_2(W_2)=1.488$, $A_2(W_2)=0.127$.

zero; so the matrix elements $\int \boldsymbol{\sigma} \times \mathbf{r}$ and $\int \mathbf{r}$ make an appreciable contribution to the beta transition. The parameter Λ is observed to have a forbidden range extending from about 0.6 to 1.6. Possible solutions for Λ exist which are compatible with the approximate value of 2.34 predicted by Fujita on the basis of the conserved vector current theory of the beta interaction[16] but not with the approximate value of 0.94 predicted by Ahrens

[15] T. Ahrens and E. Feenberg, Phys. Rev. **86**, 64 (1952).

[16] J. Fujita, Phys. Rev. **126**, 202 (1962).

and Feenberg.[15] The pair of solutions for the mixing ratio consisted in general of one value representing a predominantly $E2$ gamma transition and the other value representing a predominantly $M1$ gamma transition.

The beta-energy dependence of the A_2 coefficient was calculated in a second computer program using about 100 sets of independent variables Λ, x, u, and δ, corresponding to points over the entire range of solutions in Fig. 3. No significant difference in the beta-energy dependence of the A_2 coefficient was found among these various sets of variables. Three representative calculations are plotted in Fig. 4, superimposed upon the experimental data points. The second computer program also calculated the ratio of the beta-energy-

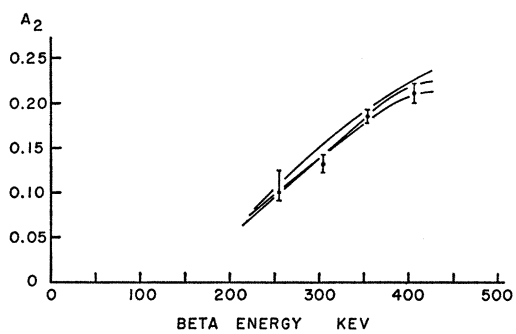

FIG. 4. Three representative curves of the theoretical beta-energy dependence of the directional correlation A_2 coefficient, each calculated from a set of intependent variables Λ, x, u, and δ, superimposed upon the experimental data points.

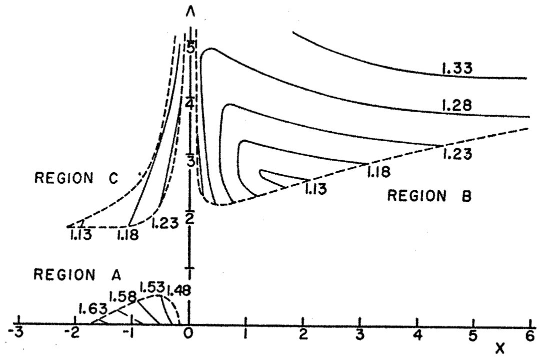

FIG. 5. The theoretical ratio of the beta-energy-spectrum shape-correction factors at beta energies 0.410 and 0.287 MeV. The unique shape-factor ratio is 1.48.

spectrum shape-correction factors at beta energies 0.410 and 0.287 MeV. These results are represented by contour lines in the $x\Lambda$ plane of Fig. 5. The corresponding unique shape factor ratio is 1.48. It appears that an accurate measurement of the shape factor could decide for or against region A which involves a range of parameter Λ smaller than that predicted by either Ahrens and Feenberg[15] or Fujita.[16]

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