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Properties of the Second Vibrational Level in Te[124]†

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$\beta\gamma$-γ coincidences in the decay of 60-day Sb^{124} were studied in order to determine the angular correlations in the γ-γ cascades from the two states of the second vibrational level in Te^{124}, and to determine the relative intensities of the beta transitions to these states. We conclude that the state at 1.248 MeV has spin 4 and the one at 1.326 MeV has spin 2, that the 2-2 transition is 94% quadrupole ($\delta=4.1\pm0.6$), and that the intensity of the beta transition to the spin-4 state is 5/9 ($\pm15\%$) of that to the spin-2 state.

I. INTRODUCTION

SIXTY-day Sb^{124} has been the subject of numerous investigations ever since Fermi and his co-workers first made it in their experiments with the thermalized neutrons they had just discovered.[1] The beta decay is complex[2] and consists of allowed transitions to high-energy levels (above 2 MeV) in Te^{124} and high-energy first forbidden transitions (with unusually high *ft* values) to lower lying levels in Te^{124}. The highest energy beta group, which leads to the first excited state in Te^{124}, has been analyzed and all its matrix elements have been determined.[3] The problem of how much of the second beta group goes to each of the two states of the second vibrational level has not been settled previously.[4] The answer will affect the subtraction procedures used in analyzing the beta spectrum, and will affect the analysis of the beta-decay matrix elements to these two states.

The measurement of the angular correlation of the gamma rays would determine the spins sequences and multipolarities of the radiation of the states. While it is generally true that cascades from the second excited state in even-even nuclei usually lead to unambiguous spin assignments when there is no ambiguity as to which cascade is being measured, complex decays such as we have here do not allow for separation of the effects of inner groups. Lindqvist and Marklund[5] applied the theory of correlation between the first and the third gamma in a cascade and concluded that the spin of the 1.326-MeV level is 2 and that the 2-2 transition is $50\pm10\%$ quadrupole. Not only is their result at variance with the systematics of the even Te nuclides[6] but the "1st gamma-3rd gamma" interpretation of the gamma coincidences they measured is ambiguous on inspection. Paul[4] also claims that $\delta=0.8(+0.2,-0.7)$ on the basis of a comparison of β–γ angular correlations. However the interpretation of γ-γ angular correlation measurements is usually more reliable than that of β-γ ones.

In the present experiment the γ-γ angular correlation is measured in coincidence with a beta ray. By raising the level of discrimination of the beta spectrum, we are able to eliminate all cascades except those from the second vibrational level. The relative intensity of the coincidences in each of the two cascades gives us the relative branching ratio of the beta groups to the two states.

Figure 1 shows the major features of the decay.

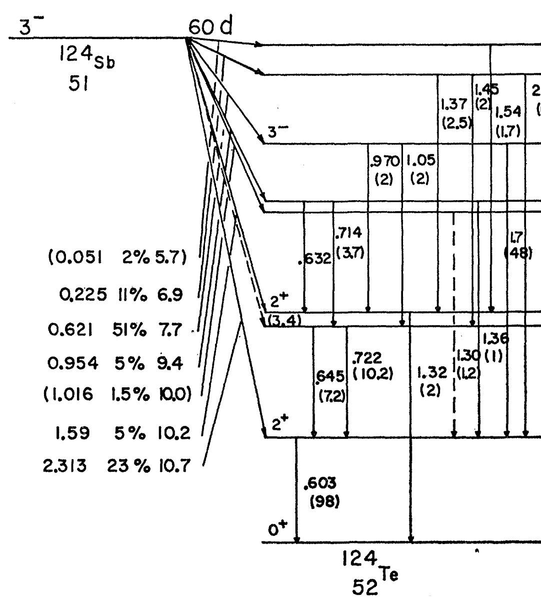

FIG. 1. Decay scheme of 60-day ^{124}Sb. This scheme is taken from the Nuclear Data Sheets NRC 60-6-76. All energies in MeV, all intensities as percentages of Sb^{124} decays. Transitions of intensity less than 1% are omitted.

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II. DESCRIPTION OF THE EXPERIMENTAL APPARATUS

The gamma detectors consisted of a 3-×3-in. Harshaw integral line detector (NaI mounted on a 6393 DuMont tube) and a $1\frac{3}{4}$-×2-in. NaI crystal on a 56AVP tube. The beta detector was a $\frac{1}{2}$-×$\frac{1}{2}$-in. right cylinder of Pilot A plastic scintillator mounted with a 2-in.-high Lucite light pipe on a 56AVP photomultiplier. The source was SbOCl (dry), placed in a small hole in the center of the scintillator and sealed with epoxy. The beta counter was placed vertically in the center of the angular correlation table, and its symmetry axis was the axis of rotation of the gamma counters. The beta detector had no external reflector and was light sealed by a $\frac{1}{32}$-in. aluminum cap. The gamma detector had lead cones that exposed the central 1 in. of the smaller crystal, and the central 2 in. of the larger one, to the source. There was a $\frac{1}{8}$-in. Pb absorber across the face of the larger crystal and a $\frac{1}{8}$-in. Al absorber across the face of the smaller one. Final alignment of the beta counter was made by assuring cylindrical symmetry in the single counting rates of the gamma counters, and the solid angle corrections were made using annihilation radiation from a Na^{22} source prepared and mounted in the same way as the Sb source was.

The electronics consisted of "fast slow" circuitry using double delay line amplifiers for the "slow" and tunnel diode circuits for the "fast" (Hamner XN690). The output of the beta counter went through an in-line (50-Ω) attenuator to a tunnel diode discriminator, and from there through a 50-Ω delay box to another discriminator that fed it into the triple coincidence circuit (with the two gamma pulses). The beta resolution was very poor and was not actually determined. The stability of the discrimination level, however, was excellent—in the course of three months the change in the fraction of the beta spectrum transmitted corresponded to a change of less than $\frac{1}{2}$ dB at 24 dB (i.e. 10% change in gain). Most of the data were taken with a 20-μ Ci source and there was no trouble with beta rates of up to 5×10^5 sec^{-1} (on a 10-Mc/sec scaler). The resolving time of the coincidence circuit (2τ) was 10^{-8} sec, and the coincidence detection efficiency was 100% (i.e., negligible time slewing near threshold).

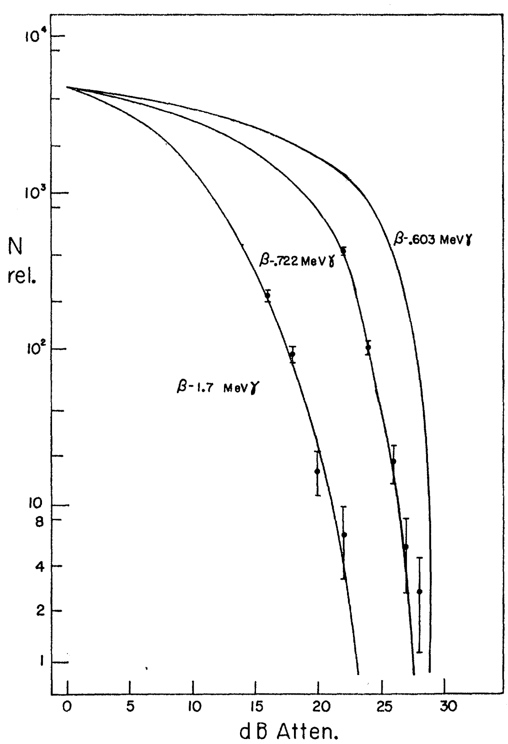

FIG. 2. Attentuation of the beta spectrum. All graphs are β–γ coincidence counts. However the shape of the β-0.603-MeVγ coincidences graph is identical with that of the β singles graph.

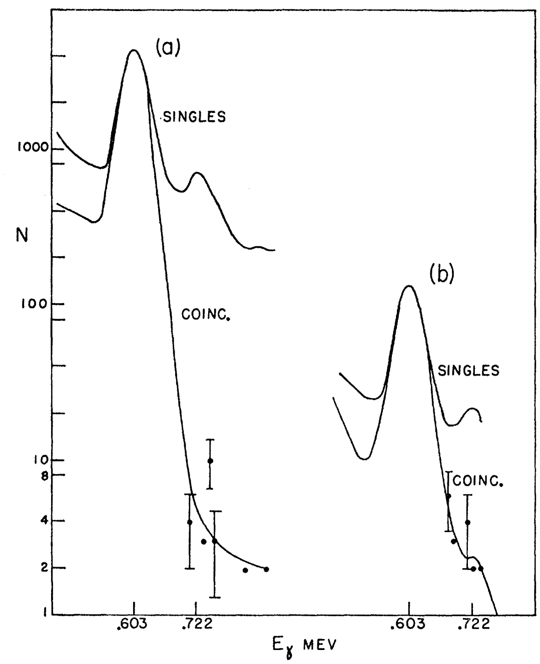

FIG. 3. Effect of coincidence gating on γ spectra. The γ spectrum in the first counter either ungated (singles), or gated by β-γ-γ fast coincidences and pulse height selected γ_2 in second counter. (a) $\gamma_2=1.7$ MeV (b) $\gamma_2=0.722$ MeV. The small peak at 0.722 MeV in case (b) is not due to chance coincidences but to the inclusion in γ_2 in this case of some 0.603-MeV gammas.

III. THE MEASUREMENTS

Figure 2 is a plot of the counts of β-singles (N_β) and β-γ coincidences ($N_{\beta-\gamma}$) versus attenuation of the β spectrum. With perfect resolution each decibel setting would correspond to an energy in the beta spectrum; the counts at that setting would correspond to the part of the beta spectrum above that energy. While the resolution was too poor to enable a calibration of dB in terms of energy (especially near the end points of the β spectra) the probabilities of β detection ($N_{\beta-\gamma}/N_\gamma$) of the most prominent groups ($\beta-0.603$-MeVγ and $\beta-1.7$-MeVγ) were consistent with what is generally known about the β spectrum. (For these comparisons a theoretical spectrum without shape factors was computed from the data of the Nuclear Data Group). The spectrum of β singles and $\beta-0.603$-MeV γ coincidences were identical as would be expected from the fact that the intensity of that γ ray is practically 100%. The probability of β detection at 0 dB was 47.7%, the probability of detecting a β from the 620-keV β transition ($N_\beta-1.7$-MeV$\gamma/N1.7$-MeVγ) was 37.7% of all 620-keV transitions (=19.3% of all β decays).

The 0.603-MeV and 1.7-MeV peaks in the γ spectrum were predominantly due to those γ rays and were used for calibrating the pulse-height selection of the γ rays for the "slow" coincidences. The 0.645-MeV line was completely submerged by the 0.603-MeV line and the 0.645-MeV and 0.722-MeV lines were barely resolvable. Thus the height of the 0.722-MeV γ peak in coincidence with the 0.603-MeV γ-high-energy β could not be directly compared to the 0.645-MeV γ in coincidence with the above combination. The chance rate, at least in the $\beta-0.722$-MeV $\gamma-0.603$-MeV γ coincidences, was negligible as can be surmised from Fig. 3. In this situation measuring the chance rate by delaying the input from one of the γ counters while the 0.603-MeV γ-β coincidences are left on time will give an indication of the chance rate. This is so because pile-up pulses in this case, while they confuse the description of the spectrum do not contribute false coincidences due to "true fast-false slow" combinations (the $\frac{1}{8}$ in. of lead in front of the large counter was put in to ensure that a fast triple coincidence signal was due to a true event in each detector). The actual rate will then be $P(\beta)\times N_1 \times N_2\times 2\tau$ if only one counter is set on the 0.603-MeV γ line and twice that if both are set there, where $P(\beta)$ is the probability of β detection at that dB setting and N_1 and N_2 are the γ counts in the two counters.

TABLE I. Angular correlations in Te^{124}.

Cascade	dB	A_2	δA_2	A_4	δA_4	Chance
1	18	0.109	0.016	0.2	0.02	1%
1	22	0.107	0.026	0.22	0.04	1.5%
1	24	0.128	0.07	0.24	0.09	3%
theoretical[a]		0.11	0.03	0.308	0.008	···
2	18	0.10	0.01	0.06	0.01	8.5%
2	22	0.083	0.019	0.05	0.03	11%
theoretical[b]	···	0.102	···	0.009	···	···

[a] 2-2-0, $\delta=4.1\pm0.6$.
[b] 4-2-0.

One counter was set on the full width of the 0.603-MeV line (up to 0.685 MeV) and the other detector counted in two channels—one on the full width of the 0.603-MeV line (up to 0.685 MeV), the other on the 0.722-MeV line (down to 0.685 MeV). Coincidences were measured at 90°, 135°, and 180° at 18, 22, and 24 dB and the data are shown in Fig. 4. They were solved for A_2 and A_4 (the coefficients of the even Legendre polynomials of the angular distribution), corrected for angular resolution, and the spin and multipolarity assignments made. The theoretical correlations of those spin and multipolarity assignments were then modified for angular resolution and plotted in Fig. 4.

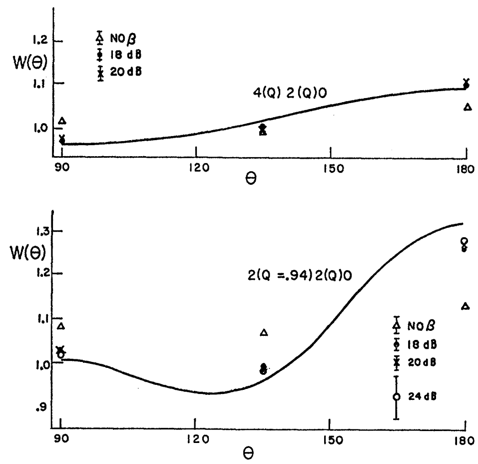

FIG. 4. Angular correlations in Te^{124}. The γ-γ angular correlations with and without β conditions for the cascades from the 1.258-MeV (upper graph) and 1.328-MeV (lower graph) levels in Te^{124}. The curves are the theoretical ones corrected for angular resolution.

Table I summarizes the results of the angular correlation measurements. Since A_2 is the same for both cascades the fact that they cannot be completely resolved does not affect it. On the other hand, the A_4 coefficient gives a clear indication of the extent of admixture. We conclude that approximately 20% of the coincidences in each cascade are due to the other one.

The effective solid angle for the 4-2-0 cascade was twice that for the 2-2-0 one. The fraction of the 0.645-MeV γ spectrum transmitted by the 0.645-MeV channel was equal (±10%) to the fraction of the 0.722-MeV γ transmitted by the 0.722-MeV channel. The number of coincidences in the 4-2-0 cascade was 1.5 times that in the 2-2-0 one. Correcting for a 10% chance rate in the 4-2-0 coincidences and a 20% crossover from the spin-2 state, we conclude that the intensity of the β decay to the spin-4 state is 5/9±15% of the intensity of the β decay to the spin-2 state. This agrees with the estimate of H. Paul[4] for the branching ratio of 1.2-MeV β-γ coincidences (after subtraction of the $\beta-0.603$-MeV γ coincidences).

IV. CONCLUSIONS

The second group in the beta decay of 60-day Sb^{124} (end point ≈1.6 MeV) consists of two transitions, one to a spin-2 state at 1.326 MeV and one to a spin-4 state at 1.248 MeV with relative intensities 5 and 9 ($\pm 15\%$), respectively. The 0.722-MeV transition from the spin-2 state to the spin-2 first excited state is 94% quadrupole and 6% dipole ($\delta = 4.1 \pm 0.6$).

The introduction of a β condition in the study of γ-γ angular correlations has proved to be not too difficult and it should be very useful in reducing ambiguities in the interpretation of the γ rays involved in γ-γ cascades in complex beta decays.

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Expectation Values of Various Operators in the Triton

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The trial functions used in a calculation of the triton binding energy with realistic forces have been used to derive the expectation values of a number of operators. These include the Coulomb energy for point and for finite protons; various products of powers of the interparticle distances; and the charge and magnetic moment form factors as given by Schiff.

INTRODUCTION

As a by-product of our calculations of the triton binding energy[1] we have calculated the expectation values of a number of simple operators over the variational ground-state functions which we have used.

These operators are of three types:

(1). Coulomb energy operators. We have calculated the expectation value of the Coulomb energy for both point protons and for protons of finite size, with parameters as given by Pappademos.[2]

(2). Products of powers of the three interparticle distances, $r_{12}{}^{\alpha} r_{23}{}^{\beta} r_{31}{}^{\gamma}$.

(3). Charge and magnetic moment form factors. We have calculated the form factors F_1 and F_2 defined by Schiff.[3]

We give here the results for two distinct wave functions ψ_1 and ψ_2.

The first of these is the wave function used in the calculations of Blatt, Derrick, and Lyness[4]; the second is derived from this by adding a component representing a neutron bound to a deuteron, and is the function (A) of a previous note.[1] In each case, results are given for three potentials, which we label Hamada,[5] Yale,[6] and Gammel-Brueckner (GB).[7] The matrix elements have not been calculated for the (better) wave functions (B) and (C) of Ref. 2.

(1) Coulomb energy for point and for finite protons. The Coulomb energy operator for point protons is

$$C(r_{12}) = e^2/r_{12}, \qquad (1)$$

while for protons of finite size the appropriate expression has been given by Pappademos,[2] assuming the protons to be undistorted within the triton. Using the same parameters for the proton charge distribution as does Pappademos, we obtain the results given in Table I. In this table we include for reference the variational

TABLE I. The Coulomb energy of He^3 for point and finite proton (MeV).

Potential	GB		Hamada		Yale	
Wave functions	ψ_1	ψ_2	ψ_1	ψ_2	ψ_1	ψ_2
Point protons	0.692	0.616	0.717	0.549	0.691	0.520
Finite protons	0.661	0.593	0.685	0.532	0.662	0.505
$E(H^3)$	−5.72	−6.186	−2.57	−4.35	−2.54	−4.24

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