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Electron-Capture and β^- Decay of ^{122}Sb Oriented in Iron*

K. S. Krane, James R. Sites, and W. A. Steyert
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico 87544

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Angular distributions have been measured of γ radiations emitted in the decay of ^{122}Sb nuclei oriented at low temperatures in an iron lattice. Angular momentum admixtures in the (first forbidden) β radiation fields have been deduced; results indicate that the component of the radiation field carrying away two units of angular momentum contributes to the electron-capture decay to ^{122}Sn with at least twice the magnitude as to the β^- decay to ^{122}Te. These results are interpreted in terms of particle-hole correlations in the nuclear shell model. In addition, the $E2/M1$ mixing ratio of the 691-keV γ transition in ^{122}Te is deduced to be -2.90 ± 0.25.

I. INTRODUCTION

The observation of anisotropic angular distributions emitted by nuclei polarized at low temperatures has been known for a number of years to be a fruitful method of obtaining information concerning radiation fields emitted in radioactive decay.[1,2] However, only in the last few years has it become possible to achieve sufficiently low temperatures (4 mK) in magnetic foils to observe the complete angular distribution of the radiations emitted from highly aligned ensembles of nonmagnetic nuclei.

Previous investigations[3-5] of the decay of oriented ^{122}Sb nuclei have been performed, but the inability to achieve sufficiently low temperatures resulted in relatively large uncertainties for the deduced parameters of the ^{122}Sb decay. For this reason, we have undertaken a new investigation of the angular distribution of γ radiation emitted by oriented ^{122}Sb nuclei.

II. DECAY OF ^{122}Sb

The decay scheme of 2.8-day ^{122}Sb to levels in ^{122}Sn and ^{122}Te is shown in Fig. 1. The essential features of the decay scheme were deduced by β and γ spectroscopy[6] and by measurement of β-γ and γ-γ angular correlations.[7] The relative simplicity of the β-ray spectrum has permitted a number of precise investigations of the β-γ angular correlation,[8-10] including the β-ray energy dependence and the γ-ray circular polarization. Such knowledge has facilitated attempts at extracting the nuclear matrix elements associated with the first-forbidden β transitions emitted in the decay of ^{122}Sb.[10-13]

According to the shell model, the ^{122}Sb nucleus consists of an odd neutron in the $h_{11/2}$ state and an odd proton in the $g_{7/2}$ state, in addition to an even number of protons and neutrons coupling pairwise to a zero-spin core. β transitions to the lowest available shell-model states of ^{122}Sn or ^{122}Te thus consist of a transition from a $g_{7/2}$ proton to an $h_{11/2}$ neutron or from an $h_{11/2}$ neutron to a $g_{7/2}$ proton, respectively. Such transitions must carry at least two units of angular momentum, and so in the first-forbidden β transition from ^{122}Sb to the phonon states of ^{122}Sn and ^{122}Te, only the $\int B_{ij}$ matrix element should contribute to the β radiation field.

By considering the effect of residual pairing and quadrupole interactions on shell-model states, Kisslinger and Wu[14] were able to estimate the magnitudes of the β-decay matrix elements for transitions from shell-model states in odd-odd nuclei to vibrational states in even-even nuclei. Their calculation indicated that if one considers neighboring shells outside the major shell, matrix elements other than the $\int B_{ij}$ can contribute, and that a cancellation occurs between terms corresponding to particle-particle and hole-hole β transitions which tends to reduce considerably the $\int B_{ij}$ value. An interesting exception was found to occur in cases in which the daughter nucleus has a magic number of either protons or neutrons, in which case both protons and neutrons could *not* contribute to the vibrational state in the daughter nucleus, and the cancellation could not occur. Thus, according to the Kisslinger-Wu calculation, β transitions to vibrational levels in singly magic nuclei should show larger $\int B_{ij}$ matrix elements than for transitions to nonmagic nuclei.

The decay of ^{122}Sb provides an opportunity to compare directly the $\int B_{ij}$ contribution for the β^+ (electron-capture) decay to ^{122}Sn (with a magic number of 50 protons) with that to ^{122}Te; Kisslinger and Wu[14] predict that the $\int B_{ij}$ contribution for the former should be some 5 times larger than that for the latter. The angular distribution of γ radiation following β radiation from oriented nuclei provides information regarding the multipole character of the (unobserved) β radiation field; thus, measurement of γ radiation from the decay of oriented ^{122}Sb nuclei should enable the relative admixture of the component of the β radiation fields carrying away two units of total angular momentum to be deduced, from which comparisons can be made regarding the relative $\int B_{ij}$ contributions to the β radiation fields in the decay to ^{122}Te with that in the decay to ^{122}Sn.

III. EXPERIMENTAL DETAILS

Radioactive sources of ^{122}Sb in iron were prepared by neutron irradiation (approximately 10^{17} neutrons/cm^2) of a Sb-Fe alloy. The alloy was produced by arc-melting Sb (highly enriched in ^{121}Sb) and 99.99% pure iron, the purity of which was confirmed (to a factor 3 in total impurities) by spectroscopic analysis, and by analyses for carbon, sulfur, and phosphorus. The alloy contained approximately 0.3-at.% Sb, and was rolled to a thickness of 60 μ. Following the irradiation, a small amount of ^{54}Mn in HCl solution was dried on the surface of the foil, and the foil was annealed in a hydrogen-argon atmosphere for 1½ h at 900°C and for 1½ h at 1100°C. A surface etch was then performed to remove any surface impurities as well as any undiffused ^{54}Mn.

At the beginning of the measurement the activity of the source consisted of 0.03 μCi of ^{54}Mn and 5 μCi of ^{122}Sb.

The orientation of the source was achieved by polarizing the iron foil in an externally applied magnetic field of 2 kG at temperatures in the range 4–20 mK. The low temperatures were obtained using a ^{3}He-^{4}He dilution refrigerator together with a cerium magnesium nitrate adiabatic demagnetization stage. The source foil was indium soldered to the base of a split copper tube, which was thermally connected to the demagnetization stage by copper wires. More complete descriptions of the apparatus have been given previously.[15,16]

The γ rays were observed using two 40-cc Ge(Li) detectors placed at 0 and 90° relative to the axis of polarization. Our statistical error was limited by the low counting efficiency of the Ge(Li) detectors for the weak, high-energy 1140- and 1260-keV γ rays; however, the use of NaI detectors was excluded because of the necessity of resolving the ^{122}Sb γ rays from the 1095- and 1290-keV γ rays of the ^{59}Fe produced by the neutron irradiation. The output of each detector preamplifier was fed to a shaping amplifier and then stored in a 400-channel analyzer. A typical γ-ray spectrum obtained with the Ge(Li) detectors is shown in Fig. 2.

The procedure involved in performing the experiment has been discussed in a previous publication.[16] The observed counting rates, obtained from analysis of the multichannel-analyzer spectra, were normalized by the (isotropic) "warm" counting rates ($T > 0.2$°K), and then fit to an equation of the form

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

with the normalization such that $Q_0 = B_0 = U_0 = A_0 = 1$. Assuming parity conservation, only even values of k are permitted. For the transitions considered in the present work, $k \leq 4$. The orientation parameters B_k are determined from the temperature T and from the hyperfine energy splitting $\Delta(=\mu H/Ik_B$; k_B = Boltzmann constant) of the initial oriented

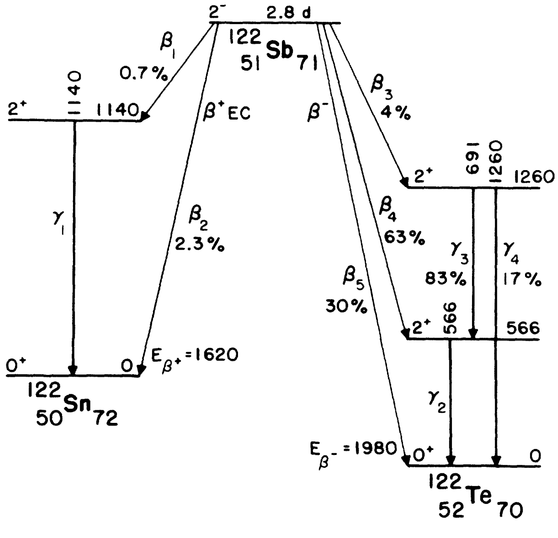

FIG. 1. Decay scheme of ^{122}Sb.

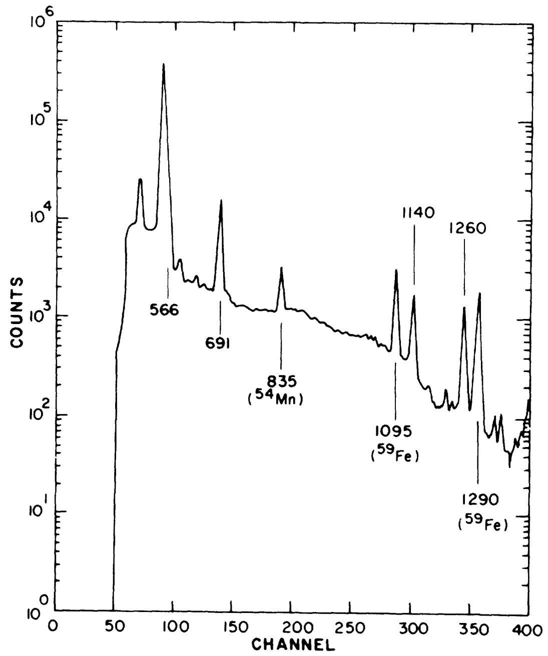

FIG. 2. Spectrum of γ rays emitted in the decay of ^{122}Sb observed with a Ge(Li) detector.

state. The deorientation parameters U_k contain information concerning the multipolarities of any unobserved intermediate radiations, and the angular distribution coefficients A_k describe the properties of the observed γ ray. The geometrical correction factors Q_k correct for the finite angular resolution of the detectors, and have been tabulated for Ge(Li) detectors by Camp and Van Lehn.[17]

For decays considered in the present work, the deorientation is due to a $2^- - 2^+$ β transition, in which case

$$U_2 = |\alpha_0|^2 + 0.500|\alpha_1|^2 - 0.214|\alpha_2|^2, \tag{2a}$$

$$U_4 = |\alpha_0|^2 - 0.667|\alpha_1|^2 + 0.286|\alpha_2|^2, \tag{2b}$$

where $|\alpha_L|^2$ is the relative intensity of the component of the β radiation field carrying away L units of total angular momentum $(\sum_L |\alpha_L|^2 = 1)$.

Previous investigations have resulted in values for the internal magnetic field H of Sb in Fe (230 kG)[18] and for the magnetic dipole moment μ of the ^{122}Sb ground state $(1.904\mu_N)$[3]. In principle, therefore, the hyperfine splitting Δ_{Sb} is known, and the orientation parameters B_k can be uniquely determined from the temperature T. In addition, each of the three excited levels populated in the decay of ^{122}Sb is deexcited by a pure $E2$ γ transition, for which the A_k are uniquely determined. Thus, the only unknown parameters to be determined are the U_k for the β radiations.

IV. RESULTS

A. β-Decay Parameters

Because of the relatively long spin-lattice relaxation time[18] of Sb in Fe as compared[19] to Mn in Fe, for the first few minutes following the demagnetization the temperature obtained from the anistropy of the ^{54}Mn γ ray will not be equal to the "true" antimony temperature. Since the first measurements are at the lowest temperatures, these measurements will exhibit the largest anisotropies and thus will contain the most information. It is therefore desirable to have an accurate knowledge of the antimony temperature during this time. Such knowledge may in principle be obtained from the angular distribution of a Sb γ ray, but since all Sb γ rays have unknown deorientation coefficients, there is some uncertainty inherent in this process.

In order to determine the deorientation parameter associated with the 566-keV γ ray, the observed counting rates of the 566-keV γ ray in the 0° direction were plotted as a function of the factor T/Δ_{Mn} determined from the anisotropy of the ^{54}Mn-γ ray; such a plot is shown in Fig. 3. The solid lines represent theoretical curves, computed by assuming a value for U_2 associated with β_4 (see Fig. 1) and adjusting the parameter $\Delta_{\text{Sb}}/\Delta_{\text{Mn}}$ to provide the best fit to the data points. (It should be noted here that we are referring to the U_k associated with the β decay only. A decrease of 5% in U_2 is necessary to take into account the depolarization due to the 691-keV γ ray.) The coefficient $U_4(\beta_4)$ was determined by assuming the relationship obtained by Bradley, Pipkin, and Simpson[4] of $U_2/U_4 = 1.2 \pm 0.2$. It is apparent from Fig. 3 that values of $U_2(\beta_4)$ less than 0.8 do not provide good fits to the data points, and that $U_2(\beta_4)$ must be close to 1.0. Figure 4 illustrates a similar set of curves, all drawn for $U_2(\beta_4) = 0.95$, with the value $\Delta_{\text{Sb}}/\Delta_{\text{Mn}} = 1.1$ providing the best fit to the data. The best over-all fit to the data points is obtained for

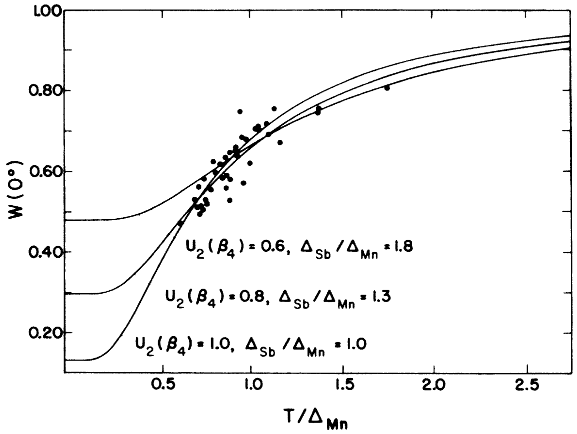

FIG. 3. Counting rate of 566-keV γ ray observed in the direction of the orientation axis, as a function of the factor T/Δ_{Mn}. The solid lines are computed for various values of the deorientation parameters U_k (β_4) and for the most favorable corresponding value of $\Delta_{\text{Sb}}/\Delta_{\text{Mn}}$.

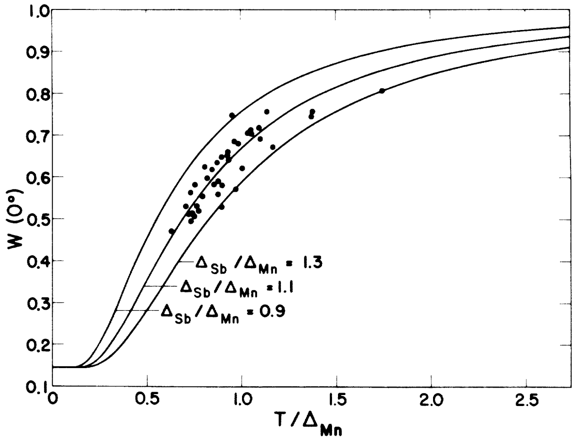

FIG. 4. Counting rate of 566-keV γ ray observed in the direction of the orientation axis, as a function of the factor T/Δ_{Mn}. The solid lines are computed for various values of the relative hyperfine energy splittings $\Delta_{\text{Sb}}/\Delta_{\text{Mn}}$, with $U_2(\beta_4)$ fixed at 0.95 and $U_2/U_4 = 1.2$.

$$\Delta_{\mathrm{Sb}}/\Delta_{\mathrm{Mn}} = 1.13 \pm 0.05,$$

$$U_2(\beta_4) = 0.95^{+0.05}_{-0.10},$$

$$U_4(\beta_4) = 0.8 \pm 0.2.$$

These results may then be employed to analyze the angular distribution of the other γ rays emitted in the ^{122}Sb decay. The results of such an analysis are summarized in Table I and are discussed below.

1260 keV. The A_k for this pure $E2$ transition are uniquely determined, and thus

$$U_2(\beta_3) = 0.899 \pm 0.025,$$

$$U_4(\beta_3) = 1.00 \pm 0.23.$$

From Eqs. (2a) and (2b), we obtain

$$|\alpha_1(\beta_3)|^2 = 0.00^{+0.11}_{-0.00},$$

$$|\alpha_2(\beta_3)|^2 = 0.08^{-0.06}_{+0.02}.$$

1140 keV. This transition is also pure $E2$, and thus

$$U_2(\beta_1) = 0.828 \pm 0.026,$$

$$U_4(\beta_1) = 1.13 \pm 0.23,$$

from which follow

$$|\alpha_1(\beta_1)|^2 = 0.00^{+0.10}_{-0.00},$$

$$|\alpha_2(\beta_1)|^2 = 0.16^{-0.05}_{+0.03}.$$

691 keV. Using the above results for $U_k(\beta_3)$, we obtain

$$A_2(\gamma_3) = 0.447 \pm 0.016,$$

$$A_4(\gamma_3) = 0.23 \pm 0.10.$$

From the value of A_2, the $E2/M1$ mixing ratio of γ_3 is computed to be

$$\delta(\gamma_3) = -2.90 \pm 0.25 \quad \text{or} \quad -0.93 \pm 0.04,$$

using the mixing-ratio sign convention from Krane and Steffen.[20] The former value of δ requires $A_4 = 0.27$ and the latter, $A_4 = 0.14$. Both A_4 values are within the range of uncertainty of the measured A_4, with the larger value of δ providing slightly better agreement. Directional correlation measurements[6, 7, 21] have yielded $\delta = -3.40 \pm 0.07$, also in agreement with the larger of our values. Thus we conclude

$$\delta(691) = -2.90 \pm 0.25.$$

566 keV. The values deduced above for $U_k(\beta_4)$ may be interpreted in terms of the multipolarities of the β radiation field as

$$|\alpha_1(\beta_4)|^2 = 0.1 \pm 0.1,$$

$$|\alpha_2(\beta_4)|^2 = 0.00^{+0.05}_{-0.00}.$$

The angular momentum multipole components deduced for the β radiation fields are summarized in Table II.

B. Hyperfine-Splitting Parameters

Based on the currently accepted values of the hyperfine splitting energies of Sb and Mn, $\Delta_{\mathrm{Sb}} = 8.0$ mK and $\Delta_{\mathrm{Mn}} = 9.1$ mK,[19] the ratio $\Delta_{\mathrm{Sb}}/\Delta_{\mathrm{Mn}} = 0.9$; this is not in good agreement with the value 1.1 deduced above. It is unlikely that the explanation lies in incorrect Sb parameters. Previous investigations[15, 16] of Sb isotopes in Fe have been consistent with the accepted hyperfine-field value (230 kG).[18] In order to confirm the value of the ^{122}Sb magnetic moment, an additional experiment was performed in which the angular distribution of the 566-keV γ ray was observed using a separate ^{60}Co in Fe foil (indium soldered to the Sb-Fe foil) as a thermometer. The two foils were maintained in thermal equilibrium at $T \sim 19$ mK, so that relaxation effects need not be considered. Based on the value $U_2(\beta_4) = 0.95$, we deduced $\Delta_{\mathrm{Sb}} = 8.1 \pm 0.1$ mK, which yields the value $\mu = 1.92 \pm 0.02 \mu_N$, in good agreement with Ref. 3.

Thus the reason for the discrepancy between the values of the ratios of the hyperfine-splitting energies must lie with the Mn. The source used for the experiment contained only a small amount of ^{54}Mn; the peak-to-background ratio of the 835-keV γ ray was only 1 : 2. Small amounts of undiffused Mn on the surface of the foil would not be subjected to the proper hyperfine field and hence would tend to reduce the effective value of Δ_{Mn}. A 20% reduction would be sufficient to account for the difference in the hyperfine energy ratios; in view of the small

TABLE I. Angular-distribution coefficients of γ rays from oriented ^{122}Sb nuclei.

γ energy (keV)	U_2A_2	U_4A_4
γ_2 566	$-0.57^{+0.03}_{-0.06}$	-0.86 ± 0.12
γ_3 691	$+0.402 \pm 0.008$	-0.23 ± 0.08
γ_1 1140	-0.495 ± 0.015	-1.21 ± 0.25
γ_4 1260	-0.538 ± 0.015	-1.07 ± 0.24

TABLE II. Angular momentum components of β radiation fields emitted in the decay of ^{122}Sb.

β energy (keV)	$\|\alpha_1\|^2$	$\|\alpha_2\|^2$
β_1 480	$0.00^{+0.10}_{-0.00}$	$0.16^{-0.05}_{+0.03}$
β_3 720	$0.00^{+0.11}_{-0.00}$	$0.08^{-0.06}_{+0.02}$
β_4 1414	0.1 ± 0.1	$0.00^{-0.00}_{+0.05}$

quantities of ^{54}Mn present, such an effect would be not be unreasonable. However, the results deduced above for the β-decay parameters are not sensitive to the temperature or to the Δ_{Sb}/Δ_{Mn} ratio, and are valid independent of these considerations.

V. DISCUSSION

The β radiation fields emitted in the decay of ^{122}Sb to excited states of ^{122}Sn and ^{122}Te all appear to be predominantly $L=0$, with small $L=2$ components and little or no $L=1$ admixtures. The contributions of the $L=2$ components in the decays to Te appear to be smaller than in the decay to Sn, as indicated by the $|\alpha_2|^2$ factors derived above. This is a qualitative agreement with the prediction of Kisslinger and Wu[14] that the $\int B_{ij}$ value of β_1 should be some 5 times larger than that of β_3 or β_4; however, the exact implications concerning the $\int B_{ij}$ values based on our $|\alpha_2|^2$ values is not clear, since there are a total of six first-forbidden β matrix elements which must be varied to fit the observed spectrum shape factors and β-γ directional and circular-polarization correlations, as well as our nuclear-orientation data. Such calculations are under way at the present time.[22]

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