Nuclear Orientation of ^{124}Sb†

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The magnetic moment of ^{124}Sb has been found to be $\pm(1.26\pm0.07)\mu_N$ by observing the anisotropy of the 1691-keV γ ray following the decay of oriented antimony nuclei. The results obtained from sources prepared by ion bombardment are in good agreement with those from a source prepared by diffusion. The observed anisotropy of the 2091-keV γ ray is consistent with a pure Gamow-Teller β feed and an $E1$ γ transition.

INTRODUCTION

WHEN nuclei are oriented, the correlation between the nuclear spin and the direction of emission of γ rays following β decay may be observed. Information about the nature of the β decay and the multipolarities of γ rays of the daughter nucleus is contained in this correlation if the degree of nuclear orientation is known. Conversely, if the nature of a particular β-γ cascade is understood, the orientation parameters may be found. In the case of static nuclear orientation, these depend on the ratio of the interaction energy to the thermal energy of the nuclei. In this work, it is the magnetic hyperfine interaction energy μH which produces the orientation, so that if the field at the impurity nuclei is known the magnetic moment of the parent nuclei can be determined.

We have oriented ^{124}Sb nuclei in iron and used the anisotropy of the 1691-keV γ ray and a knowledge of the temperature of the sample to determine the hyperfine energy of ^{124}Sb in iron. Since the magnetic field of antimony nuclei in iron is known, the ^{124}Sb magnetic moment can be computed. We also obtained information on the character of the 222-keV (β)–2091-keV (γ) cascade.

The decay scheme of ^{124}Te fed by the β decay of ^{124}Sb, as recently determined by Stelson,[1] is shown in Fig. 1. Studies of the ^{124}Sb β decay indicate that the spin and parity of the ^{124}Sb ground state are 3^-.

APPARATUS

The ^{124}Sb was placed in a thin iron foil, which was cooled by thermal contact with a demagnetized chrominum potassium alum salt pill. When a magnetic field strong enough to saturate the iron was applied to the sample, the hyperfine fields at the impurity nuclei were aligned, thus polarizing these nuclei.

The orientation apparatus used in this experiment has been described elsewhere.[2] The guarded salt pill was employed with the sample mounted in an open circular frame to reduce β ray heating.

The γ rays from ^{124}Te and ^{60}Co, which was used as a thermometer, were detected by a 30-cm^3 Ge(Li) coaxial detector. The detector was located on the axis of orientation approximately 15 cm from the source. The axis of the detector was perpendicular to the axis of orientation.

The data were stored in a 400-channel analyzer and read out periodically onto magnetic tape. Following demagnetization, with the sample cooled to roughly 0.014°K, 10-min spectra were taken. When the sample had warmed to approximately 0.020°K, usually in 2 to 3 h, exchange gas was admitted to the salt chamber to warm the sample to 1°K, thus destroying the nuclear orientation. Normalization data were taken for several hours at this temperature. A typical spectrum is shown in Fig. 2.

ANGULAR DISTRIBUTIONS

When this orientation technique is used, the orientation of the initial state is expressible in terms of the spin of the initial state (j_0) and $\mu H/kT$ (μH is the magnetic hyperfine energy). For theoretical discussions, the angular distribution of this radiation is conveniently given[3] by

$$W_c(\theta)/W_H=\sum B_k(j_0;\mu H/kT)Q_kU_kF_kP_k(\cos\theta), \quad (1)$$

where $W_c(\theta)$ and W_H are, respectively, the counting rates when the nuclei are oriented and when they are not. $B_k(j_0;\mu H/kT)$ are statistical tensors describing the orientation of the initial state, F_k describe the angular distribution of the observed radiation, and U_k account for unobserved intermediate transitions. Q_k are the finite solid angle attenuation factors of the detector, which give a measure of the effect of averaging the angular distribution of radiation over a finite solid angle. Because parity is conserved in electromagnetic interactions, F_k with k odd vanish. For purposes of data analysis a handier form for the angular distribu-

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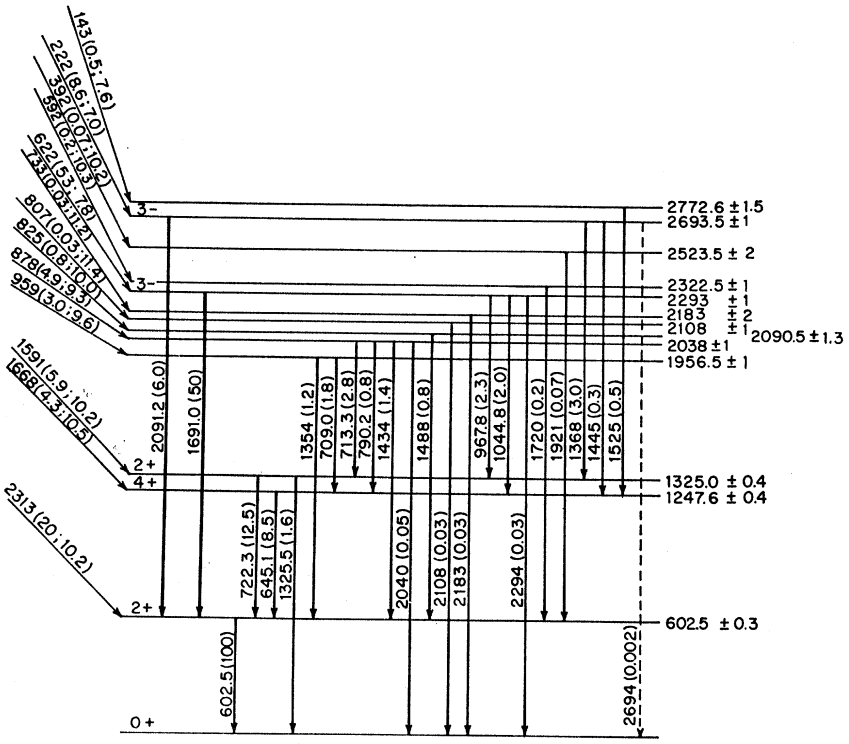

FIG. 1. Decay scheme of ^{124}Te fed by β decay of ^{124}Sb according to Stelson. All energies are in keV. The numbers in parentheses following the γ-ray energies are the intensities relative to the 602.5-keV γ ray. Those following the β end-point energies are the relative intensities and ft values, respectively.

tion is[4]

$$W_c(\theta)/W_H=1+\sum Q_k B_k f_k(j_0;\mu H/kT)P_k(\cos\theta). \quad (2)$$

Equation (2) is related to Eq. (1) by noting that in the latter

$$B_k=\binom{2k}{k} j_0{}^k\left[\frac{(2k+1)(2j_0+1)(2j_0-k)!}{(2j_0+k+1)!}\right]^{1/2} U_k F_k. \quad (3)$$

In this paper, Eq. (2) is used.

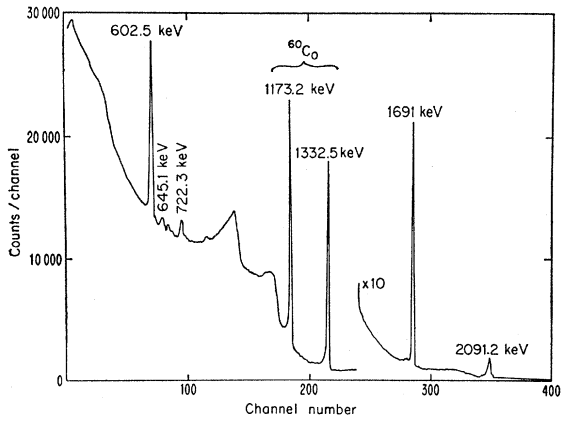

FIG. 2. Typical 20-min warm spectrum of ^{124}Sb+^{60}Co in the demagnetization crystostat.

[4] *Alpha-, Beta-, and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Co., Amsterdam, 1965), Chap. XIX(B).

DATA ANALYSIS

A system developed by one of the authors[5] was used to transfer the recorded spectra to IBM punched cards. The first stage of data processing consisted of correcting the spectra for analyzer dead time, the decay of the ^{124}Sb in the foil and background under the peaks. The last was done by linear interpolation from the background above and below the peak. Using the normalization data (W_H) taken at 1°K, the anisotropies

$$\epsilon=W_c(0°)/W_H-1$$

were computed for all peaks of interest.

The ^{60}Co anisotropy in these experiments ranged from ~30% at the lowest temperature to ~20%. The ^{124}Sb anisotropies were typically 1 and 2%. In order to determine whether rate-dependent effects or systematic errors in the analysis program were affecting the ^{124}Sb results, a ^{60}Co anisotropy of 32% was simulated in a test run by moving a ^{60}Co source relative to a fixed ^{124}Sb source. The weighted average of the 1691-keV and 2091-keV anisotropies was -0.0007 ± 0.0034, indicating that there is no systematic error in these results. However, the 602.5-keV γ ray, which was riding on a background of about twice the true peak intensity, had $\epsilon=0.0049\pm0.0023$. The anisotropy of this γ ray is expected to be of about this magnitude and of the opposite sign, so that no information about its character could be obtained.

[5] B. Greenebaum, Nucl. Instr. Methods **29**, 25 (1964).

By comparing the anisotropies of the ^{60}Co γ rays as measured with the Ge(Li) detector and with a 3×3-in. NaI(Tl) scintillation crystal, the ratio of their finite solid angle correction factors was determined. Using known values for the finite solid angle correction factors of NaI(Tl) crystals,[6] we found that in this experiment the Ge(Li) detector has $Q_2=0.98\pm0.01$.

From Eq. (2) we see that if the temperature and either B_2 or μH are known, the other may be determined. This was done using a nonlinear least-squares-fitting program, based on the method of Deming.[7] The errors quoted in this paper are purely statistical.

SOURCES

Three different ^{124}Sb sources were used in this work. The first was a thermally diffused source, prepared by electroplating approximately 20 μCi of 2.25 Ci/g specific activity ^{124}Sb onto a $\frac{1}{2}$-in.-diam disk of 0.003-in. thick Armco iron. The diffusion was carried out in hydrogen at 900°C for 24 h. After diffusion, the foil was etched to remove surface activity. The small amount of activity removed showed that the antimony was well diffused into the foil. Assuming uniform distribution of activity, the impurity concentration was 0.005 at.%.

The other two sources were prepared by Santry at the Chalk River isotope separator. 40-keV ^{124}Sb ions were injected into 0.001-in. thick Armco iron disks masked so that the ^{124}Sb was placed in a circle $\frac{3}{16}$ in. in diameter at the center of the foil. Autoradiographs of test samples prepared at the same time showed good centering and focusing. The foils were cut from iron which had been annealed in hydrogen for 12 h at 1300°C. Following etching in hydrochloric acid and washing in methanol, they were sealed in Pyrex tubes under vacuum. Between washing and seal-off the foils were kept in a helium atmosphere. The foils were removed from the ampoules, and immediately put in the isotope separator vacuum system. After implantation they were again sealed in evacuated ampoules until the orientation experiment was carried out. These foils were soldered into the foil-holder in a helium atmosphere using cerrobend solder. No flux was used.

Such precautions were necessary because most of the implanted activity is within 10 μg/cm^2, or 130 Å, of the surface. Oxidation or etching of the surface can easily destroy the usefulness of implanted sources.

The ^{124}Sb used in making the implanted sources was prepared by irradiating natural Sb for 10 days in a flux of approximately 2.5×10^{14} n/cm^2 sec. The Chalk River isotope separator has an enrichment factor of 1000, so that 3.5×10^{12} Sb ions were implanted for each μCi of ^{124}Sb activity. The maximum local impurity concentration can be estimated from the measured distribution of ions injected into Al.[8] These will be upper limits, since the distribution spreads with increasing A and Z of the target. The center of the range-distribution curve is at ~7 μg/cm^2 and its full width at half-maximum is ~5 μg/cm^2. If the range distribution is assumed to be Gaussian, the source which was oriented without any annealing (76 μCi initial activity) had a maximum Sb concentration at 0.68 at.%. The other implanted source (93 μCi initial activity) which was annealed for $\frac{1}{2}$ h at 900°C in a catalytically purified hydrogen atmosphere, had a maximum concentration of Sb of 0.83 at.%. The average concentrations are roughly one-half the maximum.

The ^{60}Co source was prepared by diffusion and soldered in the source holder in good thermal contact with the ^{124}Sb sources.

TABLE I. Summary of results of measurements of hyperfine energy. The units of $\mu_{Sb}H_{Sb^{Fe}}$ are nuclear magnetons × kG. The number of measurements is the number of 10-min spectra taken with the nuclei oriented. P is the probability of obtaining a larger value of χ^2 if the experiment was repeated.

Source	$\mu_{Sb}H_{Sb^{Fe}}$	Number of measurements	χ^2	P
Thermal diffusion	240±29	77	83	0.27
Ion implantation	270±19	62	65	0.35
Ion implantation and annealing	305±24	73	54	0.94
Average	274±13	(3)	3.09	0.21

MAGNETIC MOMENT OF ^{124}Sb

The hyperfine energy of ^{124}Sb, $\mu(^{124}\text{Sb})\times H_{Sb^{Fe}}$, was measured by observing the anisotropy of the 1691-keV γ ray of ^{124}Te following the β decay of the oriented ^{124}Sb nuclei. γ-ray circular polarization measurements suggest that there is some mixing of the 622-keV β feed to the 2293-keV level of ^{124}Te. Tirsell and Talbot[9] find $Y\equiv C_V M_F/C_A M_{GT}=-0.17\pm0.003$, while Mann *et al.*[10] find $Y=-0.10\pm0.01$. The 1691-keV γ ray is at least 99.9% $E1$,[11] so that mixing of the γ ray may be ignored.

The angular distribution of the 1691-keV γ ray is given exactly by

$$W_c(\theta)/W_H=1+B_2 f_2 P_2(\cos\theta)$$

if it is pure dipole.

For the transitions involved here,

$$B_2=0.675[(1+4Y^2/3)/(1+Y^2)]. \quad (3)$$

The experimental Y value of Tirsell *et al.* suggests that mixing in the β decay produces at most a 1% increase in B_2. The result of Mann *et al.* gives an increase of $\frac{1}{3}$%.

[6] *Alpha-, Beta-, and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Co., Amsterdam, 1965), p. 1691.

[7] W. Edwards Deming, *Statistical Adjustment of Data* (John Wiley & Sons, Inc., New York, 1944), Chap. IX.

[8] I. Bergström, F. Brown, J. A. Davies, J. S. Geiger, R. L. Graham, and R. Kelley, Nucl. Instr. Methods **21**, 249 (1963).

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[10] L. G. Mann, D. C. Camp, J. A. Miskel, and R. J. Nagle, Phys. Rev. **137**, B1 (1965). See also Ref. 9.

[11] F. R. Metzger, Phys. Rev. **90**, 328 (1953).

TABLE II. B_2 values for 2091-keV γ ray. μH is the value used to determine B_2. The last three columns have the same meaning as in Table I. The B_2 have not been corrected for the attenuation of the anisotropy due to the finite solid angle subtended by the counters.

Source	μH	B_2	Number of measurements	χ^2	P
Thermal diffusion	240	0.71±0.48	78	54	0.93
Ion implantation	270	0.21±0.28	62	45	0.93
Ion implantation with annealing	305	0.59±0.25	73	74	0.43
Average	···	0.46±0.18	(3)	1.33	0.50

As mentioned earlier, the solid angle correction to the P_2 term is small and has been incorporated in the B_2 values used for the analysis of these data. The computed values for the hyperfine energy determined from each of the three samples studied are given in Table I. The last line of that table gives the weighted average, for which there is a 21% probability of obtaining a worse fit if the experiment were repeated. This clearly indicates that the average is meaningful. Reid *et al.*[12] have recently published a comparison of the hyperfine fields in implanted sources with those in conventionally prepared sources; their results confirm one's reasonable suspicions about the variability of internal fields with source preparation and handling. A preliminary report[13] by the present authors confirms their conclusion that it is possible to obtain the full field in implanted sources.

Recent measurements of internal fields reported by Kontani and Itoh[14] include a determination of $H_{\mathrm{Sb}^{\mathrm{Fe}}}$ in a dilute alloy. They used the NMR spin-echo technique at liquid-helium temperature, and found $H_{\mathrm{Sb}^{\mathrm{Fe}}}=+(230\pm5)$ kG. Barclay *et al.*[15] obtained a similar result using NMR detected by the destruction of nuclear orientation. Recent nuclear-orientation studies[16] of ^{125}Sb suggest that the average field at Sb nuclei diffused into iron is 218±5 kG. The decrease of 5% from the field found by NMR methods is presumably due to the existence of impurity sites in a polycrystalline foil at which the nuclei do not experience the well-defined field detected by NMR. This lower value is appropriate to the analysis of the ^{124}Sb data.

Thus the absolute value of the moment of ^{124}Sb is

$$|\mu(^{124}\mathrm{Sb})| = (1.10\pm0.13)\mu_N$$

as determined from the diffused sample, and

$$|\mu(^{124}\mathrm{Sb})| = (1.26\pm0.07)\mu_N$$

as determined from the average of the three.

Greenebaum *et al.*[17] measured the moment of ^{124}Sb by methods similar to those employed in this work, but using NaI(Tl) detectors. They found $|\mu(^{124}\mathrm{Sb})| = (1.18\pm0.20)\mu_N$. It is interesting to note that the semiempirical shell-model calculation, with the odd proton in a $g_{7/2}$ state and the odd neutron in an $h_{11/2}$ state,[18] gives $\mu(^{124}\mathrm{Sb})\sim-1.2\mu_N$.

2091-keV γ RAY

The anisotropy of the relatively weak 2091-keV γ ray has also been measured. The measured B_2 values for the 2091-keV γ ray are summarized in Table II. This γ ray is 99.95% $E1$ and involves a transition from the 3^- level, at 2693.5 keV, to the 2^+ level at 602.5 keV.[19] The upper level is fed by the 222-keV β from ^{124}Sb. B_2 for the cascade is given by Eq. (3).

The measured B_2 for the 2091-keV γ ray, corrected by the finite solid angle attenuation factor determined from ^{60}Co γ rays, is

$$B_2=+0.47\pm0.18.$$

For a pure Gamow-Teller β decay, $B_2=+0.675$, while for a pure Fermi transition, $B_2=+0.900$. The experimental value is within one standard deviation of the pure Gamow-Teller value and about two standard deviations of the pure Fermi values. Thus, our results are consistent with the accepted properties of this cascade and favor somewhat a pure Gamow-Teller β decay.

ACKNOWLEDGMENTS

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