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Nuclear Orientation of ^{125}Sb†

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The anisotropies of the 176-, 379-, 426-, 598- plus 604-, 633-, and 668-keV γ rays from oriented ^{125}Sb have been observed. The results corroborate the spin assignment of $\frac{5}{2}$ to the 668-keV level, $\frac{7}{2}$ to the 633-keV level, and $\frac{9}{2}$ to the 321-keV level. The following mixing parameters $\delta(E2/M1)$ were found: 633-keV γ ray, $\delta = +0.327 \pm 0.004$ or $+32.4_{-3.5}^{+4.5}$; 426-keV γ ray, $\delta = -0.512 \pm 0.025$ or -1.05 ± 0.05; 176-keV γ ray, $-1.49 \leq \delta \leq -0.570$. The data suggest that the β feeds to the 640-, 633-, and 321-keV levels are mostly $L=1$. The average magnetic hyperfine energy of ^{125}Sb in iron was found to be $(572 \pm 3)\mu_N$ kG by simultaneously orienting ^{60}Co and ^{125}Sb.

INTRODUCTION

THE development of high-resolution lithium-drifted germanium γ-ray detectors with large sensitive volumes has greatly extended the usefulness of nuclear orientation in the study of complex level schemes and nuclear matrix elements connected with β and γ emission. This laboratory carried out orientation experiments on ^{125}Sb, using NaI(Tl) scintillation counters to detect the γ rays.[1] Although the anisotropies observed with this isotope were large, the complexity of the spectrum coupled with the poor resolution of the detectors made it difficult to deduce unambiguous conclusions from the data. We have repeated these early measurements with a 30-cm^3 Ge(Li) detector which combines high resolution with good efficiency. The high resolution has not only the advantage that most of the γ rays are resolved but also that the extraction of the anisotropies from the raw data is quite straightforward and free of systematic error.

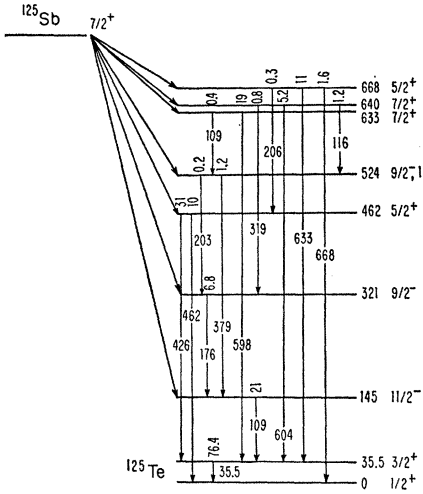

FIG. 1. Decay scheme of ^{125}Sb proposed by Stone *et al.* The intensities of each γ ray per hundred decays of ^{125}Sb are given. These data were taken from Nuclear Data Card 60-6-91.

DECAY SCHEME OF ^{125}Sb

The ^{125}Sb decay scheme given in the Nuclear Data Card 60-6-91 is based largely on the work of Narcisi.[2] He made accurate measurements of the γ-ray energies, intensities, and conversion coefficients with a double focusing magnetic spectrometer. The decay scheme shown in Fig. 1 is a modification of that given by Narcisi. The reasons for the changes are discussed in the rest of this section. The fact that the energy of the 35.5-keV first excited state is very nearly equal to the separation of the 633- and 668-keV levels has been a major source of confusion. The 633-keV γ ray, on energetic grounds, could originate from either or both of these levels. On the basis of his K/L conversion coefficient ratio for the 633-keV γ ray, Narcisi suggested that it is $E2$, originating at the 633-keV level to which he gave the assignment $\frac{5}{2}^+$. He also pointed out the possibility of a weak transition of the same energy from the 668-keV level.

A Coulomb excitation experiment by Fagg *et al.*[3] yielded γ rays at 426, 462, and 633 keV. If the 633-keV γ ray had originated at the 633-keV level, the 598-keV γ ray should have shown up strongly. Similarly, if it had originated at the 668-keV level, some sign of the 668-keV transition would be expected. Mann *et al.*[4] pointed out, however, that if half or more of the 633-keV γ ray comes from the 668-keV level, the presence of the 668-keV γ ray would be masked.

The work of Stone *et al.*[5] has clarified this situation. By using Ge(Li) detectors to look at coincidences between the 35.5-keV γ ray and the other γ transitions, they found that 95±5% of the 633-keV γ rays come from the 668-keV level. They proposed a spin of $\frac{7}{2}^+$ for the 633-keV level in order to explain the absence of

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[1] J. Hess, W. Weyhmann, B. Greenebaum, and F. M. Pipkin, Bull. Am. Phys. Soc. 9, 562 (1964).

[2] R. S. Narcisi, thesis, Harvard University, 1959 (unpublished).

[3] L. W. Fagg, E. A. Walicki, R. O. Bondelid, K. L. Dunning, and S. Snyder, Phys. Rev. **100**, 1299 (1955).

[4] K. C. Mann, F. A. Payne, and R. P. Chaturvedi, Can. J. Phys. 42, 1700 (1964).

[5] N. J. Stone, R. B. Frankel, J. J. Huntzicker, and D. A. Shirley, University of California Radiation Laboratory Report No. UCRL-11828, 1964, p. 58 (unpublished).

a transition to the ground state. They also carried out a nuclear orientation experiment which yielded results compatible with the assignment of $\frac{7}{2}^+$ to the 633-keV level and $\frac{5}{2}^+$ to the 668-keV level. Recently Metzger and Raghavan[6] have corroborated this result for the 633-keV level with resonance-fluorescence experiments on ^{125}Te, using ^{125}Sb as the γ-ray source. The decay scheme which we give in Fig. 1 is that proposed by Stone *et al.*[5] We shall discuss our nuclear orientation results in terms of this diagram.

THEORY

In this section we shall give a brief summary of the theory used in the interpretation of our results. The theory is discussed more fully in Ref. 7, where the original sources are quoted. The angular distribution of a γ ray with respect to the axis of orientation, taken as $\theta=0$, may be written

$$W(\theta)=W_0[1+\sum_{k,\text{even}} U_kF_kB_kP_k(\cos\theta)], \tag{1}$$

where $W(\theta)$ is the intensity with the nuclei oriented; W_0 is the intensity when they are not; and $P_k(\cos\theta)$ is the Legendre polynomial of order k. The B_k, which describe the orientation of the initial state of spin j, are given by

$$B_k=(2j+1)^{1/2}\sum_m a_m(-1)^{j-m}\langle jmj-m|jjk0\rangle, \tag{2}$$

where the a_m are the populations of the nuclear magnetic substates. The U_k account for the change in nuclear orientation produced by any unobserved preceding transitions. For an unobserved emission of angular momentum L between states of angular momentum J_0 and J, we have

$$U_k=[(2J_0+1)(2J+1)]^{1/2}(-1)^{J+J_0-k-L}\times W(J_0,J_0,J,J;k,L). \tag{3}$$

If there are unobserved transitions in cascade, the net U_k is a product of the individual U_k and if there are several feeds or multipole mixing in a feed to a given level, the weighted average of the U_k is taken.

The F_k describe the angular distribution of the γ ray from a state of orientation U_kB_k. They have been tabulated by Ferentz and Rosenzweig,[8] who use the definition

$$F_k(LL'JJ_i)=(-1)^{J-J_i-1}[(2L+1)(2L'+1)\times(2J_i+1)]^{1/2}\langle LL'k0|L1L'-1\rangle\times W(J_i,J_i,L,L';k,J). \tag{4}$$

When the γ ray shows mixing between multipoles of order L and L', the F_k of Eq. (1) becomes

$$F_k=(1+\delta^2)^{-1}[F_k(LLJJ_i)+\delta^2F_k(L'L'JJ_i)+2\delta F_k(LL'JJ_i)], \tag{5}$$

where δ is the ratio of amplitudes for radiation of orders L' and L.

In most nuclear orientation experiments, including this one, only the $k=2$ term in Eq. (1) is large enough to measure. With the γ-ray detector at $\theta=0°$, the anisotropy defined by $[W(\theta)-W_0]/W_0$ is simply equal to $U_2F_2B_2$.

In this experiment, the nuclear orientation was produced by the "brute force" combination of a high magnetic field and low temperatures. The orientation parameters B_k are known functions of the product $\mu(^{125}\text{Sb})H/kT$, which is the usual argument of a Boltzmann factor. H is the magnetic field at the nucleus, which in this case is the hyperfine field of antimony in iron. This method is further described in the next section.

We are reporting two kinds of orientation measurements in this paper. In the first we found the ratio of the anisotropies of the various γ rays to the 462-keV transition for which the value of U_2F_2 can be calculated. The orientation parameter B_2 simply cancels out. The other work used the known value of U_2F_2 for the 462-keV γ ray to compute B_2 from the measured anisotropy. The temperature of the sample was simultaneously determined by measuring the anisotropies of the γ rays of ^{60}Co for which both U_2F_2 and the magnetic hyperfine energy are known. The hyperfine energy of the ^{125}Sb in iron was then computed from the B_2 and the sample temperature.

EXPERIMENTAL METHOD

The demagnetization cryostat has been described in detail elsewhere.[9] In this experiment the guarded salt-pill arrangement was used. The samples were in the form of $\frac{1}{2}$-in.-diam circular disks of 0.001-in.-thick Armco iron foil. These foils were soldered around the edges with cerrobend solder into an annular holder. This geometry allows most of the β rays to escape from the sample so that radioactive heating is minimized.

The sources were prepared by electroplating about 40 μCi of carrier-free ^{125}Sb onto each foil. This activity was then diffused into the foils for 24 h at 900°C in a hydrogen atmosphere. After the diffusion, the samples were etched in hydrochloric acid to remove surface activity. The results of the etching showed that the activity had been diffused well into the foils. The sources for the ^{125}Sb hyperfine energy measurements were prepared in the same way except that about 5 μCi of ^{60}Co was electroplated and diffused before the addition of the ^{125}Sb. Both isotopes were introduced into the

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[6] F. R. Metzger and R. S. Raghavan, Phys. Rev. **145**, 968 (1966).

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

[8] M. Ferentz and N. Rosenzweig, Argonne National Laboratory Report No. 5324 (unpublished).

[9] J. Hess, B. Greenebaum, F. M. Pipkin, and W. Weyhmann, Rev. Sci. Instr. **36**, 21 (1965).

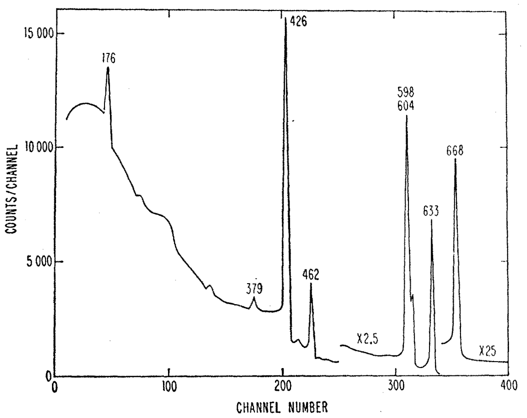

FIG. 2. γ-ray spectrum of ^{125}Sb with the source inside the demagnetization cryostat. The counting time was 10 min.

same foil in order to ensure accurate temperature measurements.

The samples were cooled to about 0.015°K from 1°K by the adiabatic demagnetization of a chromium potassium alum salt pill from a field of 25 kG. This magnetic field was produced by a superconducting solenoid. The sample foil was connected to the salt pill by a 6-in.-long $\frac{1}{8}$-in.-diam oxygen-free high-conductivity copper rod. Thermal contact was made with the salt pill by approximately 5000 No. 40 bare copper wires which were silver soldered to the end of the copper rod. A slurry of the salt in Octoil-S was compressed around the wires under about 15 000 lb/in.^{2} pressure to yield a firm pill which was stable at room temperature. This pill has been cycled between helium temperature and room temperature at least 20 times without any sign of deterioration. The sample foils were polarized by a small superconducting solenoid which produced a field at the sample of roughly 1500 G.

The γ rays were detected outside the cryostat with a 30-cm^3 Ge(Li) detector which had been drifted from five sides. A room-temperature field effect transistor preamplifier was used followed by a pulse-shaping amplifier and a 400-channel analyzer. A typical ^{125}Sb spectrum is given in Fig. 2. After demagnetization, data were taken in 10-min lots for 3 to 4 h; the sample was then warmed to 1°K and a comparable amount of normalization data were taken.

TABLE I. The experimental U_2F_2 values for the γ rays which could be measured. The theoretical values given for the 598+604 keV complex assume a spin of $\frac{7}{2}$ for both the 633- and 640-keV levels. The value $U_2F_2=-0.378$ corresponds to pure Gamow-Teller β feeds to both levels. $U_2F_2=-0.466$ corresponds to pure Fermi β feeds to both levels.

γ-ray energy (keV)	U_2F_2 (Expt)	U_2F_2 (Theory)
176	-0.445 ± 0.018	
379	$-0.31\ \pm0.05$	
426	$+0.899\pm0.012$	
462		-0.468
598+604	-0.373 ± 0.004	-0.378 to -0.466
633	-0.218 ± 0.006	
668	-0.460 ± 0.015	-0.468

The data, which had been stored on magnetic tape, were transferred to IBM cards, using a system designed by one of the authors.[10] The data from each demagnetization cycle were analyzed to yield the anisotropies of all the γ rays of interest. The computer program corrected for analyzer dead time and the decay of the source. The background under each peak was subtracted by a linear interpolation across the peak. The output was obtained in the form of punched cards.

In the second stage of the analysis, the output data from several demagnetizations were combined and statistically analyzed to obtain the U_2F_2 of the various γ rays or the hyperfine energy of the ^{125}Sb in iron. The latter was determined with a nonlinear least-squares program[11] which fitted the ^{60}Co and ^{125}Sb data to give the best value for the ^{125}Sb hyperfine energy. This program also calculated the χ^2 for the fit and the statistical error in the result. The U_2F_2 were calculated by taking the ratios of each γ-ray anisotropy to that of the 426-keV γ ray, which showed the largest anisotropy. The actual values were determined by using the theoretical value of -0.468 for the 462-keV γ ray. Both the 462- and 426-keV γ rays were used in the hyperfine energy determination since the U_2F_2 for the 426 was known from the first part of the experiment. The results of the U_2F_2 measurements are given in Table I and the hyperfine energy values are given in Table II.

DISCUSSION OF THE RESULTS

The weighted average of our hyperfine energy measurements is $(572\pm3)\mu_N$ kG where the quoted error is statistical only. We estimate that our systematic error due to source misalignment, background subtraction, and finite solid-angle corrections is not greater than 1 to 2%. Errors arising from source alignment are largely compensated because they apply to both isotopes. For example, a misalignment causing a change of 5% in the measured U_2F_2 results in only a 1% change in the value of the ^{125}Sb hyperfine energy. The value for the ^{125}Sb hyperfine energy was obtained by assuming an internal field for Co in iron of 286.3 kG.[12] This field for Co in Fe is based on NMR measurements. If the average effective Co field in our sample is smaller, the computed result for ^{125}Sb will be higher than the actual value in the same proportion.

Recently, Barclay *et al.*[13] have reported a value for the hyperfine energy of ^{125}Sb in iron based on the

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

[11] This program is based on the treatment of the nonlinear least-squares problem by W. E. Deming in his book, *Statistical Adjustment of Data* (John Wiley & Sons, Inc., New York, 1944).

[12] D. A. Shirley and G. A. Westenbarger, University of California Radiation Laboratory Report No. UCRL-11664 Rev., 1965 (unpublished).

[13] J. A. Barclay, W. D. Brewer, E. Matthias, and D. A. Shirley, University of California Radiation Laboratory Report No. UCRL-17716, 1967 (unpublished).

method of nuclear magnetic resonance detected by the destruction of nuclear orientation (NO-NMR). Their resonant frequency at zero applied field is 131.71±0.03 MHz which, assuming a spin of $\frac{7}{2}$, gives a hyperfine energy of 604.7 μ_N kG. This result is about 5% higher than ours. The NO-NMR sample was prepared by melting and rolling while ours was prepared by thermal diffusion. Comparison of the two results shows that the average field acting on Sb atoms in a diffused source is less than that measured by nuclear magnetic resonance. If a similar effect occurs with the ^{60}Co, the Sb discrepancy will be larger. This difference of about 5% would be produced if about 10% of the ^{125}Sb was unoriented. However, the results of our sample etching showed that there was no significant surface activity. There was also no significant contamination on the sample holder. Thus, either about 10% of the ^{125}Sb is in sites with no internal field or a correspondingly larger fraction is in positions where the field is less than the NMR value. Effects due to incomplete magnetization of the foil would affect both the ^{60}Co and ^{125}Sb and would tend to be compensated. These results show that, whether or not there is a difference between the NMR and average Co fields, there is a greater difference between the NMR and average fields for Sb in iron.

We shall now discuss our U_2F_2 measurements in terms of the proposed decay scheme.

668-keV Level

This level has an assignment of $\frac{5}{2}^+$ and the expected value of U_2F_2 for the 668-keV transition is -0.468. The experimental value, -0.460 ± 0.015, is in good agreement. The 633-keV γ ray is now expected to be mixed. Figure 3 shows F_2 as a function of the mixing parameter δ for a $\frac{5}{2}$ to $\frac{3}{2}$ transition. The possible values of δ are $+0.327\pm0.004$ or $32.4_{-3.5}^{+4.5}$.

640- and 633-keV Levels

The 604- and 598-keV γ rays were not well enough resolved to compute individual anisotropies. The combined U_2F_2' is -0.373 ± 0.004. The expected value, if both levels are $\frac{7}{2}^+$ and both β feeds are pure Gamow-Teller, is -0.378. Pure Fermi β feeds lead to a U_2F_2 of -0.466. Hence our result supports the $\frac{7}{2}^+$ assignment with the β feeds predominantly $L=1$. As further evidence of the consistency of Stone's scheme, the U_2F_2 for a $\frac{7}{2}\rightarrow\frac{1}{2}$ transition is -0.662 which does not agree with the measured value of -0.218 ± 0.006 for the 633-keV γ ray.

524-keV Level

This level has a 116-keV γ feed of about 20% in addition to the β feed. The possible spin assignments are $\frac{7}{2}^-$, $\frac{9}{2}^-$, or $\frac{11}{2}^-$. The measured U_2F_2 for the 379-keV γ ray is -0.31 ± 0.05. If the level is $\frac{7}{2}^-$, assuming the 116-keV γ ray to be $E1$, the value of U_2F_2 lies between -0.203 and -0.170. A spin of $\frac{7}{2}$ is thus pretty well ruled out. For a spin of $\frac{9}{2}$, the value of F_2 must lie between -0.551 and $+0.991$. Again assuming the 116-keV γ feed to be $E1$ we can write

$$U_2=0.658+0.232\alpha_1,$$

where α_1 is the fraction of $L=1$ in the β feed to this level. From the experimental U_2F_2, we find that F_2 varies between -0.47 ± 0.08 and -0.35 ± 0.06 as α_1 varies between 0 and 1. In Fig. 4 we show the variation of F_2 for a $\frac{9}{2}$ to $\frac{11}{2}$ transition as a function of δ. Going one standard deviation to $F_2=-0.29$, we conclude that for the assignment $\frac{9}{2}$ the mixing ratio of the 379-keV γ ray lies between -0.4 and -2.3, depending on the β-ray mixing.

If the spin is $\frac{11}{2}$, the U_2 is 0.846. Our experimental result now yields $F_2=-0.37\pm0.06$. Figure 5 shows that for this assignment the mixing ratio is 0.8 ± 0.1 or

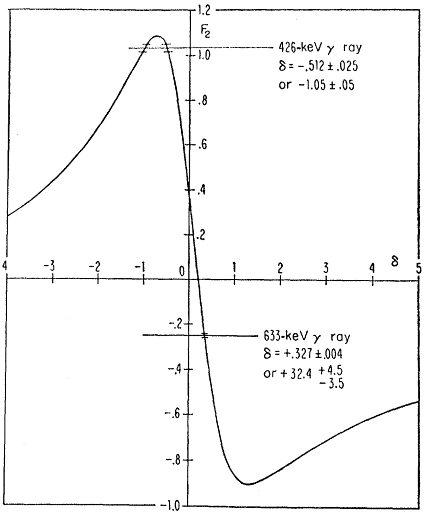

FIG. 3. This figure shows F_2 as a function of the $E2$ to $M1$ γ-ray mixing ratio δ for a $\frac{5}{2}^+$ to $\frac{3}{2}^+$ transition. The experimental values of F_2 for the 426- and 633-keV γ rays are shown with the corresponding values of δ.

Table II. The results of two sets of measurements of the hyperfine energy of ^{125}Sb in iron. The errors quoted for the values of μH obtained from the 426-keV γ-ray anisotropies include the error in the value of U_2F_2 for this γ ray. The number of measurements refers to the number of 10-min spectra recorded while the nuclei were oriented. P is the probability that a poorer fit to the data would be obtained if the experiment were repeated. The P quoted for the weighted average shows that the four individual values of μH agree within statistics.

γ-ray energy (keV)	μH (μ_N kG)	Number of measurements	χ^2	P (%)
426	573.0±5.3	28	30.2	30
462	582 ±16	26	18.7	80
426	565.7±4.7	36	23.0	93.6
462	579.7±8.1	36	37.1	38
Weighted average	572 ±3	4	3.15	40

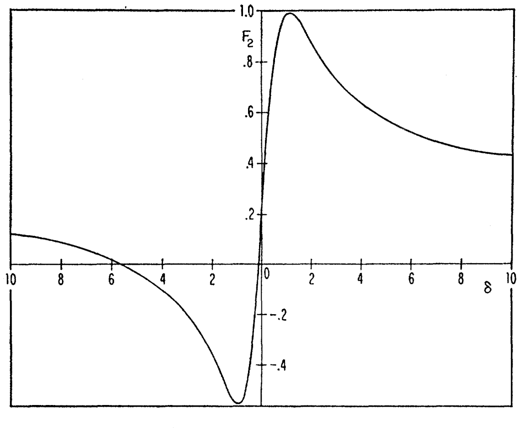

FIG. 4. F_2 for a $\frac{9}{2}^-$ to $\frac{11}{2}^-$ γ-ray transition as a function of $\delta(E2/M1)$.

-0.10 ± 0.07. Thus either a spin of $\frac{9}{2}$ or $\frac{11}{2}$ is consistent with the orientation data.

462-keV Level

As mentioned before, the U_2F_2 of the 462-keV γ ray has been assumed to be -0.468 in accordance with the accepted decay scheme. The good agreement between the hyperfine energy measured in this work and that of Ref. 13 supports the spin assignments which were used.

The 426-keV γ ray shows a very large positive anisotropy due to $M1$-$E2$ mixing. The measured U_2F_2 is $+0.899\pm0.012$, which leads to mixing ratios of -0.512 ± 0.025 or -1.05 ± 0.05. This is also shown in Fig. 3.

321-keV Level

This level could possibly be $\frac{7}{2}^-$, $\frac{9}{2}^-$, or $\frac{11}{2}^-$. The measured U_2F_2 of the 176-keV γ ray is -0.445 ± 0.018. The $\frac{7}{2}$ assignment is ruled out by this result because the closest theoretical value of U_2F_2 for spin $\frac{7}{2}$ is -0.218. A spin of $\frac{9}{2}^-$ is most likely considering the nuclear orientation results as well as those of the β-γ angular correlation experiment of DuBard *et al.*[14] We shall briefly consider the consistency of an $\frac{11}{2}$ assignment with our data.

Taking the most favorable individual U_2 for the γ rays feeding this level, we can state

$$U_2\leq0.872\,,\quad F_2\leq-0.51\pm0.02\,.$$

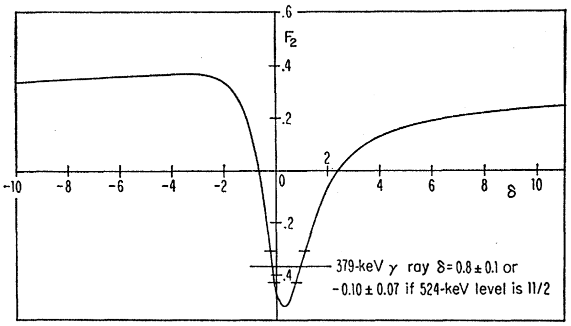

FIG. 5. F_2 for an $\frac{11}{2}^-$ to $\frac{11}{2}^-$ γ-ray transition as a function of $\delta(E2/M1)$. The experimental F_2 and the corresponding values of δ for the 379-keV γ ray are shown. These results depend on the assumption of a spin of $\frac{11}{2}$ for the 524-keV level.

For an $\frac{11}{2}$ assignment we see from Fig. 5 that

$$-0.508\leq F_2\leq0.375\,.$$

Thus a spin of $\frac{11}{2}$ is just barely consistent with our data.

If the spin is $\frac{9}{2}$, we have

$$U_2=(0.637\pm0.012)+0.269\alpha_1\,,$$

where the quoted uncertainty represents the extremes of possible values due to the presence of the 204- and 320-keV γ rays, and α_1 is the fraction of $L=1$ in the β feed. Figure 4 shows that for a $\frac{9}{2}$ to $\frac{11}{2}$ γ transition F_2 must lie between -0.551 and $+0.991$. Combining this with our experimental U_2F_2 we can say

$$\alpha_1\geq0.64\pm0.13\,.$$

This value of α_1, corresponding to $F_2=-0.551$, results in a γ-ray mixing ratio of -0.931. The other extreme has $\alpha_1=1$, yielding an F_2 of -0.49 ± 0.02. Going one standard deviation to $F_2=-0.47$, from Fig. 4 we see that

$$-1.49\leq\delta\leq-0.570\,.$$

Narcisi[2] has measured the K/L conversion coefficient ratio for the 176-keV γ ray. He found that $K/L\geq5.45$, which leads to $|\delta|\leq1.3$. This is consistent with our limits. Narcisi was hampered by the fact that the K line of the 203-keV γ ray fell on the L line of the 176-keV γ ray. By taking account of the intensity of the 203-keV γ ray and assuming it to be $M1$, Narcisi arrived at a probable value of 6.6 for the K/L ratio. This corresponds to a $|\delta|$ of 0.55, which lies at our limit for $\alpha_1=1$. Thus the available evidence suggests that the β feed to the 321-keV level is certainly more than 50% and probably mostly $L=1$.

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[14] J. L. DuBard, L. D. Wyly, Jr., and C. H. Braden, Phys. Rev. **150**, 1013 (1966).