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Directional and Polarization Correlation Studies in the Decay of 5-hour Sb^{118}†

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Directional and polarization correlation measurements have been carried out on the gamma rays accompanying the decay of 5-hour Sb^{118}. These measurements lead to the following spin and parity assignments for excited levels in Sn^{118}: 1.22 Mev (2^+), 2.25 Mev (4^+), and 2.51 Mev (5^-). A search for positrons was made, and an upper limit on positron emission was set at 0.2% of the 1.22-Mev decays, giving a lower limit of 2500 hours for the partial half-life of positron emission to any of the excited levels in Sn^{118}. The level scheme is discussed in terms of various nuclear models.

I. INTRODUCTION

THE decay of 5-hour Sb^{118} has been recently studied by McGinnis and Kundu,[1] who found that the decay proceeded by electron capture, 10% feeding the 2.55-Mev level and the remainder feeding the 2.51-Mev level in Sn^{118}. Gamma rays of 0.260, 1.03 and 1.22 Mev, all in cascade, as well as conversion electrons corresponding to a 40-kev transition, were observed. The K-conversion coefficient of the 0.260-Mev gamma ray was determined to be 0.039 ± 0.003. The decay scheme shown in Fig. 1 was proposed with levels in Sn^{118} at 1.22, 2.25, 2.51, and 2.55 Mev. The only spin and parity assignments made were 2^+ for the 1.22-Mev level, from Coulomb excitation.[2] The present investigation was undertaken to assign spins and parities for the other levels, by means of directional and polarization correlation studies of the cascaded gamma rays, and to compare the level structure of Sn^{118} with those of neighboring even-even tin isotopes.

II. EXPERIMENTAL PROCEDURE AND RESULTS

Five-hour Sb^{118} was produced by bombarding 99.99% pure natural indium metal with 24-Mev alpha particles for 2–2.5 hours. This reaction also produces 2.5-hour Sb^{117} which decays mainly by electron capture to the 0.160-Mev level in Sn^{117} and a single gamma ray of this energy. The production of Sb^{117} was reduced by degrading the alpha-particle beam by means of aluminum absorbers. A typical gamma spectrum of Sb^{118} as observed in a 1 in.×2 in. NaI(Tl) detector mounted on an EMI 9536B photomultiplier tube is shown in Fig. 2. Gamma rays at 0.260, 1.03, and 1.22 Mev are clearly seen.

For the angular correlation experiments, the equipment consisted of four counters all employing 1 in.×2 in. NaI crystals mounted on EMI 9536B phototubes, with one fixed and the other three permuted successively through angular positions of 90°, 135°, and 180° with respect to the fixed counter. The counters all had energy resolutions of 8–11%. A resolving time of 16 nano seconds was employed, which kept the chance coincidence rate below 3% of the prompt rate. Singles and coincidence counts were simultaneously recorded for all counters in each of the permutations of the movable counters. With this procedure, the source strength, the differences in efficiencies and solid angles of the detectors, and inequalities in the fast coincidence circuit efficiencies cancel in the expression for the correlation.

A. 1.03–1.22 Correlation

The first correlation measurement was made on the 1.03–1.22 Mev cascade, in order to establish the spin of the 2.25-Mev level and the character of the 1.03-Mev transition. The above transitions follow the 0.260-Mev photon in the cascade, and for convenience we designate them as the "second" and "third" transitions. The pulse-height discriminators in all counter channels were adjusted to accept the photopeaks of both gamma rays; counts were accumulated in each detector permutation for 1000 seconds, long enough to obtain statistically significant results at each position, but also short

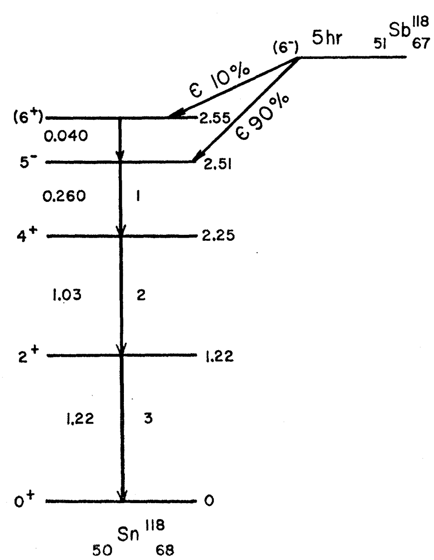

FIG. 1. Decay scheme of Sb^{118} showing levels in Sn^{118} at 1.22, 2.25, 2.51, and 2.55 Mev with spins and parities determined from the present work.

† Supported by the U. S. Atomic Energy Commission.
[1] C. L. McGinnis and D. N. Kundu, Bull. Am. Phys. Soc. 3, 62 (1958).
[2] P. H. Stelson and F. K. McGowan, Bull. Am. Phys. Soc. 2, 69 (1957).

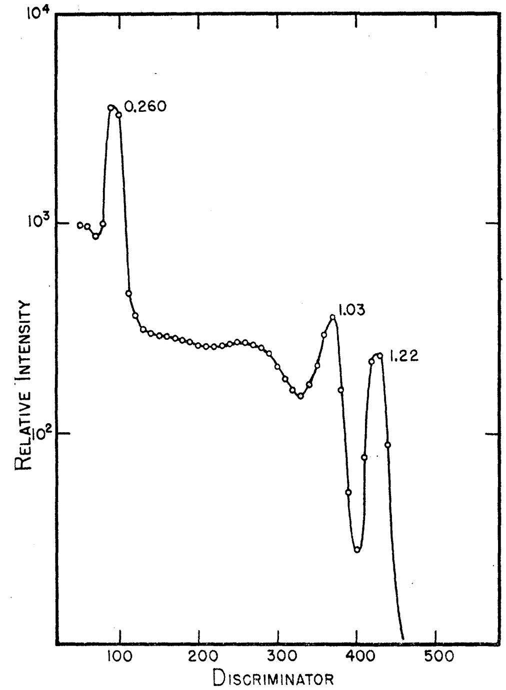

FIG. 2. Gamma spectrum of 5-hour Sb^{118} observed in a 1 in.×2 in. NaI(Tl) detector, showing gamma rays at 0.260, 1.03, and 1.22 Mev.

enough so that instrumental drift during the counting period was negligible, and so that the counting rate, decreasing due to source decay, remained nearly the same for the three permutations which comprised a "run." The cumulated data from four separate runs, after correction for finite detector solid angle, yield the following values for the coefficients in the Legendre polynomial expansion for the correlation,

$$W(\theta)=1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta):$$
$$A_2=0.137\pm0.012, \quad A_4=0.014\pm0.010.$$

In Fig. 3, the experimental point is compared with the parametric A_4 vs A_2 plots[3] which correspond to spins of 0 and 2 for the ground and first excited states of Sn^{118}. The measured coefficients are consistent with the following spin sequences and 1.08-Mev transition mixing ratios:

$$3(1,2)2(2)0, \quad \delta=-0.1;$$
$$4(2,3)2(2)0, \quad \delta=+0.02;$$
$$2(1,2)2(2)0, \quad \delta=-0.18.$$

Only the 1(1,2)2(2)0 spin sequence is eliminated; the second-third correlation alone is not sufficient to give unique assignments. In order to resolve this ambiguity the first-third correlation between the 0.260-Mev and 1.22-Mev gamma rays was measured.

[3] P. S. Jastram, G. T. Wood, and J. P. Hurley, Bull. Am. Phys. Soc. **3**, 65 (1958).

B. 0.260–1.22 Mev Correlation

For the first-third correlation, the fixed-counter discriminator was set to accept the photopeak of the 0.260-Mev gamma ray, while the movable counters accepted only the 1.22-Mev photopeak. In this case it is necessary to estimate and correct for the contribution of the 1.03-Mev gamma ray to the observed correlation. The resulting values for the expansion coefficients are

$$A_2=0.121\pm0.015, \quad A_4=0.029\pm0.013.$$

Experimentally the first-third correlation presents no greater difficulty than that between contiguous transitions. Biedenharn and Rose[4] have treated the general triple correlation problem as well as the special case of the first-third correlation for a triple gamma-cascade in which the transitions are pure multipoles. If the cascade is designated by $j_1(L_1)j_2(L_2)j_3(L_3)j_4$ the first-third correlation function assumes the simple form

$$W(\theta)=N\sum_{\nu \text{ even}} F_\nu(L_1L_1j_1j_2)F_\nu(L_3L_3j_4j_3) \times W(j_2j_2j_3j_3;\nu L_2)P_\nu(\cos\theta),$$

where

$$N=(-1)^{L_2-j_2-j_3}[(2j_2+1)(2j_3+1)]^{\frac{1}{2}}.$$

The F coefficients are tabulated[5] as are also the Racah coefficients[6] $W(j_2j_2j_3j_3;\nu L_2)$. The extension to triple correlations with mixed multipoles is straightforward;[4] thus, if the first transition is mixed with multipolarities L_1 and $L_1'=L_1+1$, one obtains

$$W(\theta)=N\sum_{\nu \text{ even}}[F_\nu(L_1L_1j_1j_2)+2\delta_1F_\nu(L_1L_1'j_1j_2)+\delta_1^2F_\nu(L_1'L_1'j_1j_2)]F_\nu(L_3L_3j_4j_3) \times W(j_2j_2j_3j_3;\nu L_2)P_\nu(\cos\theta),$$

where δ_1^2 is the reduced intensity ratio of the L_1' to the L_1 multipole. If the second (unobserved) radiation is mixed, then the correlation is given by a simple weighted average of the correlations corresponding to the two multipoles that contribute to the mixture[7]:

$$W=\frac{1}{1+\delta_2^2}[W(L_2)+\delta_2^2W(L_2')],$$

where $L_2'=L_2+1$, and δ_2 is the mixing ratio. The third radiation could in principle also be mixed, but in the present case it is in fact pure electric quadrupole. The still undetermined parameters on which the first-third correlation depends are the spins of the second and

[4] L. C. Biedenharn and M. E. Rose, Revs. Modern Phys. **25**, 729 (1953).

[5] K. Alder, B. Stech, and A. Winther, Phys. Rev. **107**, 728 (1957). M. Ferentz and N. Rosenzweig, Argonne National Laboratory Report ANL-5324 (unpublished).

[6] L. C. Biedenharn, Oak Ridge National Laboratory Report ORNL-1098, 1952 (unpublished).

[7] The absence of an interference term linear in δ_2 is due to the nonobservance of the intermediate radiation, with consequent summation over all emission directions.

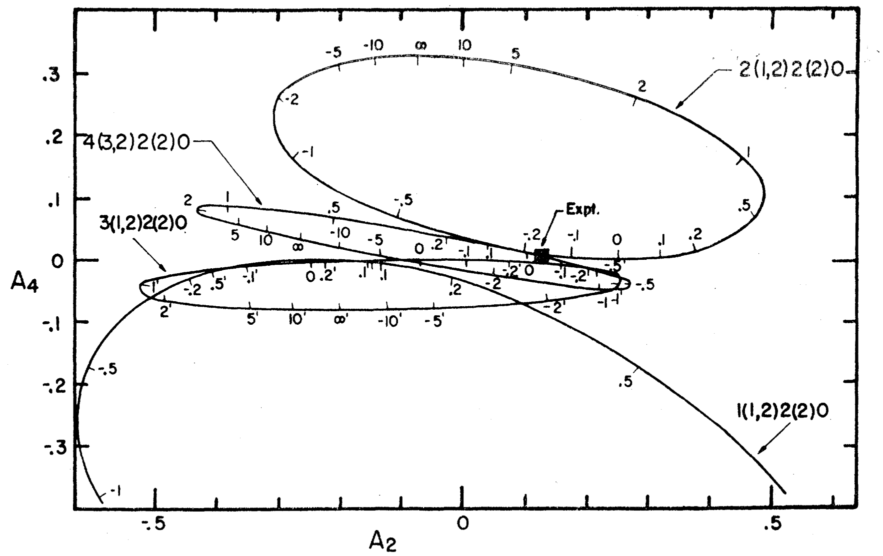

FIG. 3. Plot of the direction-correlation coefficients A_4 vs A_2 as a function of the mixing ratio δ_2 for various possible spin sequences. The experimental point for the 1.03–1.22 Mev (second-third) correlation is plotted as a rectangle, to indicate the statistical errors.

third excited states, and the mixing ratios δ_1 and δ_2 of the first and intermediate transition, respectively.

Figure 4 shows a set of plots of A_4 vs A_2 as a function of the mixing ratio δ_1 of the first transition (0.260 Mev), corresponding to the spin choices and particular values of the mixing ratio δ_2 of the unobserved 1.03-Mev gamma ray which are consistent with the previously measured second-third correlation. The experimental point at once permits elimination of the 4(1,2)4(2,3)2(2)0 and 3(1,2)2(1,2)2(2)0 possibilities and leaves a choice between the 5(1,2)4(2,3)2(2)0 and 6(2,3)4(2,3)2(2)0 sequences, with mixing ratios $\delta_1=0.33$ and 0.1, respectively.

The K-conversion coefficient of the 0.260-Mev gamma ray has been measured[1] to be 0.039±0.003, consistent with the transition being $E1$-$M2$ with a mixing ratio $\delta_1=0.35$. The only assignment consistent with both this result and the first-third correlation is the 5(1,2)4(2,3)2(2)0 sequence. This implies that either the spin-4 level or the spin-5 level must have odd parity. The mixing ratio $\delta_2=0.02$ for the 1.03-Mev gamma ray is nearly zero; hence odd parity seems unlikely for the 2.25-Mev (spin-4) level, and correspondingly probable for the 2.51-Mev (spin-5) level. In order to obtain a decisive answer a measurement was made of the polarization correlation of the 1.03-Mev gamma ray in the second-third cascade.

C. Polarization Direction Correlation of the 1.03–1.22 Mev Gamma-Ray Cascade

The polarization direction correlation of the 1.03–1.22 Mev gamma cascade was measured by means of a conventional gamma polarimeter using Compton scat-

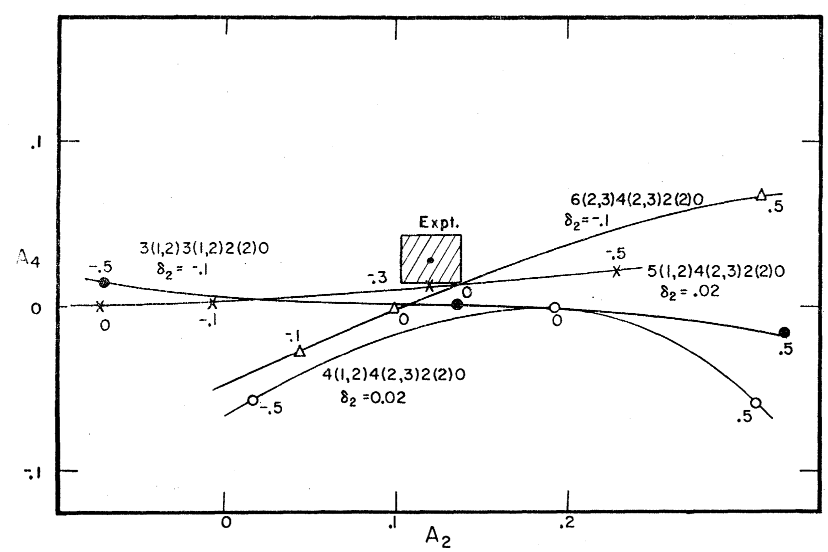

FIG. 4. Set of plots of A_4 vs A_2 as a function of the mixing ratio δ_1 of the 0.260-Mev gamma ray (first transition) corresponding to the spin choices and particular values of the mixing ratio δ_2 of the unobserved intermediate transition which are consistent with the second-third correlation. The experimental point is the result of the 0.260–1.22 Mev (first-third) correlation.

tering, with the 1.03-Mev photon accepted in the polarization-sensitive detector. The detection sensitivity of the polarimeter to the degree of plane polarization was determined empirically from a corresponding measurement on the well-known Co^{60} gamma cascade—particularly applicable in this case because of the similarity in energy of the relevant gamma transitions. The result may be expressed in terms of a parameter p, the ratio of the degree of polarization (of the 1.03-Mev photon) parallel to the plane of the emission directions of the two photons to that perpendicular to this plane $(n_{\parallel}/n_{\perp})$:

$$p=1.46\pm0.17,$$

$$1/p=0.69\pm0.08.$$

The value of p is plotted against the directional correlation coefficient A_2 in Fig. 5, where it may be compared with the locus of pairs of value of (p, A_2) which correspond to the various spin and multipole assignments, and mixtures of the 1.03-Mev transition. The significance of considering $1/p$ is that $p(EL,ML')=p^{-1}(ML,EL')$; i.e., interchanging the electric and magnetic multipole assignments in the mixed radiation converts p into $1/p$, reflecting the curves in Fig. 5 in the line $p=1$. Instead of plotting all the curves twice, we may look for agreement between a measured value of p and also of $1/p$ with some part of one of the p vs A_2 plots; if agreement is found for p, the corresponding assignment is as indicated on the various curves; if for $1/p$, the assignment holds with E and M interchanged. The present result evidently corresponds uniquely to a pure electric quadrupole assignment for the 1.03-Mev transition. Consequently, the parity of the 2.25-Mev (spin-4) level is even, and, in the light of the results of the preceding sections, that of the 2.51-Mev (spin-5) level must be odd. The level scheme of Sn^{118}, including spin and parity assignments from the present work, is shown in Fig. 1, and also in Fig. 6.

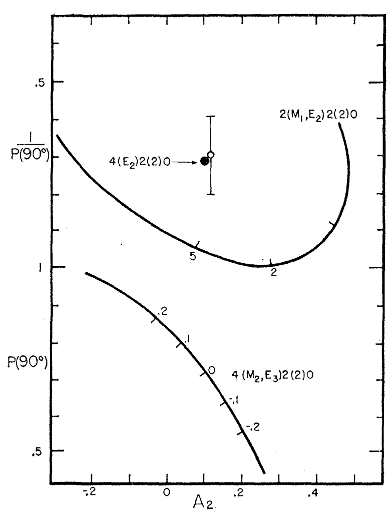

FIG. 5. Plots of the polarization parameter p vs A_2 for various possible multipole radiations and spin sequences. The experimental point for Sb^{118} is seen to correspond uniquely to a pure electric quadrupole assignment for the 1.03-Mev gamma ray.

D. Search for Positrons

Since the Sb^{118}-Sn^{118} decay energy is at least 2.55 Mev, there is sufficient energy available for positron emission to both the ground and first excited state. An attempt was made to detect positrons by looking for triple coincidences between the two annihilation radiations and the 1.22-Mev gamma ray. No positrons could be found, and consequently an upper limit of 0.2% of the 1.22-Mev decays can be placed on positron emission to the first excited state. It if is assumed, as is indicated by the present decay-scheme results, that all excited states in the Sn^{118} that are populated de-excite via the 1.22-Mev level, the lower limit of the partial half-life for positron decays to any of the excited levels of Sn^{118} is 2500 hours. The corresponding lower limit of $\log ft$ for positron decay directly to the 1.22-Mev level is 12.

III. DISCUSSION

The fact that the lifetime of the first excited level of Sn^{118} as determined from Coulomb excitation is 8 times shorter than the single-particle estimate disfavors a purely single-particle description. This is not surprising in view of the large number of neutrons (18) outside the closed shell at 50. The energy ratio $E_{4+}/E_{2+}\approx 2$ suggests that these levels may be due to quadrupole vibrations; on the other hand, the ratio $E_{6+}/E_{2+}\approx 2.1$ indicates that the 6^+ level is not a 3-phonon state. The nature of the excitation which forms the 5^- level is an open question. An argument can be made against a simple coupling of single-particle orbitals as follows: Assuming that the 50 protons in Sn^{118} form an inert core, the state requires the coupling of at least two neutron orbitals, including $h_{11/2}$. The only available pair that can couple to a 5^- state is $(s_{1/2},h_{11/2})$. The corresponding (proton and neutron) orbitals that can account for the 6^- (or 5^-) Sb^{118} ground-state spin assignment derived from our work are $(d_{5/2},h_{11/2})$ and $(g_{7/2},h_{11/2})$. The first of these gives the least required change in the l value for the beta-decay $(\Delta l=2)$. The resulting $\log ft$ value for such an allowed (l-forbidden) transition is ordinarily found to lie in the range 7.5 to 8.5. Our experimental estimate of this number is, however, between 5 and 6. It therefore appears unlikely that the single-particle configuration gives a good description of the 5^- level in Sn^{118}. It is possible that this is a collective state corresponding to a $\lambda=5$ deformation. The level scheme of Sn^{120} becomes almost identical to that of Sn^{118} if we reinterpret the 7^- level as 5^-, and assign a spin of 6^- (or 5^-) to the ground state of Sb^{120}.

The assignment of 5^- to levels in Sn^{118} and Sn^{120} and its possible interpretation as a collective state due to a $\lambda=5$ deformation raises the question whether there are any similar states known in other nuclei of this type. Table I lists all the known 5^- levels.

We may note the following points: (1) The excitation

TABLE I. Table of 5^- levels.

Nucleus	Level (Mev)
Zr^{90}	2.32
Cd^{108}	(2.54)
Cd^{110}	2.92
Sn^{118}	2.51
Sn^{120}	2.51
Xe^{130}	2.34
W^{182}	1.62
Pb^{202}	2.04
Pb^{206}	2.8
Pb^{208}	3.20, 3.71
Po^{210}	2.91

energy of the 5^- levels varies very little with mass number; (2) No 5^- level is known for $A<90$. This is consistent with a breakdown of collective motion characterized by a given number of nodes when the corresponding wavelength at the nuclear surface becomes comparable with or less than the internucleon distance; (3) If the proposed vibrational description of the 5^- states is correct, excitation of these levels should be possible and in fact favorable by electron inelastic scattering.

It is instructive to compare the level schemes of Sn^{116}, Sn^{118}, and Sn^{120} (Fig. 6). In Sn^{116} there appears to be a doublet (2^+ and 4^+) at about twice the energy of the first excited state, as predicted by the Goldhaber-Weneser model. It is not unlikely that similar 2^+ levels exist in Sn^{118} and Sn^{120}, but that they are not excited because of an unfavorable combination of spin and energy position in the decay scheme. It would be interesting to determine whether a 2^+ and possibly a

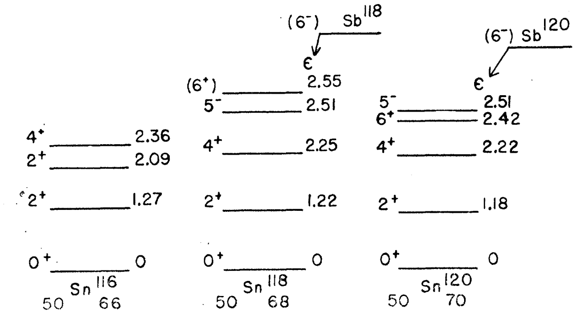

FIG. 6. Comparison of level structures of Sn^{116}, Sn^{118}, and Sn^{120}.

0^+ level in the neighborhood of the 4^+ level in Sn^{118} are populated in the decay of Sb^{118m}, which has presumably a spin and parity of 1^+ (the positron decays from this level to both the 0^+ ground state and the 2^+ state of Sn^{118} are allowed[8]).

In conclusion, we may remark that Sn^{118} and Sn^{120} both appear to be examples of structures in which the low-lying excited states are formed by distinctly different modes of excitation.

We are indebted to Professor Bernard Margolis for a number of stimulating and illuminating discussions of these results. We should also like to express our thanks to Professor H. J. Hausman for providing the considerable number of cyclotron bombardments necessary to make possible the correlation measurements with a 5-hour source; and to Mr. H. C. Vanderleeden for his assistance in carrying out these experiments.

[8] C. L. McGinnis, Phys. Rev. **109**, 888 (1958).