Sn^{116} Levels Populated by the Decay of 54-Min In^{116m}†

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The decay of the 54-min In^{116} isomer was reinvestigated by means of scintillation singles and coincidence spectroscopy techniques. Angular-correlation measurement of four pairs of successive γ rays served as a basis for the assignment of the spin and parity of all levels, and the multipole order of all transitions. The excitation energies (MeV, relative to the 0^+ ground state) and characters (j^π) of the observed levels were 3.06 (4^+), 2.78 (4^+), 2.53 (4^+), 2.38 (4^+), 2.12 (2^+), 1.72 (0^+), and 1.29 (2^+). In addition, two new transitions with energies of 0.385 and 0.435 MeV (previously unreported in this decay) were observed to feed and depopulate, respectively, the level at 1.72 MeV. The relative intensities of all transitions are presented. The experimental results are compared with previously reported work and are discussed in the light of recent pairing-force calculations. All levels populated in this decay, with the exception of the 1.29-MeV first excited state, were found to be distinctly different from those populated in the same nuclide by the decay of 1-h Sb^{116}. These findings are discussed, and arguments are presented to account for these differences.

I. INTRODUCTION

CALCULATIONS which have employed a pairing-force interaction as an approximation for the residual short-range nuclear force have stimulated a great deal of interest in the detailed characteristics of the excited states of those classes of nuclei which this theory treats most simply and directly. The detailed pairing-force calculations of Kisslinger and Sorensen,[1] Arvieu,[2] and others,[3] have dealt with singly closed-shell nuclei, in general, and with the Sn isotopes ($Z=50$), in particular. In the case of the Sn isotopes, experimental investigations of the levels of the even-A isotopes Sn^{118} and Sn^{120} (populated by the β decay of the corresponding Sb parent isotopes)[4,5] have provided considerable experimental information that has been shown to be satisfactorily described by the early pairing-force calculations.[1]

It was felt that an extension of these experimental studies to other even-A Sn isotopes could enlarge the scope and degree of these important comparisons between experiment and theory (a) by providing experimentally determined detailed parameters of levels and transitions in an additional isotope, and (b) by permitting a consolidation of such information with those of previous investigations on other isotopes into a summary of the behavior of these levels as a function of mass in this isotopic system. Among the other even-A Sn isotopes, only Sn^{116} combines all the necessary features to permit a detailed experimental-theoretical comparison. The levels in this isotope are fed by the β decay of both In^{116} and Sb^{116}. These decays are sufficiently long-lived (54 min and 1 hr, respectively) to permit extensive experimental studies to be conducted on all levels and transitions observed. In addition, each of these parent decays populates a sufficient number of excited states to provide a meaningful test of currently available theoretical models. In this respect, Sn^{116} has more states so populated than do either Sn^{118} or Sn^{120},[6] and a detailed experimental description of the levels in Sn^{116} might be expected to present an even more significant and interesting case for theoretical comparison.

Previously reported experimental work[7–10] on the Sn^{116} levels populated by the decay of 13-sec In^{116}, 54-min In^{116}, and 1-h Sb^{116} combine to illuminate some salient features which are of sufficient interest to deserve mention and attention. Perhaps the most striking characteristic of these decays is the marked difference between the level schemes proposed for the decay of 54-min In^{116} and 1-hr Sb^{116}. Although these decays seem to populate distinctly different levels in the daughter (with the exception of the first excited 2^+ state), the previously proposed decay schemes[8–10] were not sufficiently complete to establish this difference with certainty. Gamma rays with energies of 0.137 and 0.415 MeV are reported in the 54-min In^{116} decay,[8,9] and two transitions with almost these same energies had been found[10] in the decay of 1-h Sb^{116} and had been assigned[6] to proceed from and to distinctly different sets of levels in Sn^{116}. However, the incomplete parametrization of these levels and transitions observed in Sn^{116} leaves these and other aspects of these decays in doubt. In addition, in the decay of 54-min In^{116}, the 0.415-MeV gamma ray has been assigned a doublet character in order to account for a reported intensity

† Work performed under the auspices of the U. S. Atomic Energy Commission.

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[3] R. Arvieu and M. Veneroni, Compt. Rend. 252, 670 (1961); R. Arvieu, E. Baranger M. Veneroni, M. Baranger, and V. Gillet, Phys. Letters 4, 119 (1963).
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[5] H. Ikegami and T. Udagawa, Phys. Rev. 124, 1518 (1961).
[6] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences—National Research Council, Washington, D. C., 1962) NRC, 60-3-117.
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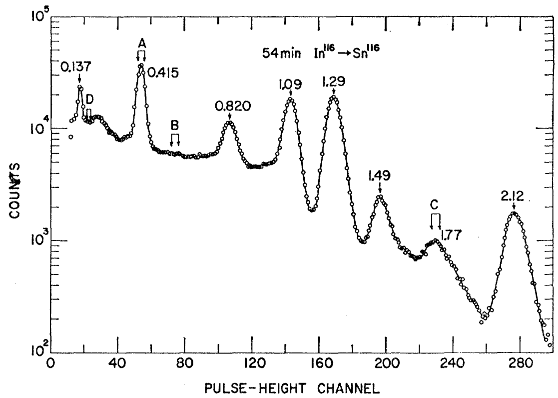

FIG. 1. NaI(Tl) (3×3 in.) pulse-height spectrum of γ rays in Sn^{116} following the decay of 54-min In^{116}.

imbalance.[8] The final important feature concerns a proposed 0^+ level[7] in Sn^{116} populated in the 13-sec In^{116} ground-state decay which has not been observed in the 54-min In^{116} isomer activity, although the previously proposed decay schemes[8,9] of the latter decay provide no clear reason why this particular level should not be populated by cascade γ rays from higher levels.

Because of the importance of Sn^{116} in any detailed comparison with current pairing-force calculations, and the necessity of having a more detailed parametrization of the levels and transitions between levels available before differences in the various decays can be certified or can lead to reliable and definitive conclusions, and the need to understand the population (or lack of population) of the proposed 0^+ level, it was felt that complete and thorough re-examinations of both the 54-min In^{116} and 1-h Sb^{116} decays were warranted. These reinvestigations have been conducted and are reported here and elsewhere.[11] The present work on the decay of 54-min In^{116} is described here, together with a comparison of previous work on this decay and that of the 13-sec In^{116} activity. In the paper immediately following, the reinvestigation of the 1-h Sb^{116} decay is described and discussed in combination with previously reported studies[4,5] of the decay of 5.1-h Sb^{118} and 5.8-day Sb^{120}.

The present work on the decay of 54-min In^{116} employed scintillation singles and coincidence γ-ray techniques. Included are the results of $\gamma-\gamma$ angular-correlation measurements on several sets of cascade transitions.

II. SOURCE PREPARATION

Sources of 54-min In^{116} were produced by means of the reaction $In^{115}(n,\gamma)In^{116}$ induced by thermal neutrons from the Argonne National Laboratory CP-5 reactor. Samples of naturally occurring In, and In_2O_3 enriched to 99.9% in In^{115} were irradiated by means of a pneumatic "rabbit." Identical results were obtained for both types of samples. However, samples of normally occurring In could not be repeatedly irradiated because of the build-up of 50-day In^{114} resulting from neutron capture in the 4.3% abundant In^{113} present. Liquid sources were used for the angular-correlation measurements.

III. SCINTILLATION γ-RAY STUDIES

The γ-ray spectra were obtained with 3×3-in. NaI(Tl) detectors (Harshaw integral line) and were recorded on an 800-channel pulse-height analyzer after pulse amplification and pulse pile-up rejection.[12] Coincidence studies employed a fast-slow coincidence circuit of unconventional design[13] operated at a fast resolving time of $2\tau \approx 50\times10^{-9}$ sec. A matched fast-slow coincidence circuit simultaneously routed chance coincidences to a selected location in a subgroup of the analyzer memory. These chance coincidences were later subtracted from the coincidence spectra obtained. By recording the chance-coincidence spectrum at the same time as the normal coincidences, such data automatically take source decay and source replacement and/or

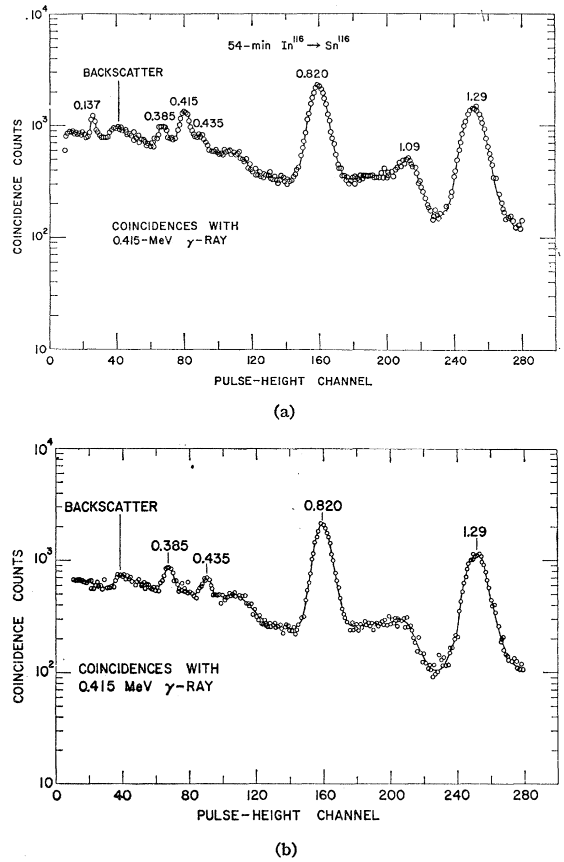

FIG. 2. Spectra in coincidence with the 0.415-MeV gamma ray (a) with chance-coincidence contribution subtracted and (b) with chance coincidences and coincidences with underlying Compton distributions subtracted.

[11] H. H. Bolotin, Phys. Rev. **136**, B1566 (1964), following article.

[12] M. Strauss, Rev. Sci. Instr. **34**, 335 (1963).

[13] M. Strauss, Rev. Sci. Instr. **34**, 1248 (1963).

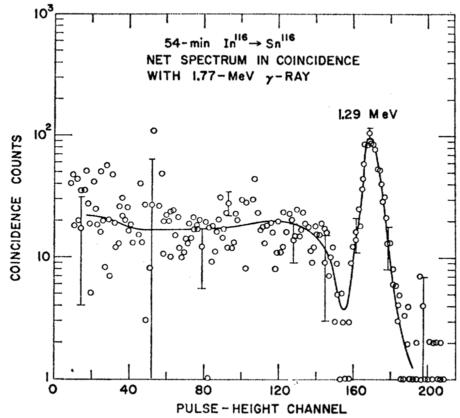

FIG. 3. Spectrum in coincidence with the 1.77-MeV gamma ray. The coincidences due to the underlying Compton distribution of the 2.12-MeV gamma ray have been subtracted.

replenishment into account. This feature is especially useful when sources with short half-lives are used.

In addition, an external 100-channel analog-to-digital converter and as many as eight digitally selected pulse-height-window gates directed the coincidence pulses from the second detector to selected associated subgroups of the multichannel analyzer.[14]

The present investigation began with a detailed search for the 0.45-MeV transition in the 54-min decay which had previously been observed[7] in the 13-sec In^{116} activity and assigned to depopulate the proposed 0^+ level at 1.72 MeV. Figure 1 shows a typical singles γ-ray spectrum which displays all of the previously observed transitions in this 54-min decay. The coincidence spectrum obtained by setting a narrow gate on the 0.415-MeV γ-ray peak (indicated by bracket A in Fig. 1) is presented in Fig. 2(a) with a small chance contribution subtracted. This spectrum clearly shows the presence of additional transitions in the region closely surrounding the 0.415-MeV line. The 0.137- and 0.415-MeV gamma rays appear in this spectrum because Compton distributions due to higher energy coincident transitions underlie that portion of the spectrum used as the coincidence gate. To compensate for the contribution of these coincidences, a second digital gate was set on these underlying Compton distributions (indicated by bracket B in Fig. 1) and the coincidences associated with this gate were recorded at the same time as those associated with the gate set on the 0.415-MeV peak. By recording these spectra at the same time, complications of source decay, source strength, and the like were obviated. This contribution was subtracted from the spectrum in Fig. 2(a), the remaining spectrum [Fig. 2(b)] being due solely to coincidences with the 0.415-MeV transition. Clear evidence of γ rays with energies of 0.385 and 0.435 MeV is seen. Neither of these transitions has been previously reported in the 54-min In^{116} decay, and Fettweiss *et al.*[7] did not observe the 0.385-MeV gamma ray in their study of the 13-sec In^{116} ground-state activity. The 0.435-MeV γ ray is taken to be identical to that of the 0.45-MeV transition previously seen in the 13-sec In^{116} decay and assigned[7] to proceed from the 1.72- to the 1.29-MeV level.

The singles γ-ray spectrum shown in Fig. 1 displays a line at 1.77 MeV superimposed on the shoulder of the Compton distribution of the 2.12-MeV transition. A coincidence spectrum was obtained by gating one detector of the coincidence system on a small pulse-height interval at the 1.77-MeV peak (indicated by bracket C in Fig. 1). In addition, a second gate was set above this line on the 2.12-MeV Compton distribution, and the spectrum in coincidence was simultaneously recorded in a separate subgroup of the analyzer memory. The latter contribution represents that portion of the coincidence spectrum due to the Compton distribution of the higher-energy gamma ray which underlies the 1.77-MeV peak. After subtraction, the resulting net spectrum in coincidence with the 1.77-MeV gamma ray is as shown in Fig. 3. This clearly demonstrates that the 1.77-MeV γ ray is in coincidence only with the 1.29-MeV transition. Ricci *et al.*,[8] using scintillation summing techniques in a well crystal, observed a sum peak at 3.04 MeV which they attributed to a 1.77–1.29-MeV cascade. By means of sum-coincidence techniques, Hansen *et al.*[9] showed clearly that the 3.05-MeV peak seen in their work was due to coincidences between the 1.29- and 1.77-MeV gamma rays. The present result is not only a direct corroboration of their results by an alternative method, but also shows that no other transition is in coincidence with the 1.77-MeV gamma ray.

Figure 4 is the pulse-height spectrum obtained in coincidence with the 1.29-MeV gamma ray. The presence of the 0.137-, 0.415-, 0.820-, 1.09-, and 1.49-MeV lines is in agreement with previously reported work. This spectrum clearly demonstrates the 1.29–1.77-MeV coincidences seen above. The strong coincident line at 0.415 MeV masks the weak 0.385- and 0.435-MeV gamma rays to a large extent. However, these data give sufficient indication that they are also

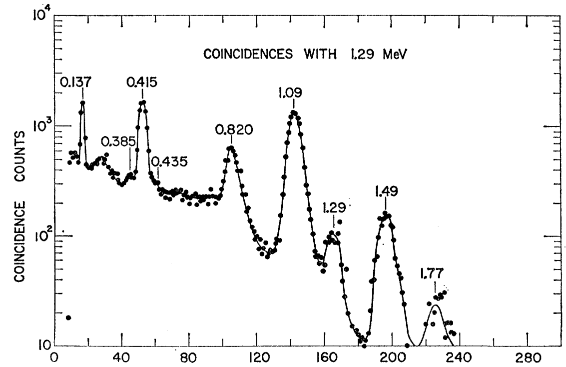

FIG. 4. Spectrum in coincidence with the 1.29-MeV gamma ray.

[14] M. Strauss, Nucl. Instr. Methods (to be published).

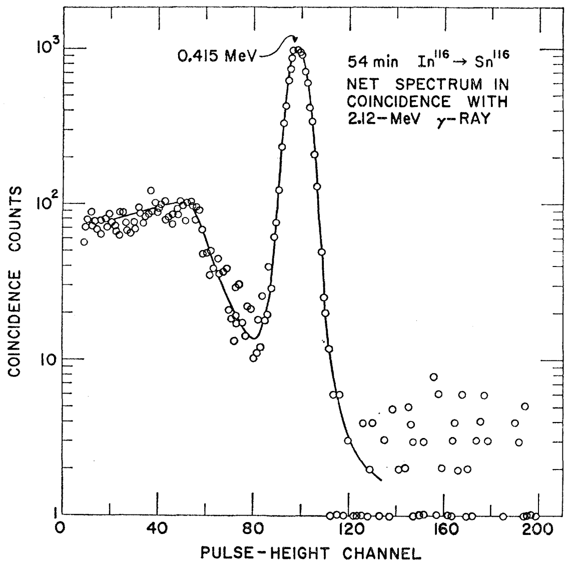

FIG. 5. Spectrum in coincidence with the 2.12-MeV gamma ray.

in coincidence with the 1.29-MeV transition, as expected. The appearance of a weak peak at 1.29-MeV in this spectrum (from which the chance-coincidence contribution has already been subtracted) can be accounted for completely as due to coincidences between the 1.29-MeV gamma ray in one detector and the Compton distribution from the 1.49-MeV gamma ray underlying the 1.29-MeV peak in the second detector used to gate the coincidence spectrum; it does not indicate a second γ ray at this energy. An upper limit obtained for the intensity of this possible second 1.29-MeV gamma ray is $<0.5\%$ of that of the 1.29-MeV gamma ray that proceeds from the first excited state to the ground state. A previous search[9] for such a second 1.29-MeV γ ray led to a corresponding upper limit of $<2.6\%$.

The spectrum in coincidence with the 2.12-MeV transition is presented in Fig. 5. The presence of the strong 0.415-MeV gamma ray in this spectrum is expected from previous work. The absence of the 0.137-MeV line, in particular, and of any other lines, in general, should be noted.

The net spectrum in coincidence with the 0.137-MeV gamma ray was obtained by setting two digital windows, one on the 0.137-MeV peak and one on the Compton distributions underlying this peak (bracket D in Fig. 1). After subtraction, the resultant spectrum due solely to coincidences with the 0.137-MeV transition is as presented in Fig. 6. The only coincident transitions are those at 1.09 and 1.29 MeV.

A careful scintillation search for any higher energy transitions was extended up to an energy of 3.5 MeV. None were found.

TABLE I. Results of coincidence studies.[a]

Gamma-ray transition	E_γ=0.137	0.415	0.820	1.09	1.29	1.49	1.77	2.12
0.137	···	no	no	yes	yes	no	no	no
0.385	no	yes	no	no	yes	no	no	no
0.415	no	···	yes	no	yes	no	no	yes
0.435	no	yes	no	no	yes	no	no	no
0.820	no	yes	···	no	yes	no	no	no
1.09	yes	no	no	···	yes	no	no	no
1.29	yes	yes	yes	yes	no[b]	yes	yes	no
1.49	no	no	no	no	yes	···	no	no
1.77	no	no	no	no	yes	no	···	no
2.12	no	yes	no	no	no	no	no	···

Columns E_γ=0.137 through 2.12: Coincident γ-ray transition.

[a] All transition energies are in MeV.
[b] The lack of a 1.29-MeV doublet is specifically noted.

TABLE II. Gamma-ray intensities in Sn^{116}.

Transition energy (MeV)	Measured γ-ray intensities[a]: Girgis *et al.* (Ref. 8)	Hansen *et al.* (Ref. 9)	Present work
0.137	0.06±0.02	0.04±0.01	0.03 ±0.01
0.385	···	···	0.010±0.003[c]
0.415	0.40±0.04[b]	0.30±0.05	0.36 ±0.05
0.435	···	···	0.006±0.002[c]
0.820	0.15±0.02	0.19±0.03	0.17 ±0.02
1.09	0.57±0.06	0.61±0.05	0.53 ±0.06
1.29	0.83±0.07	0.84±0.05	0.80 ±0.05[d]
1.49	0.10±0.02	0.07±0.02	0.11 ±0.02
1.77	0.02±0.005	0.02±0.005	0.015±0.004
2.12	0.17±0.02	0.16±0.02	0.20 ±0.02

[a] All intensities are relative to the sum of the intensities of the 1.29- and 2.12-MeV γ rays.
[b] Girgis *et al.* (Ref. 8) proposed two transitions with energies of 0.415 MeV with relative intensities of 0.32 and 0.08 to account for their reported intensity inbalance to and from the 2.12-MeV state.
[c] The intensities of these γ rays were first obtained relative to that of the 0.820-MeV gamma ray from the spectrum in coincidence with the 0.415-MeV gamma ray and were later translated in terms of the sum of the intensities of the 1.29- and 2.12-MeV gamma rays by use of the relative intensities of the 0.820- and 1.29-MeV gamma rays obtained from the singles spectrum.
[d] No second 1.29-MeV gamma ray ($<0.5\%$ of the intensity of the 1.29-MeV gamma ray from the first excited state to the ground state).

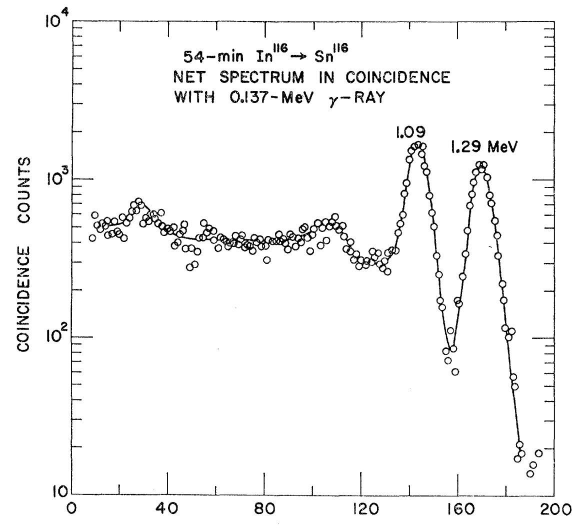

FIG. 6. Spectrum in coincidence with the 0.137-MeV gamma ray. The coincidences due to the underlying Compton distributions have been subtracted.

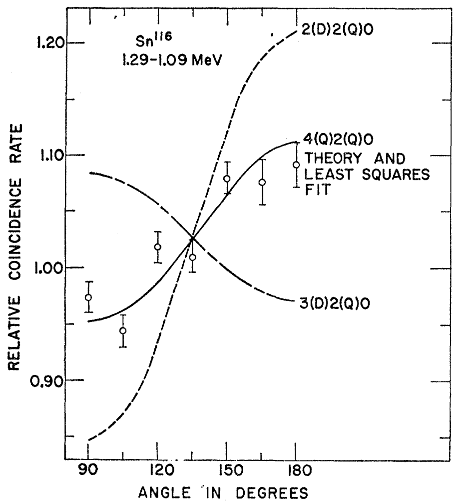

FIG. 7. Results of angular-correlation measurements between the 2.12- and 0.415-MeV γ-ray cascade. Some theoretical correlations are shown for comparison.

By way of summary, Table I lists the results of the coincidence studies, while Table II presents the relative intensities of the transitions observed in the present work, together with corresponding values obtained by previous investigators.

IV. γ-γ ANGULAR CORRELATIONS

The complete set of angular-correlation measurements described here were obtained simultaneously by use of a system which permits the recording of the entire spectrum in coincidence with one or more digital gates. In this case, one window was set on the 1.29-MeV peak and a second window was set to accept the 2.12-MeV gamma ray. The spectra in coincidence with these gates were stored in separate memory subgroups of the multichannel analyzer, while the chance-coincidence spectrum associated with each gate was stored in the remaining locations in the analyzer memory. These spectra represent coincidence cascades that lead to all levels populated in the decay. In these studies, data were automatically taken and recorded at 15° intervals from 90° to 270°. The two 3×3-in. NaI detectors were placed 14 cm from the source (a weak acid solution) which was contained in a thin-walled polyethylene capsule. The source strength, reflected by the singles γ-ray intensity in each detector, was monitored and stored at each angle and used to correct these data for decay. This arrangement permitted replenishment and/or replacement of the source material as needed. Gain shifts due to source strength changes or other factors were obviated by the use of gain stabilizers.[15]

TABLE III. Angular-correlation results.

Gamma-ray energies (MeV)	Experimental coefficients $P_2(\cos\theta)$	Experimental coefficients $P_4(\cos\theta)$	Theoretical coefficients for indicated sequence $P_2(\cos\theta)$	Theoretical coefficients for indicated sequence $P_4(\cos\theta)$
1.29–0.820	0.231±0.022	···	0.250	0
			$2(D)2(Q)0$	
1.29–1.09	0.103±0.009	−(0.009±0.022)	0.102	0.009
			$4(Q)2(Q)0$	
1.29–1.49	0.097±0.021	0.013±0.035	0.102	0.009
			$4(Q)2(Q)0$	
2.12–0.415	0.102±0.019	0.002±0.032	0.102	0.009
			$4(Q)2(Q)0$	

The correlation coefficients for each cascade were obtained from a weighted least-squares-fit analysis[16] of the data and then corrected for attenuation[17] due to the finite solid angle of the detectors.

A. 2.12–0.415-MeV Correlation

Since the 2.12-MeV gamma ray is the most energetic transition present in the decay and is in coincidence only with the 0.415-MeV gamma ray, no corrections for underlying coincident Compton distributions are necessary. The results of this measurement are given in Fig. 7 and Table III. The solid line is a least-squares fit to these data and is indistinguishable from the theoretical correlation for a $4(Q)2(Q)0$ cascade. Shown for comparison are the theoretical correlation distributions for the sequences $3(D)2(Q)0$ and $2(D)2(Q)0$. The result presented is in marked disagreement with the only other previously reported angular-correlation measurement[18] which assigned a $2(D,Q)2(Q)0$ sequence to this

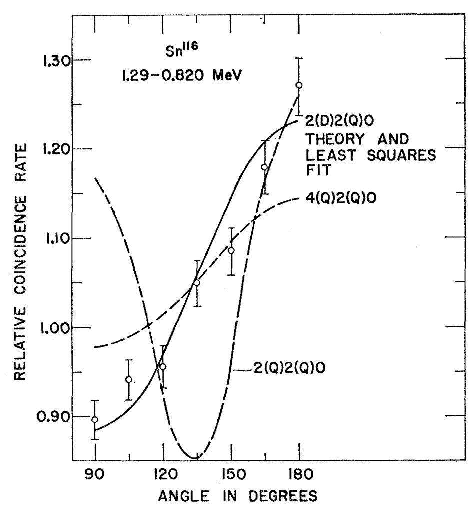

FIG. 8. Results of angular-correlation measurements between the 1.29- and 0.820-MeV γ-ray cascade. Some theoretical correlations are shown for comparison.

[15] "Spectrostats" obtained from Cosmic Radiation Laboratories, Bellport, New York.
[16] M. E. Rose Phys. Rev. **91**, 610 (1953).
[17] M. J. L. Yates, in *Perturbed Angular Correlations*, edited by E. Karlsson E. Matthias, and K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1964), p. 453.
[18] R. P. Scharenberg, M. G. Stewart, and M. L. Wiedenbeck, Phys. Rev. **101**, 689 (1956).

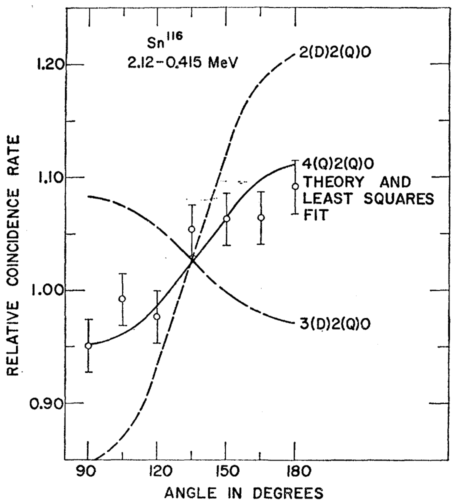

FIG. 9. Results of angular-correlation measurements between the 1.29- and 1.09-MeV γ-ray cascade. Some theoretical correlations are shown for comparison.

cascade with the 0.415-MeV gamma ray designated as almost wholly quadrupole. No reason is presented here for the discrepancies in these measurements, but it is felt that the present measurement can be taken as reliable since ample precautions were taken to free these data from gain shifts, chance-coincidence contributions, and uncertainties in decay corrections. As is seen in Sec. VI, the $4(Q)2(Q)0$ sequence obtained in the present work is more consistent with other evidence for the spin of the level giving rise to the 0.415-MeV gamma ray than is the $2(D,Q)2(Q)0$ assignment.

B. 1.29–0.820-MeV Correlation

In this measurement, the Compton distributions of higher energy γ rays in coincidence with the 1.29-MeV transition underlie the 0.820-MeV peak. However, the present method of recording the entire coincident spectrum makes it extremely easy to subtract these contributions from the desired 0.820-MeV peak. The results of these measurements are shown in Fig. 8 and Table III. Again, the solid line is the least-squares fit to the data and is indistinguishable, in this plot, from the theoretical correlation function for the sequence $2(D)2(Q)0$. Shown for comparison are the theoretical correlation functions for the sequences $2(Q)2(Q)0$ and $4(Q)2(Q)0$. These results are in substantial disagreement with those of Scharenberg *et al.*[18] who, on the basis of their measurements, proposed a $2(D,Q)2(Q)0$ sequence in which the dipole content of the 0.820-MeV transition was only about 8%. Again, no explanation for this disagreement is offered.

C. 1.29–1.09-MeV Correlation

The only coincidence contribution that underlies the 1.09-MeV peak in the spectrum in coincidence with the 1.29-MeV gamma ray is that of the 1.29–1.49-MeV combination. This contribution is very small and was taken into account rather simply since the entire coincidence spectrum was available for inspection and analysis at each angle. The results of the measurement of the directional correlation of the 1.29–1.09-MeV cascade is shown in Fig. 9 and Table III. The solid line in this figure is the least-squares fit to the data and is in excellent agreement with the theoretical angular distribution for the sequence $4(Q)2(Q)0$. Here, too, the theoretical distributions for the $3(D)2(Q)0$ and $2(D)2(Q)0$ sequences are presented for comparison. The present results are in excellent accord with those obtained by previous workers.[18]

D. 1.29–1.49-MeV Correlation

The measurement of this correlation is straightforward. The results (presented in Table III) are in agreement with a $4(Q)2(Q)0$ sequence, which is in accord with the previous work of Scharenberg *et al.*[18]

The extremely small 1.29–1.77-MeV coincidence counting rate made the measurement of the angular correlation of this cascade very difficult. The poor statistics in this measurement prevent any spin assignment based upon it. However, other arguments based on the decay characteristics of the 3.06-MeV level, presented in Sec. VI, suggest that this state has a spin and parity of 4^+. No angular-correlation measurements of this cascade have appeared in the literature.

V. PROPOSED DECAY SCHEME

A proposed revised decay scheme of the 54-min In^{116} decay is shown in Fig. 10 (a). The spins, parities, and level ordering are based upon the results of the present investigation and the internal-conversion and β-decay studies of previous authors.[19,20] The level ordering of all transitions, with the exception of the 0.385- and 0.435-MeV transitions found in the present work, are in accord with all previous investigations. The spectra in coincidence with the 0.137-, 0.415-, and 2.12-MeV gamma rays were used to search for any connecting links between the 2.12- and 0.137-MeV transitions. None were found. Indeed, the total absence of the 0.137-MeV gamma ray in the spectrum in coincidence with the 2.12-MeV transition (<1% of the 0.415-MeV gamma ray in this spectrum) is conclusive evidence that no such interconnecting transition is present.

The placement of the 0.385- and 0.435-MeV transitions in cascade, in the order shown, and with the 0.820-MeV gamma ray as the crossover is supported by several observations. Fettweis and Vervier[7] observed this transition in the 13-sec In^{116} ground-state activity and did not observe the 0.385-MeV gamma ray. If these transitions are in cascade, their results indicate the

[19] H. Slatis, S. J. duToit, and K. Siegbahn, Phys. Rev. 78, 498 (1950).
[20] J. Colard, P. Gepts, L. Grenacs, A. Jones, and P. Lipnik, J. Phys. Radium 21, 863 (1960).

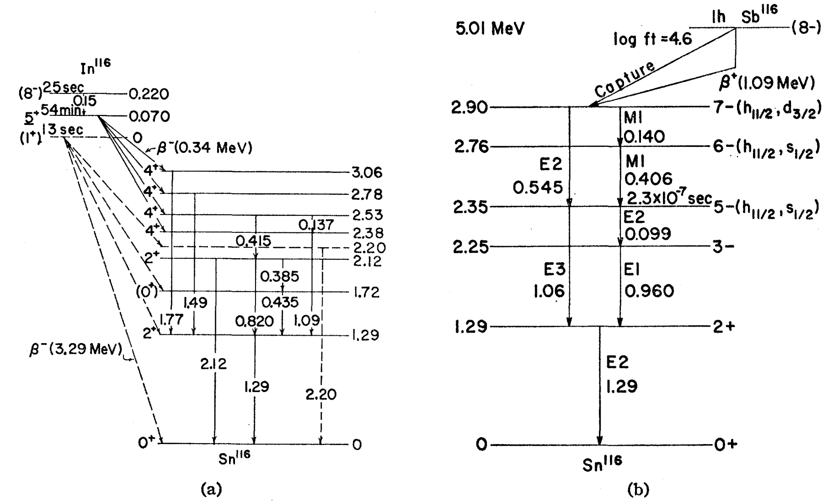

FIG. 10. (a) Proposed decay scheme of Sn^{116} populated from the decay of 54-min In^{116}. All energies are in MeV. The pertinent features of the decay scheme of 13-sec In^{116} (shown dashed) are taken from Ref. 7. (b) Shown for comparison is the proposed decay scheme of Sn^{116} populated from the decay of 1-hr Sb^{116} (Ref. 11). All energies are in MeV.

ordering shown in Fig. 10 (a), which is in agreement with their placement of the 0.435-MeV transition. The cascade feature of these transitions, with the 0.820 MeV as the crossover, is supported by the arithmetic sum of their energies in the present work and in the same way (but to higher accuracy) by the work of John and Jewell.[21] Three lines at 385.27, 434.11, and 819.4 keV (among others) were observed by these authors in the course of their study of the thermal-neutron-capture γ-ray spectrum following neutron capture in In^{115}.The detector used was a high-resolution 2-m bent-crystal spectrometer. Although these authors cannot unambiguously distinguish in all cases between the direct γ rays in In^{116} and those in Sn^{116} resulting from the decay of the In^{116} ground state and the 54-min In^{116} isomer, the sum of the energies of the two lower energy γ rays (819.38 keV) agrees so remarkably well with the energy of the 819.4-keV transition (known to be in the decay of the 54-min In^{116} isomer) that there seems little doubt they are identical to the 0.385- and 0.435-MeV gamma rays, seen in the present work. This same agreement supports the cascade character of these transitions as proposed in the decay scheme of Fig. 10 (a).

The relative intensities of the 0.385- and 0.435-MeV gamma rays, which from the above evidence must populate and depopulate the 1.72-MeV level, shows that any possible transition from this level to the ground state would have an intensity only $\sim$0.5% of that of the 1.29-MeV gamma ray. Because of this small intensity, this transition is extremely difficult to observe experimentally. No evidence for its presence is seen in any of the coincidence spectra (the 1.77-MeV γ ray would prevent observation in the singles spectrum). If the proposed[7] 0^+ assignment is correct, this transition would have an $E0$ character and γ-ray decay would be absolutely forbidden ($0^+ \rightarrow 0^+$). The transition would then proceed principally by internal conversion. Such an internal-conversion line was sought at this energy[22] in the present investigation by use of a Li-drifted silicon detector having a sensitive thickness of only 2 mm. This search proved inconclusive because of the presence of the E2 1.77-MeV conversion line, the small and uncertain intensity of the 1.72-MeV transition sought, and the thinness of the detector available. There was some indication of an excess of internal-conversion electrons at $\sim$1.75-MeV, but the above difficulties and uncertainties preclude any reliable conclusions concerning the presence of this possible $E0$ transition. The weak intensity of this transition (if, indeed, it does exist) would make it extremely difficult to observe even in an experiment involving coincidences between the 0.415-MeV gamma ray and the conversion-electron spectrum.

VI. DISCUSSION

The present experimental observation of the population of the 1.72-MeV state from the 2^+ level at 2.12 MeV lends credence to the proposal by Fettweis and Vervier[7] that this state, seen in the decay of the 13-sec In^{166} 1^+ ground state, should be characterized as 0^+. The failure to observe a γ-ray transition from this level to the 0^+ ground state[23] supports this assignment since, if the spin were 1^+ or 2^+, an $M1$ or $E2$ transition from the 1.72-MeV state to the ground state would be expected to complete favorably with, or even overshadow, the 0.435-MeV transition to the first excited state. Because of the failure (discussed in the last section) to observe a possible 1.72-MeV $E0$ transition, no cogent conclusions for or against the 0^+ assignment can be made.

[21] W. John and R. W. Jewell, International Conference on Nuclear Physics with Reactor Neutrons, edited by F. E. Throw, Argonne National Laboratory Report ANL-6797, 1963 (unpublished), p. 143; W. John (private communication).

[22] This search was conducted by E. B. Shera and the author.

[23] This 1.77-MeV gamma ray is not present in the decay of the 13-sec In^{116} ground state and therefore would not serve to mask the presence of a 1.72-MeV gamma-ray transition from the 1.72-MeV level to the ground state. No evidence of this transition was found (Ref. 7).

Ikegami and Udagawa[5] have reported a 0^+ level in Sn^{118} at 1.74 MeV in the decay of the 1^+ Sb^{118} ground state; and, in their studies of the (d,p) and (d,t) reactions, Cohen and Price[24] have observed levels at 1.56 MeV in Sn^{114}, 1.75 MeV in Sn^{116}, 1.75 MeV in Sn^{118}, and 1.89 MeV in Sn^{120}, which their results indicate are either 0^+ or 1^+. The finite-range shell-model calculations of Arvieu[2] predict 0^+ excited states at 1.63 MeV in Sn^{114}, 1.54 MeV in Sn^{116}, 1.56 MeV in Sn^{118}, and 1.61 MeV in Sn^{120}. Unfortunately, the predicted energies are not reliable to better than a few hundred kiloelectron volts. However, for the isotopes of a particular element, the trend of the predicted energies of a particular state with respect to isotopic mass is expected to be one of the more reliable aspects of these calculations.[25,26] Therefore, Arvieu's predictions[2] of these 0^+ levels at virtually the same excitation energy does support the conclusion that this state would be expected at about the same energy in these four Sn isotopes. Thus all available experimental evidence and the theoretical predictions seem to point to the proposed 0^+ assignment[7] for the 1.72-MeV level in Sn^{116}. From Arvieu's description of these states (based solely on a two-quasiparticle picture), they are expected to be strong admixtures of the $(s_{1/2})^2$, $(d_{3/2})^2$, and $(h_{11/2})^2$ configurations. The proposed[2] constitution of the second excited 2^+ state, which can be associated with the 2.12-MeV 2^+ state, is dominantly composed of admixtures of the $(s_{1/2}, d_{3/2})$, $(d_{3/2})^2$, and $(h_{11/2})^2$ configurations. Thus, the 0.385-MeV $E2$ transition from this state to the 1.72-MeV level would be allowed, but would be strongly out-rivaled, solely on energy considerations, by the 0.820- and 2.12-MeV transitions originating from the 2.12-MeV state.

The 1.29-MeV $E2$ transition from the first excited 2^+ state has been found[27] to proceed at about 10 times the single-particle speed. This level has been interpreted as a collective one-phonon vibrational state, which the calculations of Kisslinger and Sorensen[1] and Arvieu[2] treat rather well.

The rather large over-all energy separation (665 keV) between the 1.72-MeV (0^+) level, the second excited 2^+ state, and the first excited 4^+ state argues against a two-phonon triplet assignment to this *group* of levels. Although such a triplet could be expected at about twice the excitation energy of the first excited 2^+ level, the members of such a triplet have never been observed so far apart.

The next four excited states have been assigned spins and parties of 4^+ and are, perhaps, the most interesting. The β^- decay from the measured[28] 5^+ 54-min In^{116} isomer only proceeds to each of these 4^+ levels and each has a logft value[8,19] (≈ 5) which indicates its allowed character. Thus the spins and parties of these four levels are restricted to 4^+, 5^+, or 6^+. The angular-correlation results select the 4^+ assignments for the 2.38-, 2.53-, and 2.78-MeV states. The decay of the 3.06-MeV state solely to the 1.29-MeV 2^+ level strongly indicates the same assignment to this state. The 5^+ and 6^+ possibilities must be ruled out since this 1.77-MeV transition would then be either an $M3$ or $E4$ transition and could not compete with possible lower energy transitions (not observed) from this state to one of the 4^+ levels below.

The allowed β^- decay to the 2.53-MeV state supports the 4^+ assignment taken from the present angular-correlation measurements and is inconsistent with the 2^+ assignment made by Scharenberg *et al.*[18]

The 3.06-, 2.78-, and 2.38-MeV 4^+ states proceed by $E2$ transitions solely to the first excited 2^+ state at 1.29 MeV and by-pass the second excited 2^+ state at 2.12 MeV. On the basis of energy considerations, the stopovers at 2.12 MeV are expected to have less than 1% of the strength of the transitions to the 1.29-MeV level, so they would not be expected to be observed. However, the 4^+ state at 2.53 MeV is most singular in behavior, decaying by E2 transitions to the 4^+ level at 2.38 MeV and the second excited 2^+ level at 2.12 MeV; but it does not decay to the first excited 2^+ level (intensity $<0.5\%$ of the 1.29-MeV gamma ray from the first excited state to the ground state, as described earlier). To correspond to this upper limit on the intensity, the missing $E2$ transition must be hindered by at least a factor of about 10^5. The cause of this severe retardation is not clear nor simple to evaluate, but does strongly indicate that the 2.53-MeV 4^+ level is singular when compared with the other 4^+ levels in Sn^{116}. The allowed nature of the β^- decay to each of these 4^+ levels could imply that these levels are strongly mixed and/or that the configurational constitution of the 5^+ In^{116} level is rather complicated. At the energies of these 4^+ levels, it has been suggested[29] that seniority-4 admixtures could be expected to enter the makeup of these states. The calculations of the Arvieu-Veneroni[3] type treat only two-quasiparticle excitation, but despite this possible shortcoming, even the two-quasiparticle picture predicts[2] four 4^+ levels in this energy region and prescribes a rather strongly mixed configurational makeup to each. Although Arvieu predicts that some particular two-quasiparticle component will be dominant in each 4^+ level, other configurations enter the makeup of all these levels to an extent that cannot easily be neglected. Because of the accuracy limitations inherent in these theoretical calculations and the possible four-quasiparticle contribution which has been neglected, no

[24] B. L. Cohen and R. E. Price, Phys. Rev. **118**, 1582 (1960); R. E. Price, Ph.D. thesis, University of Pittsburgh, 1962 (unpublished).

[25] A. K. Kerman, R. D. Lawson, and M. H. Macfarlane, Phys. Rev. **124**, 162 (1961).

[26] See Ref. 11 for an example of a comparison of experimental data with this facet of the pairing calculations.

[27] P. H. Stelson and F. K. McGowan, Bull. Am. Phys. Soc. **2**, 69 (1957).

[28] L. S. Goodman and S. Wexler, Phys. Rev. **108**, 1524 (1957).

[29] S. Cohen, R. D. Lawson, M. H. Macfarlane, and M. Soga, Phys. Letters **9**, 243 (1964).

reliable one-to-one correspondence between the levels observed and predicted can be made at the present time. Even the singular characteristics observed of the 2.53-MeV level must await more detailed and accurate calculations before definitive conclusions concerning this level can be drawn and properly assessed.

The doublet nature proposed[8] for the 0.415-MeV gamma ray was not confirmed either by Hansen *et al.*[9] or in the present experiment. From the relative intensities of the transitions found in the present work, (Table II) there is no evidence of an intensity imbalance between the transitions to and from the 2.12-MeV state, and the suggestion[8] of an additional unresolved γ ray of approximately 0.415 MeV between the 2.78- and 2.38- MeV levels does not appear needed or warranted.

Figure 10 (b) displays the decay scheme proposed[11] for the 1-h Sb^{116} activity. As was mentioned earlier, it was not clear whether the levels in Sn^{116} populated from the 54-min In^{116} and 1-h Sb^{116} were indeed different and distinct. This uncertainty was primarily due to the incomplete parameter assignments, etc., in the previously reported[10] 1-h Sb^{116} decay. A comparison of Fig. 10 (b) with Fig. 10 (a) shows that, with the exception of the 1.29-MeV 2^+ first excited state, the Sn^{116} levels populated are distinctly different for the two decays. Even allowing for minor errors in the excitation energies, none of the states excited in these two decays are in one-to-one correspondence, with the exception noted. The 7^- and 6^- levels would not be expected to decay to any of the 4^+ levels (or vice versa) since the $E3$ and $M2$ transitions which would be involved could not be expected to complete[30] successfully with the existing $M1$ and $E2$ transitions proceeding to other levels. The large spin and parity difference of the parent In^{116} (5^+) and Sb^{116} (8^-) levels explains why β decay directly populates different sets of levels in the two cases.

The γ-ray decay from the 5^- level to the second excited 2^+ level would entail an $E3$ transition which (from energy considerations) would be disfavored by a factor of about 4×10^4 relative to the 1.06-MeV $E3$ transition, which does proceed to the 1.29-MeV 2^+ state. This accounts for the failure to observe this transition in this decay. Similarly, the $E1$ transition from the 3^- to 2^+ state at 2.12 MeV does not proceed, since the 0.960-MeV $E1$ transition to the 1.29-MeV 2^+ state is favored by a factor of about 400.

Thus far the lack of population of the second 2^+ level and the four 4^+ levels from all the negative-parity levels seems to be accounted for satisfactorily. However, the failure of the three highest 4^+ levels to reach the 5^- and 3^- levels by $E1$ γ-ray emission, cannot be explained purely by energy considerations, since each of these $4^+\rightarrow5^-$ and $4^+\rightarrow3^-$ transitions should then be highly favored over the more energetic $E2$ and $M1$ transitions which proceed to the positive-parity states. The retardations of these $E1$ transitions must be about 10^4 in order to explain their absence. $E1$ retardations of this magnitude are not rare. The 5^- level in Sn^{116} has been characterized[11] by two-quasiparticle configurations which contain an $h_{11/2}$ neutron orbital. Arvieu[2] describes each of the 4^+ levels, with the exception of the one at lowest excitation energy, as made up primarily of two-quasiparticle configurations in which the neutron orbital of highest angular momentum is $g_{7/2}$, and in which the $(h_{11/2})^2$ configuration plays a relatively minor role. Thus the $E1$ transitions from these 4^+ levels to the 5^- state could be expected to be retarded, as observed. As described in the following paper,[11] the 3^- level is most probably collective and the $4^+\rightarrow3^-$ transitions could similarly be retarded. These arguments, which appear reasonable, satisfactorily account for the differences between the set of Sn^{116} states populated in the decay of 54-min In^{116} and the set from the 1-h Sb^{116} decay.

An additional facet of the 54-min In^{116} decay is interesting. The relative intensities of the 0.820-MeV $M1$ and the 2.12-MeV $E2$ transitions are comparable, while γ-ray transition rates based upon purely single-particle estimates[30] favor the 0.820-MeV $M1$ transition by a factor of about 10. In this region in which quadrupole vibrational excitation is present, the usual case[31] is for the $M1$ $2^+\rightarrow2^+$ transitions to be strongly retarded, while the $E2$ transitions from the second excited 2^+ state to the ground state normally proceed with approximately single-particle speed. Thus, the discrepancy in the transition rates (specified above) could readily be explained on these grounds. In addition, although the $E2$ parts of these $2^+\rightarrow2^+$ transitions are normally 30 times as fast as single-particle estimates,[30,31] single-particle estimates favor the $M1$ part of the 0.820-MeV $2^+\rightarrow2^+$ transition by a factor of about 10^3. This could account for the lack of $E2$ contribution to this transition and favor the present angular-correlation results over the results of Scharenberg *et al.*[18] which classify this transition almost wholly as quadrupole radiation.

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[30] All estimates of single-particle transition probabilities are calculated according to the Weisskopf estimate given by A. H. Wapstra, G. J. Nijgh, and R. Van Lieshout, *Nuclear Spectroscopy Tables* (North-Holland Publishing Company, Amsterdam, 1959), p. 71, and include corrections for internal conversion.

[31] A summary of the experimental situation in these cases is presented by A. H. Wapstra, G. J. Nijgh, and R. Van Lieshout, *Nuclear Spectroscopy Tables* (North-Holland Publishing Company, Amsterdam, 1959), p. 117.