Level Structure of Sn^{116} from the Decay of 1-h Sb^{116}; and a Detailed Comparison of Sn^{116}, Sn^{118}, and Sn^{120} with Pairing-Force Calculations*

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The decay of 1-h Sb^{116} was studied. The spins, parities, and multipole orders of all levels and transitions observed in Sn^{116} are characterized as 2.90 MeV, 7^-; 2.76 MeV, 6^-; 2.35 MeV, 5^-; 2.25 MeV, 3^-; 1.29 MeV, 2^+; $7^- \rightarrow 6^-$, $M1$; $6^- \rightarrow 5^-$, $M1$; $5^- \rightarrow 3^-$, $E2$; $5^- \rightarrow 2^+$, $E3$; $2^+ \rightarrow 0^+$, $E2$. In addition, a strong 0.545-MeV $E2$ transition ($7^- \rightarrow 5^-$), previously unreported, was observed. The assignments of spin and multipole order were determined from angular-correlation and internal-conversion measurements. All β decay was found to proceed exclusively to the 7^- level. The half-life of the 5^- (2.35-MeV) state was determined to be $(2.3\pm0.2)\times 10^{-7}$ sec by use of delayed-coincidence techniques. The 7^- level at 2.90 MeV, previously reported to have a half-life greater than 10^{-7} sec, was found to be prompt ($t_{1/2} < 2\times10^{-9}$ sec). Triple-coincidence measurements determined a β^+-to-capture ratio of 0.237 ± 0.011, from which the transition energy was inferred to be 2.11 ± 0.03 MeV. A complete systematic summary, determined experimentally, for Sn^{116}, Sn^{118}, and Sn^{120}, as populated by the corresponding Sb isotopes, is compared with the latest detailed pairing-force calculations. In addition, the experimentally determined reduced transition probabilities in each of these nuclides are compared with the predictions of this theory.

I. INTRODUCTION

In the last several years, the use of a pairing interaction in short-range residual nuclear force calculations has increased the interest in, and the need for, detailed experimental investigations of those types of nuclides with which this theory may be most conveniently and appropriately compared. In particular, the detailed application of the pairing-force calculations for singly closed-shell nuclei by Kisslinger and Sorensen,[1] by Arvieu,[2] and by Arvieu *et al.*[3] has stimulated experimental studies of the excited states of the Sn isotopes, as well as of other nuclides possessing this closed-shell characteristic. Spherical odd-A nuclei have been treated theoretically by Kisslinger and Sorensen,[4] using pairing and long-range quadrupole-force calculations; and these, combined with the abovementioned theoretical efforts, have contributed much to the interpretation and understanding of levels of spherical nuclei.

Among the Sn isotopes (the subject of this paper), only Sn^{116}, Sn^{118}, and Sn^{120} have been found to have more than two excited states populated by the β decay of the corresponding In or Sb radioactive parent isotopes.[5] Consequently, they provide a more significant base for theoretical comparison than do the other even Sn isotopes. Previous experimental investigations[6,7] have led to complete and confirmed experimental descriptions of the excited states and level structures of Sn^{118} and Sn^{120} as populated by the decay of the corresponding Sb parents. The results were satisfactorily accounted for by the calculations of Kisslinger and Sorensen.[1] Decay schemes involving the energy levels of Sn^{116} have been inferred from recent work on the decay of 1-h Sb^{116},[8] 54-min In^{116},[9,10] and 13-sec In^{116},[11] but these level schemes differ materially from one another in several important aspects. Many of these differences are undoubtedly due to the rather large spin differences of the decaying parent levels. However, some uncertainties, ambiguities, and what seemed to be internal inconsistencies appeared to be present which, it was felt, warranted a reinvestigation of the 1-h Sb^{116} and 54-min In^{116} decays. The previously reported investigations showed that more identifiable levels in Sn^{116} were populated by both the In and Sb decays than were found for either Sn^{118} or Sn^{120}. Therefore, it was felt that a comprehensive experimental description of the levels and transitions between levels in Sn^{116} might provide an even more meaningful test of the theory than do either Sn^{118} or Sn^{120}.

The most recent and complete study previously reported on the decay of 1-h Sb^{116} was that by Skytte Jensen *et al.*,[8] whose proposed comprehensive level scheme for Sn^{116} included two isomeric levels with estimated half-lives greater than 10^{-7} sec. These investigators used internal-conversion measurements to characterize the multipolarities of all transitions observed, and, in addition, they proposed parity assignments for all levels and made (or suggested) spin assignments for the first two excited states seen in this decay. Although

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

[1] L. S. Kisslinger and R. A. Sorensen, Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd. 32, No. 9 (1960).
[2] R. Arvieu, thesis, L'Université de Paris, Institut du Radium, 1962 (unpublished).
[3] R. Arvieu, E. Baranger, M. Veneroni, M. Baranger, and V. Gillet, Phys. Letters 4, 119 (1963).
[4] L. S. Kisslinger and R. A. Sorensen, Rev. Mod. Phys. 35, 853 (1963).
[5] *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.
[6] H. H. Bolotin, A. C. Li, and A. Schwarzschild, Phys. Rev. 124, 213 (1961).
[7] H. Ikegami and T. Udagawa, Phys. Rev. 124, 1518 (1961).
[8] B. Skytte Jensen, O. B. Nielsen, and O. Skilbreid, Nucl. Phys. 19, 654 (1960).
[9] R. K. Girgis and R. Van Lieshout, Physica 25, 590 (1959).
[10] P. G. Hansen, H. L. Nielsen, and K. Wilsky, Nucl. Phys. 30, 140 (1962).
[11] P. Fettweis and J. Vervier, Phys. Letters 3, 36 (1962).

Skytte Jensen *et al.*[8] did not suggest complete characterizations of all the levels or transitions between levels in Sn^{116}, some of their characterizations were materially different from those of the Sn^{118} and Sn^{120} levels populated by the corresponding Sb decays,[6,7] even though the decay schemes of the latter two were found to be identical for all practical purposes. Because the isomeric transitions found in Sn^{118} and Sn^{120} are important tests of the detailed predictions of the pairing-force calculations, it was felt that direct determinations of the half-lives of the isomeric Sn^{116} levels proposed by these workers could be of significant value.

Clearly, a more complete experimental parametrization of the levels and transitions was required before any definitive and meaningful conclusions could be drawn from the important differences between the proposed population of levels in Sn^{116} formed by decay of Sb^{116} and the corresponding populations of Sn^{118} and Sn^{120}. Hence a rather complete reinvestigation of this decay was undertaken, both for this reason and because only a detailed comprehensive experimental description of the Sn^{116} levels populated by this decay could provide any significant and meaningful basis for comparison and understanding of the marked differences between these levels and those populated in the decay of 54-min In^{116}.[9,10,12]

The present investigation included use of the techniques of scintillation γ-ray and magnetic β-ray spectroscopy. Of considerable significance and interest, as it relates to detailed model predictions, are the lifetime measurements of levels for which only lower limit estimates were previously proposed. These results are supplemented by those obtained from the angular-correlation measurements for various γ-ray cascades, studies of internal-conversion coefficients, electron capture-to-positron ratios, and the relative intensities of all transitions. The revised decay scheme educed from these data includes an additional strong transition (previously unreported), the assignments of spin and parity for all levels, and the multipolarity assignments of all transitions.

Combined in the discussion of these results is a comprehensive summary and comparison of the results of the 1-h Sb^{116} decay with that of the corresponding results[6,7] for the Sb-populated levels in Sn^{118} and Sn^{120}. These consolidated data are compared with the most recently available and applicable theoretical calculations.

II. SOURCE PREPARATION

Samples of 1-h Sb^{116} were produced by the reaction $In^{115}(\alpha,3n)Sb^{116}$ induced by 43-MeV alpha particles from the Argonne 60-in. cyclotron. Natural In foil targets of high purity were used. The activity was separated from the target material by a procedure identical to that described in an earlier paper.[6] The chemical forms of the source material used in various aspects of the experimental work were the same as those used in the corresponding phases of the Sn^{118} work.[6]

The α-particle bombardment of the In target produced no other long-lived activities, with the exception of 2.8-h Sb^{117} [from $In^{115}(\alpha,2n)Sb^{117}$]. The details of this decay are well known,[5] and the proportion of Sb^{117} produced at the bombarding energy used presented little difficulty in the present investigation. However, at slightly lower α-particle energies ($\lesssim$37 MeV), the proportion of Sb^{117} activity was materially higher.

III. γ-RAY INTENSITIES

The γ-ray spectrum resulting from the decay of 1-h Sb^{116} was studied by scintillation methods. Figure 1 presents the singles pulse-height distribution of these radiative transitions as obtained with a 3 in.×3 in. NaI(Tl) detector. Six γ rays, all of which had been seen by previous workers,[8] are readily identified at energies of 0.099, 0.140, 0.406, 0.960, 1.06, and 1.29 MeV. In addition, the rather broad peak in the vicinity of 0.51 MeV, which had been previously attributed solely to annihilation radiation,[8] is shown in Sec. V to be com-

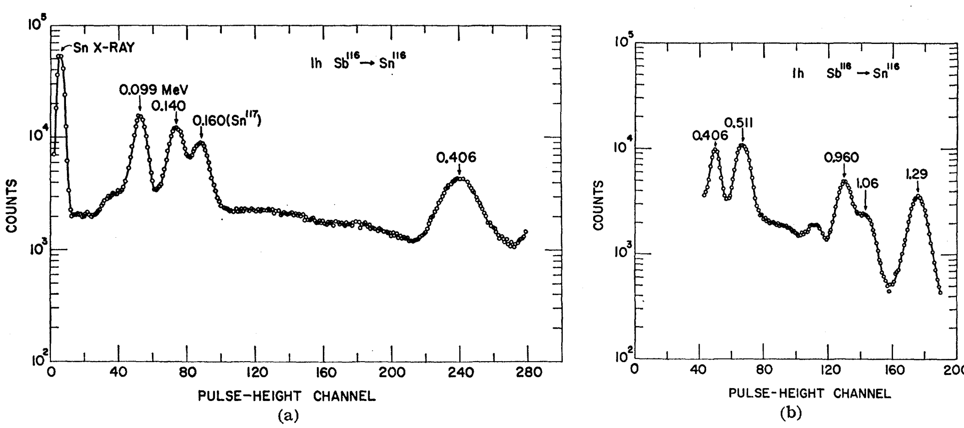

FIG. 1. NaI(Tl) (3 in.×3 in.) pulse-height spectra: (a) low-energy region; (b) high-energy region.

[12] H. H. Bolotin, preceding article, Phys. Rev. **136**, B1557 (1964).

posed of annihilation radiation and a γ ray with an energy of 0.545 MeV. The prominent Sn K x ray is also displayed.

As previously described, the peak on the high-energy side of the 0.140-MeV γ-ray peak is due to the ubiquitous 0.160-MeV γ ray from the decay of 2.8-h Sb^{117}. This peak, because of the relatively long half-life of Sb^{117} compared with that of 1-h Sb^{116}, became more prominent as the source aged. Therefore, in those studies in which the 0.160-MeV γ ray or the annihilation radiation resulting from the β^+ emission feeding this transition could be troublesome, activities obtained from a particular bombardment were discarded relatively soon after the cyclotron production of the source.

The relative intensities of the γ rays as determined from the singles, and in some cases coincidence, spectra are tabulated in the second column of Table I.

IV. COINCIDENCE AND LIFETIME MEASUREMENTS

The gamma-gamma coincidence studies made use of two 3 in.×3 in. NaI(Tl) detectors mounted on 3-in.-diam photomultiplier tubes (Harshaw Integral Line).[13] After amplification and pulse pile-up rejection,[14] the pulses from each detector were fed to a fast-slow coincidence circuit set to have a fast resolving time of $2\tau\approx 50$ nsec and a slow triple-coincidence resolving time of $\tau=1.5$ μsec. The fast coincidence circuit was of unconventional design utilizing the linearly amplified pulses and pulse-height compensation.[15]

The linear pulses from one detector were sorted by as many as eight digital pulse-height windows by employing an external 100-channel analog-to-digital converter.[16] These digital windows served as coincidence gates which directed the coincident pulses of the second detector to the proper associated 100-, 200-, 400-, or 800-channel subgroups of an 800-channel pulse-height analyzer.[17] In addition, when as few as 400 channels of coincidence data were required or desired, an auxiliary fast coincidence circuit having a resolving time identical to that of the main fast coincidence circuit simultaneously routed the chance coincidence spectrum associated with each digitally gated subgroup to the corresponding subgroup in the last 400 pulse-height channel locations. This feature permitted coincidence runs in which the coincidence true-to-chance ratio was relatively low and/or subject to large change during each run because of rapid source decay and the replacement or replenishment of the source material during the course of a run.

Since it was often necessary to replace depleted sources during a coincidence run, possible attendant gain shifts due to changes in source strength were obviated by the use of Cosmic Radiation Laboratories "Spectrostat" gain stabilizers. Of course, these stabilizers also prevented other electronic gain drifts from affecting the pulse-height distributions being recorded.

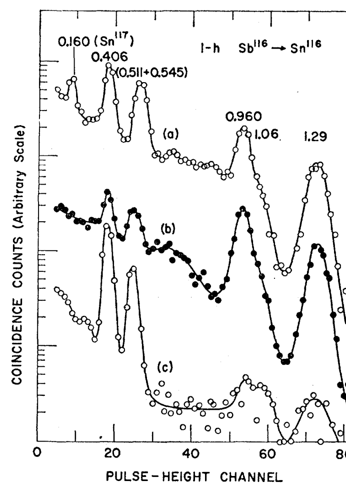

FIG. 2. Spectra in coincidence with (a) the K x ray, (b) the 0.099-MeV γ ray and (c) the 0.140-MeV γ ray, recorded simultaneously. Chance coincidence contributions have been subtracted from each spectrum. No corrections for coincidences due to underlying Compton distributions have been made.

TABLE I. Relative intensities of gamma rays from Sn^{116}.

Transition energy (MeV)	Measured γ-ray intensities
0.099	0.30 ± 0.02^a
0.140	0.30 ± 0.03^a
0.406	0.36 ± 0.02^a
0.545	0.68 ± 0.08^b
0.960	0.75 ± 0.06^a
1.06	0.27 ± 0.05^a
1.29	1^a

[a] Determined from singles scintillation spectroscopy.
[b] Determined from triple-coincidence measurements.

The high-energy portion of the spectra in coincidence with the K x ray and the 0.099- and 0.140-keV γ rays, with all chance subtracted, are shown in Fig. 2. It should be noted that these coincidence spectra were recorded simultaneously, so that the effect of changes in amplifier gain settings, source-strength changes, etc., which could affect these spectra under ordinary experimental conditions, do not enter at all in this case—or, if they enter, contribute to each of these spectra to an identical extent.

Figure 3 displays the coincident spectrum with the gate set on the "0.511-MeV" peak. In this run, the detectors were at right angles to each other. In addition, the coincidences contributed by the underlying Compton distributions in the gating window were obtained at the same time by gating additional digital windows on this distribution just below the 0.406-MeV and above

[13] Obtained from the Harshaw Chemical Company, Cleveland, Ohio.
[14] M. Strauss, Rev. Sci. Instr. 34, 335 (1963).
[15] M. Strauss, Rev. Sci. Instr. 34, 1248 (1963).
[16] M. Strauss, Nucl. Instr. Methods (to be published).
[17] Victoreen Model ST 800 M multichannel analyzer.

the "0.511-MeV" peaks, and were subtracted from the spectra in Fig. 3. Further, the chance coincidence contributions associated with each spectrum was simultaneously recorded and later subtracted. The presence of a peak in the annihilation-radiation region in coincidence with the annihilation-radiation peak is evidence of an additional γ ray which remains unresolved from the annihilation radiation. The presence of any γ rays at all in coincidence with the annihilation radiation is in disagreement with the work of Skytte Jensen *et al.*[8] who reported the complete absence of γ-ray coincidences with annihilation radiation. The same is true of the coincidences with the x ray [Fig. 2(a)]; these authors claim a total lack of such coincidences. No obvious or ready reason presents itself to account for their failure to observe either these coincidences or the additional

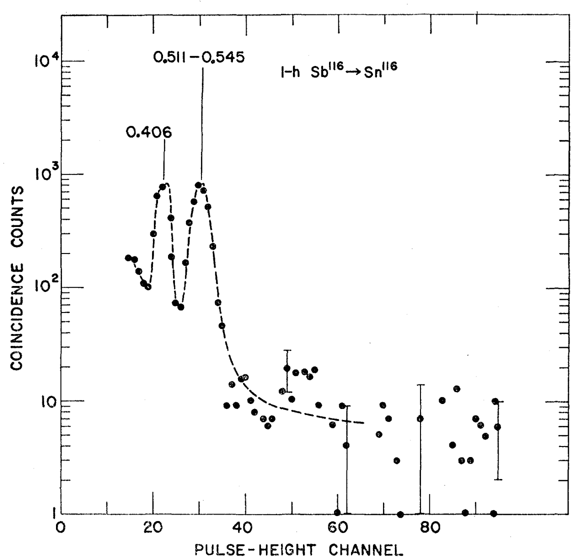

FIG. 3. Spectrum in coincidence with the "0.511-MeV" peak. This spectrum has been corrected for chance coincidences. The detectors were placed at 90° to each other.

γ ray found in the composite "annihilation radiation" peak. The present results remove the justification for a lifetime assignment of $>10^{-7}$ sec for the level at 2.90 MeV, which was proposed by these workers because of their failure to observe such prompt coincidences. An attempt to determine the lifetime of this level in the present experiment, by use of time-to-pulse-height conversion and NaI detectors, resulted in an upper limit of $<2\times10^{-9}$ sec for the half-life of this state. This positively demonstrates the "prompt" lifetime of this state, suggested by the results presented above, and rejects the isomeric character proposed for this state by previous workers.

On the other hand, an attempt to measure the lifetime of the 2.35-MeV level, for which Skytte Jensen *et al.*[8] estimate a lower limit of $>10^{-7}$ sec, resulted in a half-life determination in agreement with their esti-

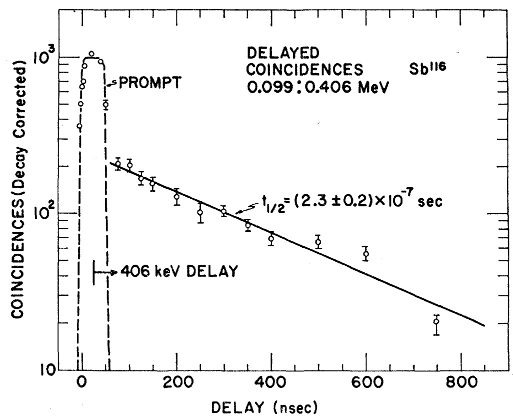

FIG. 4. Time delay curve of 0.099–0.406-MeV coincidences. The counting rates have been corrected for the decay of the Sb^{116} (half-life = 1 h).

mate. A conventional delayed-coincidence experiment (with a resolving time of $\sim4\times10^{-8}$ sec) between the 0.099- and 0.406-MeV γ rays yielded a half-life of $(2.3\pm0.2)\times10^{-7}$ sec—measured as the delay (Fig. 4) of the 0.099-MeV transition relative to the 0.406-MeV γ ray. The prompt component of this curve is principally due to the Compton distributions of the 0.960- and 1.29-MeV γ rays which underlie the 0.406-MeV peak and which have been shown above to be in prompt coincidence with the 0.099-MeV transition.

Because of differences already displayed between the present work and that of previous workers, additional delayed-coincidence spectra were felt to be worthwhile to further certify the position of the delayed state with respect to transitions proceeding to and from it, and thereby to remove any uncertainties in the time ordering of the transitions present in the decay. Figure 5 displays the results of these additional delayed-coincidence spectra obtained by gating one arm of the coincidence system on the 0.099-MeV peak and recording the spectrum in delayed coincidence with this γ ray by delaying the pulses from the second detector by 150 nsec. These data clearly show that the 0.140- and 0.406-MeV transitions, as well as the annihilation radiation (0.545-MeV γ-ray composite), precede the delayed level, while the 0.099-, 0.960-, 1.06-, and 1.29-MeV gamma rays follow the decay of the delayed state. The small residual in the delayed coincidence spectrum at 0.099 MeV is due to chance coincidences which have not been subtracted from the data presented in this figure. From the data presented in this section, and from the Coulomb excitation[18] and other evidence[5] which places the 1.29-MeV γ ray between the first excited state and the ground state, the time ordering of all transitions is known uniquely, with the exception of the ordering of the 0.140- and 0.406-MeV transitions with respect to each other. The energy of the 0.545-

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

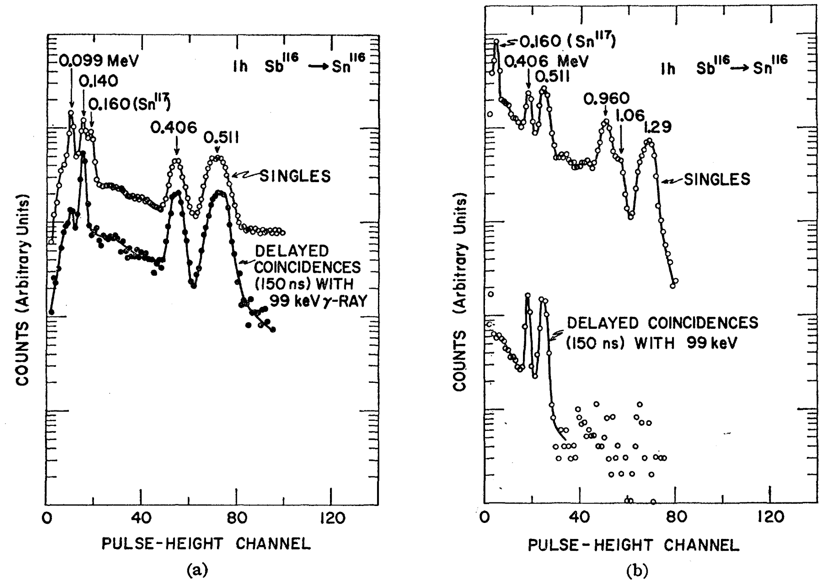

FIG. 5. Spectra in coincidence with the 0.099-MeV γ ray delayed by 150 nsec: (a) low-energy region; (b) high-energy region. The contribution from chance coincidences has not been subtracted.

MeV γ ray and the coincidence data pertaining to this transition place it as the cross-over transition corresponding to the 0.140-, 0.406-MeV cascade. Figure 6 summarizes the time ordering of the transitions dictated by the data thus far presented.

V. ELECTRON CAPTURE AND β^+ EMISSION

The sum of the relative intensities of the 0.406- and 0.545-MeV γ rays, when compared with the intensity of the 1.29-MeV γ ray, restricts any direct population of levels below the fourth excited state in Sn^{116} from the decay of 1-h Sb^{116} to less than 6% of all decays. The ambiguity in the time ordering of the 0.140- and 0.406-MeV transitions prevents the assignment of all decays to proceed exclusively to the 2.90-MeV level solely from the relative intensities or other data presented above. However, this information is sufficient to point up the serious disagreement that exists between these data and those of Skytte Jensen *et al.*,[8] who indicated that ~68% of all Sb^{116} decays proceed directly to the 2.35-MeV level. The reason for this disagreement comes from their failure to observe or recognize the presence of the 0.545-MeV cross-over transition.

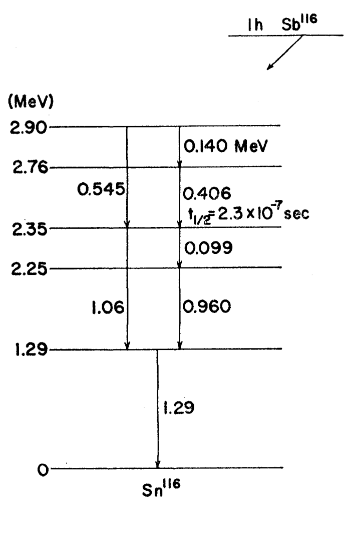

FIG. 6. Time order of transitions in Sn^{116}. The ordering of the 0.140- and 0.406-MeV transitions is uncertain.

In order to uniquely determine the branching ratio and energy release of the β decay from the 1-h Sb^{116} state, triple-coincidence measurements were made between the two annihilation-radiation quanta and the γ rays attending the decay of the levels populated by β^+ emission. The K-capture-to-positron ratios are sensitive measures of the decay energy. Because of the strong energy dependence of this ratio, data which determine this ratio can be used to uncover weak β^+ branches to lower levels. At relatively large source-to-detector distances, the nature of the annihilation process serves to sufficiently enhance the coincidence detection efficiency of the annihilation quanta at 180° to quantitatively reveal β^+ emission that is considerably less than 1% of the decay. This was demonstrated in the work on the decay of 5.1-h Sb^{118},[6] in which the use of this technique showed that β^+ emission (which was not observed in the singles or normal coincidence spectra) accounted for 0.16% of the decay. In the case of 1-h Sb^{116}, the sensitivity of this type of measurement is not demonstrated as dramatically, since the presence of annihilation radiation is evident even in the singles scintillation spectrum. In the present measurement, two 3×3-in. NaI scintillation detectors were set to accept only the full-energy "peak" of the annihilation quanta at 180° to each other at a distance of 15 cm from the source. The rather large source-to-detector distance was chosen to strongly discriminate against coincidences between the 0.545-MeV γ ray, present to some extent in the energy-selection windows associated with these detec-

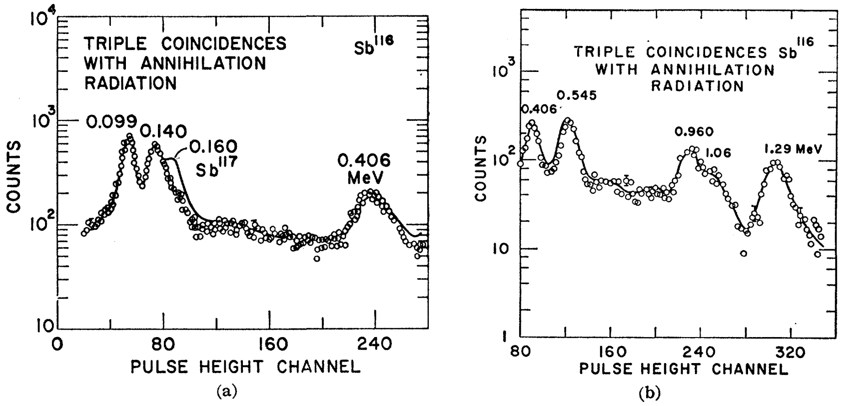

FIG. 7. Spectra in triple coincidence with annihilation radiation: (a) low-energy region; (b) high-energy region. The singles spectra are shown for comparison.

tors, and other γ rays. The pulses from these detectors were mixed in fast-slow coincidence by use of a fast resolving time of 3×10^{-8} sec. The pulses from a third 3×3-in. NaI detector were mixed with the 511-511 coincidence signal by using a relatively long resolving time of $\tau=1.5$ μsec. The relatively long resolving time was necessary to insure full coincidence efficiency for those γ rays that follow the decay of the long-lived (2.3×10^{-7} sec) 2.35-MeV level.

The spectra so obtained are shown in Fig. 7. The circles represent the recorded data. The solid line is not a fit to these data but represents the singles spectrum obtained in the third 3×3-in. detector, normalized to the 0.099-MeV peak. It is seen that, with the exception of the 0.160-MeV gamma ray (Sb^{117}) and the peak at 545 keV, the triple-coincidence spectra have the same shape as the singles spectra. This indicates that β^+ emission goes rather exclusively to the 2.90-MeV level. The 0.160-MeV gamma-ray difference is as expected, since this transition is fed only by a positron emission from Sb^{117} with an intensity of $\sim3\%$. The additional difference between the singles spectrum and triple-coincidence data at 545 keV is due to the singles peak being a composite of annihilation radiation and the 545-keV gamma ray, of which the former is not recorded in the triple-coincidence measurement.

A triple-coincidence measurement with a Na^{22} source, for which the γ-ray energy (1.27 MeV) is practically that of the 1.29-MeV Sn^{116} transition, and whose positron branching is well known,[5] yielded experimentally determined triple-coincidence detection efficiencies which, when combined with the Sb^{116} data of Fig. 7 in a detailed analysis, produced the following results. The decay proceeds entirely to the 2.90-MeV level with not more than 0.3% of all decays going to lower levels. In addition, positron emission accounts for $(19.2\pm0.6)\%$ of the decay. Analysis of these data by use of the curves of Perlman and Wolfsberg[19] for the dependence of positron-to-capture ratios upon the β-decay energy release in allowed transitions, results in an accurately determined β-decay energy of 2.11 ± 0.03 MeV. Using the 1.0-h parent half-life and these results, a log ft value of 4.6 is obtained which is consistent with what is expected for allowed decay. The value of 1.09 ± 0.03 MeV obtained here for the positron end-point energy is in good agreement with the value of 1.16 ± 0.04 MeV which Skytte Jensen *et al.*[8] obtained by magnetic β-ray spectroscopy.

VI. INTERNAL-CONVERSION STUDIES

The internal-conversion-electron spectrum of the transitions was studied with a magnetic-lens type spectrometer operated at a resolution of approximately 2.5% and with a highly effective positron baffle. Because of the relatively poor resolution, most of the data were only suitable for determinations of the total conversion coefficient. However, the $K/(L+M)$ conversion-coefficient ratio was measured for the 0.099-MeV transition, although the total internal-conversion coefficient for this transition was not held to be reliable because corrections for absorption in the counter window were necessary but were not known to sufficient accuracy. The same difficulty prevented a reliable determination of the K-conversion coefficient for the 0.140-MeV transition. In addition, the presence of the unresolved K-conversion line of the 0.160-MeV Sb^{117} contaminant, superimposed on the 0.140-MeV $(L+M)$ line, prevented a determination of the $K/(L+M)$ ratio for this transition. However, from the decay scheme, relative γ-ray intensities, and β-decay branching obtained in this work, relatively good total internal-conversion coefficients were obtained for the 0.099- and 0.140-MeV transitions. A semigraphical summary of the internal-conversion results, together with the theoretical values[20,21] expected for various electric and magnetic

[19] M. L. Perlman and M. Wolfsberg, Brookhaven National Laboratory Report BNL-485, 1958 (unpublished). Other pertinent references are given in this report.

[20] *Internal Conversion Coefficients*, edited by M. E. Rose (North-Holland Publishing Company, Amsterdam, 1958).

[21] L. Sliv and I. Band, Leningrad Physico-Technical Institute Report, 1956 [translation: Report 57 ICC K1, issued by the Physics Department, University of Illinois, Urbana (unpublished)].

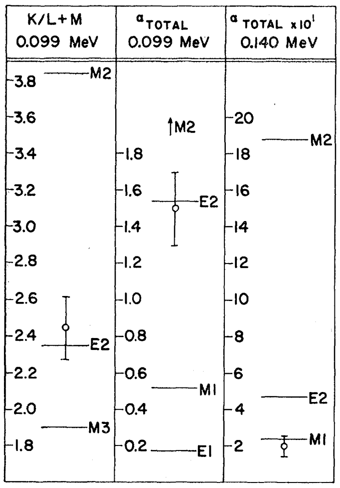

FIG. 8. Schematic representation of the observed and theoretical total conversion coefficients and $K/(L+M)$ ratio for the 0.099- and 0.140-MeV transitions.

present work (Table II and Figs. 8 and 9). The sole disagreement is in the characterization of the 1.06-MeV transition, to which they attached an $M2(+E1)$ character but which the present results clearly indicate is $E3$. However, one should not take this apparent disagreement too seriously, because, if one compares their K internal-conversion value of 1.9×10^{-3} for this transition with corresponding theoretical values[20,21], one finds that their value is only 14% lower than the theoretical $E3$ value of α_K. This is to be compared to their value being 37% lower than the theoretical $M2$ value and 4.5 times the $E1$ theoretical α_K. Although no errors have been assigned to the experimental internal-conversion coefficients reported by these workers, it would appear that their results are more consistent with an $E3$ assignment for the 1.06-MeV transition (in agreement with the present work) than with any other choice of multipolarity.

multipolarities is given in Figs. 8 and 9. This form of presentation allows a somewhat clearer delineation of the multipole designations than does the listing of the same data in Table II. The observation of the 0.545-MeV conversion electrons in this experiment not only contributes additional positive evidence for the presence of this transition, but also deepens the lack of understanding of the failure of the Copenhagen group[8] to observe this line in their internal-conversion-electron studies. The resolution used in their work was apparently sufficiently better than that available in the present work to enable them to quote K-shell internal-conversion coefficients for all transitions which they did observe.

Although the total-internal-conversion coefficients obtained here cannot be directly compared with the K-conversion results of Skytte Jensen *et al.*,[8] the multipolarity assignments made for all but one of the transitions seen by them are in agreement with those of the

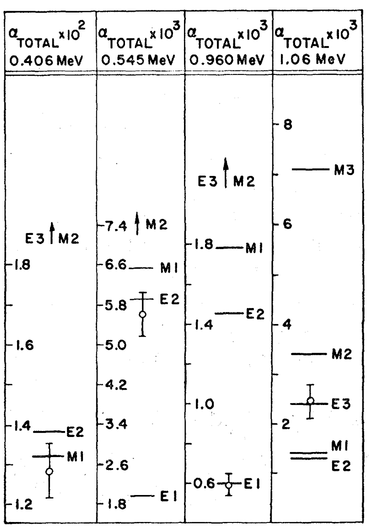

FIG. 9. Schematic representation of the observed and theoretical total conversion coefficients for the 0.406-, 0.545-, 0.960-, and 1.06-MeV transitions.

VII. γ-γ ANGULAR CORRELATIONS

As is well known, a coupling of the multipolarity assignments of the transitions obtained from internal-conversion studies with the results of γ-γ angular-correlation measurements can lead to unique spin assignments for levels populated in the decay. In the present work, γ-γ angular-correlation measurements were made for three pairs of cascade γ rays. In these studies, data were obtained at 15° intervals from 90° to 270° and were taken and recorded automatically. The 3×3-in. NaI detectors were placed 15 cm from a weak HCl liquid source contained in a thin-walled polyethylene capsule.

The coincidence data were recorded with the digitally gated circuitry described in Sec. IV and a fast resolving time of $\sim4\times10^{-8}$ sec. The pulses from one detector were digitally sorted so that several peaks or segments of underlying Compton distributions were selected, and the entire spectrum of the second detector in coincidence with each digital window setting was routed and stored in an appropriate subgroup of the 800-channel analyzer. Thus, the correlation measurement of more than one cascade could be recorded simultaneously. The inherent advantages which attend the recording of the entire or partial coincidence spectrum associated with a given γ ray should not be overlooked. This is made more evident in the description of the measurements of the 1.29–1.06- and 1.29–0.960-MeV cascades. In addition, the chance coincidence spectra were recorded at the same time and routed to corresponding additional subgroup locations in the analyzer memory. The source strength, reflected by the singles γ-ray intensity in each detector, was monitored and integrally stored for each angle at which coincidences were recorded. This arrangement permitted replacing or replenishing the source, necessary at frequent intervals because of the relatively short lifetime of the parent Sb^{116}, at any time during the run. The coincidence data at

TABLE II. Internal-conversion-electron results in Sn^{116}.

Transition energy (MeV)	Experimental coefficient or ratio[a]	Theoretical[b] conversion coefficient $E1$	$E2$	$E3$	$M1$	$M2$	$M3$	Assign-ment
0.099	$\alpha_T = 1.50 \pm 0.20$	1.76×10^{-1}	1.54	1.67×10^{1}	5.2×10^{-1}	5.4	4.9×10^{1}	$E2$
	$\alpha_K/\alpha_{L+M} = 2.44 \pm 0.17$	5.9	2.35	0.62	5.6	3.8	1.9	
0.140	$\alpha_T = (2.0 \pm 0.3) \times10^{-1}$	7.6×10^{-2}	4.9×10^{-1}	3.8	2.2×10^{-1}	1.8	1.2×10^{1}	$M1$
0.406	$\alpha_T = (1.28 \pm 0.07)\times10^{-2}$	3.9×10^{-3}	1.4×10^{-2}	4.2×10^{-2}	1.3×10^{-2}	4.8×10^{-2}	1.7×10^{-1}	$M1$
0.545	$\alpha_T = (5.7 \pm 0.5) \times10^{-3}$	2.0×10^{-3}	5.9×10^{-3}	1.6×10^{-2}	6.5×10^{-3}	2.1×10^{-2}	5.5×10^{-2}	$E2$
0.960	$\alpha_T = (6.0 \pm 0.6) \times10^{-4}$	6.0×10^{-4}	1.5×10^{-3}	3.1×10^{-3}	1.8×10^{-3}	4.4×10^{-3}	9.2×10^{-3}	$E1$
1.06	$\alpha_T = (2.41 \pm 0.35)\times10^{-3}$	5.0×10^{-4}	1.3×10^{-3}	2.4×10^{-3}	1.4×10^{-3}	3.4×10^{-3}	7.1×10^{-3}	$E3$
1.29	$\alpha_T =$		7.6×10^{-4}					$E2$

[a] The total internal-conversion coefficients (α_T) for the 0.406-, 0.545-, 0.960-, and 1.06-MeV transitions were calculated by use of the theoretical conversion coefficient for the 1.29-MeV $E2$ transition. The total internal-conversion coefficients for the 0.099- and 0.140-MeV transitions were obtained from the known decay scheme and the γ-ray intensities listed in Table I.
[b] References 20 and 21.

each angle were corrected for decay and normalized to the singles counting rate in the movable counter. The correlation coefficients for each cascade were obtained from a weighted least-squares analysis[22] of the data and then corrected for attenuation due to the finite solid angle of the detectors.[23]

A. 1.29–1.06-MeV Correlation

Because of the method used to record the coincidence spectrum, the portion of the spectrum of the partially unresolved 0.960- and 1.06-MeV γ rays in coincidence with the 1.29-MeV transition was available for inspection and detailed analysis at each angle. The coincidence spectra so obtained required a mild form of "stripping" in order to obtain the separate coincidence contributions of each of these transitions at every angle. This unfolding is straightforward, simple, and capable of sufficient accuracy that it does not materially contribute to uncertainty of the coincidence intensity measured at each angle. The uncertainty in this intensity was almost wholly due to the statistical error. Indeed, this method of recording the coincidence spectrum contributes greatly to the simplicity and feasibility of the angular-correlation measurement of each of these cascades. The usual procedure of using one pulse-height selector for each member of each cascade and merely recording the relative coincidence rate as a function of angle would be either unfeasible, impracticable, or open to large uncertainties, due to the fact that the relatively weak 1.06-MeV γ ray is not fully resolved from the 0.960-MeV peak.

The result of the 1.29–1.06-MeV correlation is presented graphically in Fig. 10 and numerically in Table III. The solid line in Fig. 10 is a least-squares fit to the data and is indistinguishable in this plot from the theoretical correlation,[24,25] corrected for solid angle, for the sequence $5(O)2(Q)0$. Taken together with the present internal-conversion results, the correlation obtained is consistent with a pure $E3$ multipole assignment for the 1.06-MeV transition.

TABLE III. Angular-correlation results.

Gamma-ray energies (MeV)	Experimental coefficients P_2 (cosθ)	P_4 (cosθ)	Theoretical coefficients for indicated sequences P_2 (cosθ)	P_4 (cosθ)
1.29 –1.06	0.182 ± 0.023	0.005 ± 0.073	0.179	-0.004
			$5(O)2(Q)0$	
1.29 –0.960	$-(0.068 \pm 0.012)$	...	-0.071	0
			$3(D)2(Q)0$	
0.140–0.406	0.049 ± 0.013	...	0.050	0
			$7(D)6(D)5$	

B. 1.29–0.960-MeV Correlation

The data for the 1.29–0.960-MeV correlation were obtained at the same time and analyzed in the same way as described for the 1.29–1.06-MeV cascade corre-

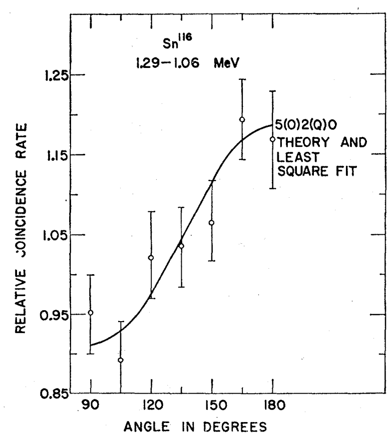

FIG. 10. Results of angular-correlation measurements of the 1.29- and 1.06-MeV γ-ray cascade.

[22] M. E. Rose, Phys. Rev. 91, 610 (1953).
[23] M. J. L. Yates, *Perturbed Angular Correlations*, edited by E. Karlsson, E. Matthias, and K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1964), p. 453.
[24] L. C. Biedenharn and M. E. Rose, Rev. Mod. Phys. 25, 729 (1953).
[25] H. N. Taylor and R. McPherson, Physics Department, Queen's University, Kingston, Canada, 1960 (unpublished).

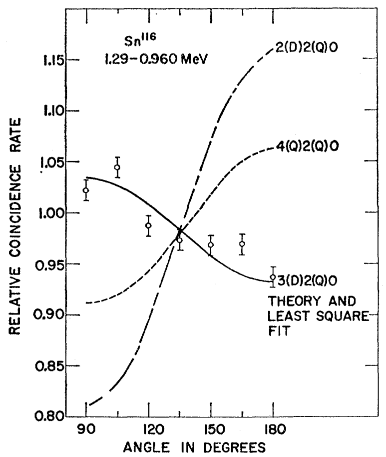

FIG. 11. Results of angular-correlation measurements of the 1.29- and 0.960-MeV γ-ray cascade. Some theoretical correlations are shown for comparison.

lation. The results of this measurement are given in Fig. 11 and Table III. Again, the solid line in the figure is the least-squares fit to the data and is indistinguishable from the theoretical correlation. This time, the sequence is consistent with a $3(D)2(Q)0$ assignment with all transitions of pure multipolarity. Shown for comparison are the theoretical correlation functions for other possible spin sequences for pure multipole transitions. As in the 1.29–1.06-MeV correlation, correlation functions involving other spins and including multipole mixing would not fit the data with multipole mixtures in any reasonable agreement with the internal-conversion results.

C. 0.140–0.406 MeV Correlation

In this measurement, one digital window was set up to accept the full-energy peak of the 0.406-MeV γ ray and a second window was set on the Compton distribution just below this peak. The low-energy portion of the spectrum coming from the second detector and in coincidence with these selections was recorded and stored simultaneously in separate analyzer subgroups. Although the 0.960-, 1.06-, and 1.27-MeV Compton distributions underlie the 0.406-MeV peak, they are materially delayed in time because of the long lifetime of the 2.35-MeV level and contribute little to prompt coincidences with either of the two transitions under consideration. However, the annihilation quanta are in prompt coincidence with these transitions and their Compton distributions do underlie the full-energy peaks of the transitions under study and contribute in a small but measurable degree to the measured coincidence spectrum. In addition, the small Sb^{117} 0.511–0.160-MeV prompt coincidences may also influence the observed coincidence spectrum in the vicintiy of the close-lying 0.140-MeV peak. The coincidences associated with these effects were recorded simultaneously by virtue of the digital window set on these Compton distributions, and after proper normalization were subtracted from the coincidence spectrum obtained for the two transitions under investigation. The result of this correlation measurement is shown in Fig. 12 and is tabulated in Table III. These results show the least-squares fit to the data (solid line) to be consistent with a spin sequence $7(D)6(D)5$ or $3(D)4(D)5$ with each transition of pure multipolarity. These data are also consistent with each transition being of pure multipolarity. This removes the possibility, left open by the internal-conversion data for the 0.406-MeV transition, that it might be a strong mixture of $M1$ and $E2$. Some other theoretical correlations for other spin sequences are provided for comparison. Within the confines of the experimental internal-conversion coefficients obtained for the 0.140- and 0.545-MeV transitions, other spin sequences using a dipole-quadrupole multipole mixing for the 0.406-MeV transition do not admit of a fit of the data for mixing ratios allowed by the experimentally determined internal-conversion coefficient obtained for this transition.

The possible $3(D)4(D)5$ sequence is rejected on the grounds that (a) the lower 3^- level at 2.25-MeV should experience some direct population by β decay if the 2.90-MeV were also 3^-; (b) the γ-ray branching of the 2.90-MeV level, if 3^-, should be expected to reach either the 2.25-MeV 3^- or 1.29-MeV 2^+ levels; and (c) the 2.76-MeV level assigned 4^- in this sequence would be expected to proceed to the 3^- level at 2.25 MeV to some degree. However, the possibility of the $7(D)6(D)5$ sequence does not suffer from any such deficiencies, and moreover provides a ready and simple check of the consistency of the observed characteristics of the decay scheme.

D. Correlations Involving the Delayed 2.35-MeV Level

Because of the long lifetime of the 2.35-MeV level, no attempt was made to measure the angular correlation of any cascades in which this level served as an intermediate state. A half-life of 2.3×10^{-7} sec allows more than ample time for the spin orientation of this level to precess about any existing internal fields as a result of the coupling of the nuclear dipole or quadrupole moment to these fields. This effect would manifest itself

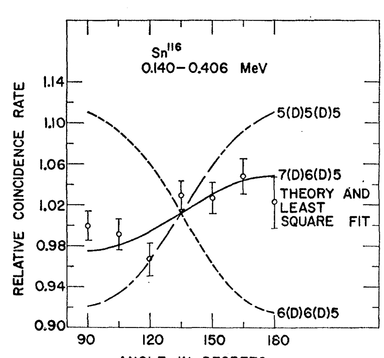

FIG. 12. Results of angular-correlation measurements of the 0.140- and 0.406-MeV γ-ray cascade. Some theoretical correlations are shown for comparison.

in the measured anisotropy being less than the unperturbed value, so that it would be extremely difficult to analyze the correlation data and assign spins and multipolarity mixing in any meaningful and reliable manner. Of course, a study of such a correlation as a function of artificially inserted delays (with or without the influence of an externally applied magnetic field) could not only overcome such objections, but could serve as a sensitive measure of the various nuclear moments associated with the 2.35-MeV level. However, for purposes of securing reliable assignments of spin and multipolarity for this level and for transitions proceeding to or from it, the angular correlations described in parts A, B, and C of this section remain the simplest and most easily interpreted.

The results of the present angular-correlation measurements and those obtained from the other studies reported in this paper are summarized in the decay scheme proposed in Fig. 13, which presents the spins, parities, and multipolarities determined from them (with no ample justification for the admission of mixed multipole assignments).

VII. DISCUSSION

A comparison (Figs. 13 and 14) of the proposed decay scheme of Sn^{116} populated by the decay of 1-h Sb^{116} with those of Sn^{118} and Sn^{120} fed by the corresponding Sb decays,[6,7] shows the latter two to be practically the same, and provides a meaningful basis for identification and examination of those aspects of the levels and transitions in Sn^{116} that exhibit similarities or differences from those of the heavier isotopes. The obvious similarities concern the 2^+, 5^-, and 7^- levels, which occur at similar excitation energies in each isotope, and the restricted and exclusive β decay to the 7^- levels. Equally striking is the presence of the 3^- and 6^+ levels and the failure to populate the 4^+ state in Sn^{116}.

An attempt is made to delineate possible choices for two-neutron configurations of given levels and to make some particular judgement as to the constitution of various other states, without recourse to any detailed

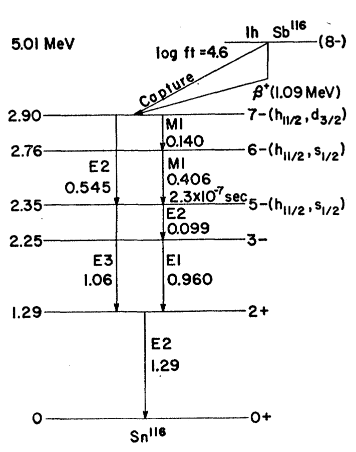

FIG. 13. Proposed decay scheme of Sn^{116} populated from the decay of 1-h Sb^{116}. All energies are in MeV.

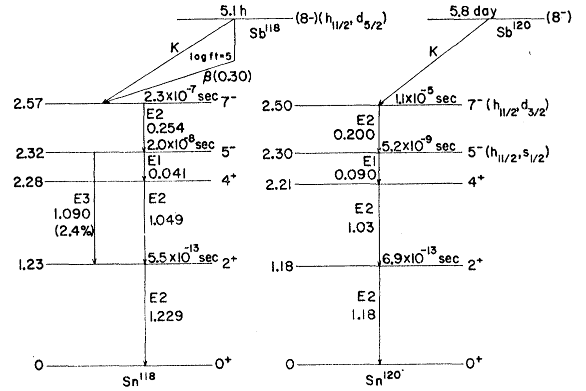

FIG. 14. Proposed decay scheme of Sn^{118} and Sn^{120} populated from the decay of 5.1-h Sb^{118} and 5.8-day Sb^{120} (Ref. 6). All energies are in MeV.

theoretical calculations. These assignments are first made for what is generally expected in the way of suitable neutron orbitals and the well-known collective features in this region. This is followed by an experimental systematic summary with which the theoretical calculations may be best compared. In other words, the attempt is made to stay as free as possible from detailed theoretical predictions in order to present an unprejudiced comparison of experiment with the detailed theoretical calculations.

The first excited 2^+ levels in each of the three isotopes have been found to have transition probabilities which are enhanced over single-particle estimates[26] by a factor of approximately ten.[18] Even before Kisslinger and Sorensen[1] used the approaches of Belyaev[27] and others[28] to make the initial quantitative comparison between experiment and theory, these 2^+ levels were interpreted as collective vibrations which fitted the pattern detailed by Goldhaber and Weneser[29] and by Davydov and Fillipov.[30] The 4^+ levels in Sn^{118} and Sn^{120} could be interpreted either as members of a two-phonon triplet (expected at an energy approximately twice that of the one-phonon 2^+ level) or as due to an even-neutron configuration [$(h_{11/2})^2$, $(s_{1/2})^2$, $(d_{3/2})^2$, etc., or a mixture of these]. From the general aspects of most theoretical approaches, these configurations would be expected at about the energy at which these levels are observed.

Proceeding higher in energy, any two-neutron configuration would, of necessity, include the $h_{11/2}$ orbital to produce the negative parity assigned to these states.

[26] All single-particle estimates of transition probabilities were taken from 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.

[27] S. T. Belyaev, Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd. **31**, No. 11 (1959).

[28] See Ref. 1 for a complete listing of other references.

[29] G. Scharff-Goldhaber and J. Weneser, Phys. Rev. **98**, 212 (1955).

[30] A. S. Davydov and G. F. Fillipov, Nucl. Phys. 8, 237 (1958); A. S. Davydov and V. S. Rostovsky, *ibid.* **12**, 58 (1959).

Consideration of the 7^- levels leads one to the conclusion that the $(h_{11/2}, d_{3/2})_{7^-}$ neutron configuration would most probably characterize this state. This assignment comes from the expectation, at this energy, that the reasonable orbital choices for the second neutron would come from the $s_{1/2}$ or $d_{3/2}$ shell, of which only the $d_{3/2}$ could couple to the $h_{11/2}$ to produce a 7^- level. In addition, with this choice, the rules of Glaubman and Talmi[31] for the coupling of two identical particles dictate that, of the various angular momentum states arising from this configuration, the 7^- level should lie lowest.

The 5^- state lies lower than the 7^- level. This 5^- level could be expected to be predominantly $(h_{11/2}, s_{1/2})_{5^-}$, with some admixture of $(h_{11/2}, d_{3/2})_{5^-}$ possible. For the former configuration, the rules of Glaubman and Talmi predict that the 5^- level of this configuration would lie lowest.

On the same basis, the 6^- level (Sn^{116}) might be dominantly the $(h_{11/2}, s_{1/2})_{6^-}$ configuration with some possible admixture of $(h_{11/2}, d_{3/2})_{6^-}$. Again, since the 6^- level lies above the 5^- state, assigning the $(h_{11/2}, s_{1/2})$ configuration to both satisfies the Glaubman and Talmi rules.

The single 3^- level found in Sn^{116} in the present work is at the same energy at which Cohen and Price[32] have observed a 3^- state, which has been interpreted as collective in nature. This could, in large part, be made up of a collective octopole excitation. [If one were to assign some two-neutron configuration which could couple to this spin and parity from neutron orbitals expected in this region, then the $h_{11/2}$ (a necessity to secure negative parity) would have to combine with a $g_{7/2}$ or a $d_{5/2}$ neutron to allow for a spin-3 coupling, although these configurations might be expected at a somewhat higher energy.]

Since the 1-h Sb^{116}, the 5.1-h Sb^{118}, and the 5.8-day Sb^{120} parent levels decay by allowed β transitions only to the 7^- levels in the corresponding Sn daughters, the spins and parities of these states would be either 6^-, 7^-, or 8^-. The odd proton, outside the closed shell at $Z=50$, would be expected to be in the $d_{5/2}$ orbital. The negative parity of these levels again requires an $h_{11/2}$ neutron. By the coupling rules of Brennan and Bernstein[33] and de-Shalit and Walecka,[34] the highest spin (8^-) of this $(h_{11/2}, d_{5/2})$ configuration should lie lowest. The $(h_{11/2}, d_{5/2})_{8^-}$ assignment is completely consistent with the allowed β decay going exclusively to the $(h_{11/2}, d_{3/2})_{7^-}$ level since this is a transition of the $d_{5/2}$ proton to the $d_{3/2}$ neutron orbital.

Figure 15 summarizes the experimental energy systematics for levels in Sn^{116}, Sn^{118}, and Sn^{120} as populated from the decays of 1-h Sb^{116}, 5.1-h Sb^{118}, and 5.8-day

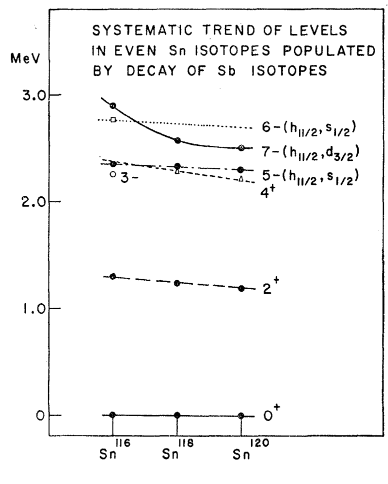

FIG. 15. Systematics of the trend of experimentally determined energy levels in Sn^{116}, Sn^{118}, and Sn^{120}, as populated from the decay of the corresponding long-lived Sb isotopes. The experimental points are taken from the decay schemes of Figs. 13 and 14.

Sb^{120}. The lines drawn through the points representing the experimentally observed excitation energies of states of the same spin and parity merely trace the experimental systematics by a smooth curve. The neutron configurations which the above arguments suggest as the reasonable or dominant ones for the 5^-, 6^-, and 7^- levels appear as labels.

The dotted line going through the single 6^- level in Sn^{116} is drawn so as to explain the failure to observe this state in Sn^{118} and Sn^{120}. The simplest explanation for the absence of this state in the decay schemes of the heavier isotopes is that the 6^- level lies above the 7^- level, since β decay to this 6^- level is forbidden on the reasonable assumption that the Sb level is $(h_{11/2}, d_{5/2})_{8^-}$. The slope of the line was taken in a semiarbitrary manner to be that of the 5^- level which has been attributed to the same configuration.

The line joining the two 4^+ levels in Sn^{118} and Sn^{120} and extrapolated to lie slightly higher than the 5^- level in Sn^{116} was drawn to be consistent with the lack of population from the 5^- level and to agree with the observation of the first 4^+ level at this energy in Sn^{116} populated by the decay of 54-min In^{116}.[9,10,12] No point has been plotted here, since the experimental points have been restricted to the experimental work on the Sb decay to avoid confusion and to keep the discussion and theoretical comparison within bounds.

The sole 3^- level (Sn^{116}) is shown for completeness. To be consistent with its absence in the Sb^{118} and Sb^{120} decays, it must lie somewhere above the 5^- level. Indeed, Cohen and Price[32] found that their identified 3^- levels in Sn^{116}, Sn^{118}, and Sn^{120} showed a sharp energy increase with mass number, a behavior which is consistent with this interpretation.

In comparing these experimental data with theory, one must bear in mind some specific criteria which provide a base for what can be expected in such a detailed comparison. Kerman, Lawson, and MacFarlane,[35] who

[31] M. J. Glaubman, Phys. Rev. **90**, 1000 (1953); I. Talmi, *ibid.* **90**, 1000 (1953).
[32] B. L. Cohen and R. E. Price, Phys. Rev. **123**, 283 (1961).
[33] M. H. Brennan and A. M. Bernstein, Phys. Rev. **120**, 927 (1960).
[34] A. de-Shalit and J. D. Walecka, Phys. Rev. **120**, 1790 (1960).
[35] A. K. Kerman, R. D. Lawson, and M. H. Macfarlane, Phys. Rev. **124**, 162 (1961).

performed an exact diagonalization of the pairing Hamiltonian, found that the ground-state energies obtained in the approximate calculations of Kisslinger and Sorensen[1] agreed with their results within 500 keV, and that the energies of excited states (pure two-quasiparticle levels) agreed to within about 200 keV, relative to the ground state. Thus, 200 keV is an absolute limit on the significance to which comparisons between Kisslinger and Sorensen and experimental energies can be made; since the real nuclear interaction differs in many respects from a pure pairing force, the actual degree of accuracy is probably even poorer.

Arvieu,[2] Arvieu and Vénéroni,[36] and Arvieu *et al.*[3] have used an approach in which the pairing force and long-range quadrupole force are combined into a single finite-range shell-model interaction. In addition, their results for a level with given spin and parity predict not only the expected energy but also the particular strengths of the various two-quasiparticle admixtures making up a given level. Therefore, calculations of the Arvieu type provide parameters which permit a detailed comparison of each experimentally observed level. However, an exact energy comparison is not warranted for the reasons stated above.

However, what is expected to be a more reliable aspect of these calculations is the general energy trend of particular levels as a function of mass number for a given set of isotopes. This property not only helped to stimulate the experimental study of the last member of the isotopic trio (Sn^{116}) but suggested the approach used in the experimental systematic summary presented in Fig. 15. Another feature to be taken up below is a comparison of the lifetimes of excited states which the detailed two-quasiparticle parameter predictions of the theory are expected to handle capably.

Let us turn now to the work of Arvieu. The predictions of Arvieu for the energies of particular levels are given in Fig. 16 for the "best" choice of parametres entering the calculation. It is obvious that a slight renormalization of some of the two-quasiparticle energies would be sufficient to bring the 4^+, 5^-, 6^-, and 7^- levels into excellent agreement with the experimental data presented in Fig. 15. This agreement would include the crossing of the 4^+ and 5^- levels at Sn^{116}. In addition, a small energy readjustment would position the 7^- level between the 5^- and 6^- states in Sn^{118} and Sn^{120} and cause the predicted crossing of the 7^- and 6^- levels to move in between Sn^{116} and Sn^{118}. An energy readjustment of some of these levels is not unwarranted nor unreasonable, since the predicted two-quasiparticle energies are expected to be inaccurate by more than the amount necessary to bring these predicted levels into accord with experimental findings. However, the theoretically predicted energy *trend* of each particular level with isotopic mass follows the experimental trend rather well. The comparison between experiment and theory

[36] R. Arvieu and M. Veneroni, Compt. Rend. **252**, 670 (1961).

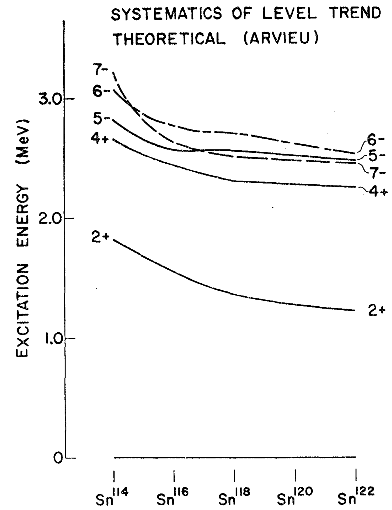

FIG. 16. Systematics of the theoretical trend of the energy levels, as predicted by Arvieu's "best" parameters for the levels shown in Fig. 15.

presented here may serve as the most reliable estimate of the accuracy of the pairing-force calculations and may point out the particular aspects of the calculations which require adjustment.

Again, it is worth noting that the 3^- levels are predicted much too high, but one expects this "failure" because of the collective nature of these states.

In probing somewhat deeper into the two-quasiparticle constitution of these states, as detailed by Arvieu, let us start the discussion at the top of the intrinsic energy gap. Arvieu does not treat the 4^+ state in terms of the two-phonon approach; but if this level were interpreted as purely a two-quasiparticle state,[37] his calculations predict it to be $>96\%$ $(h_{11/2})^2$. The 5^- levels are not pure $(h_{11/2}, s_{1/2})$ but are predicted in these calculations to be an admixture of the $(h_{11/2}, s_{1/2})$ and $(h_{11/2}, d_{3/2})$ configurations—as had been allowed for, to some extent, in the initial phases of this discussion. The various strengths of these configurations are predicted to vary as a funtion of mass, being $\sim 23\%(h_{11/2}, d_{3/2})_{5^-}$ in Sn^{116}, $\sim 65\%$ in Sn^{118}, and $\sim 90\%$ in Sn^{120}, with the remainder attributed to $(h_{11/2}, s_{1/2})_{5^-}$.

The 6^- level is not treated in such detail by Arvieu, but the 7^- state is described in terms of almost pure $(h_{11/2}, d_{3/2})$ in agreement with the configurational assignment made earlier on more general grounds.

To within the scrutiny allowed by the accuracy limitations inherent in the theoretical calculations, it appears that the calculations of Arvieu describe the experimental features, so far discussed, in a highly satisfactory manner.

An additional interesting facet of the comparison of

[37] It is almost certain that the physical 4^+ states are mixtures of two-quasiparticle and two-phonon states. As pointed out by S. Cohen, R. D. Lawson, M. H. Macfarlane, and M. Soga, Phys. Letters **9**, 243 (1964), at energies about twice that of the 2^+ level, seniority-4 (four-quasiparticle) admixtures could be expected to contribute. The neglect of these admixtures may be the biggest shortcoming of the Arvieu-Veneroni approximation.

TABLE IV. Transition probabilities in Sn^{116}, Sn^{118}, and Sn^{120}.

Transition and multipole order	Sn^{116} Transition energy (MeV)	Sn^{116} $T_{1/2}$ of initial level (sec)	Sn^{116} $T_\gamma/T_{\gamma(\text{S.P.})}$[a] of gamma ray	Sn^{118} Transition energy (MeV)	Sn^{118} $T_{1/2}$ (sec)	Sn^{118} $T_\gamma/T_{\gamma(\text{S.P.})}$	Sn^{120} Transition energy (MeV)	Sn^{120} $T_{1/2}$ (sec)	Sn^{120} $T_\gamma/T_{\gamma(\text{S.P.})}$
$E2$[b] $2^+ \longrightarrow 0^+$	1.29	$5\ \times 10^{-13}$	0.11	1.229	5.6×10^{-13}	0.097	1.175	6.9×10^{-13}	0.097
$E1$ $5^- \longrightarrow 4^+$	...	...	...	0.041	2.0×10^{-8}	1.5×10^{4}	0.090	5.2×10^{-9}	1.6×10^{4}
$E3$ $5^- \longrightarrow 2^+$	1.06	2.3×10^{-7}	0.5	1.090	8.7×10^{-7}	1.1	1.12 (not observed)	...	>0.3[c]
$E2$ $5^- \longrightarrow 3^-$	0.099	2.3×10^{-7}	0.49	...	...	...	...	...	...
$E2$ $7^- \longrightarrow 5^-$	0.545	$<2\ \times 10^{-9}$	<10[d]	0.254	2.3×10^{-7}	16	0.200	1.1×10^{-5}	250

[a] $T_{\gamma(\text{S.P.})}$ calculated according to Weisskopf estimate (Ref. 26). It includes the internal-conversion correction.
[b] From Coulomb excitation (Ref. 18).
[c] A search (Ref. 6) for the internal-conversion line of this transition resulted in this lower limit.
[d] This upper limit is derived from the γ-ray branching ratio (Table I) and the estimated upper limit for the lifetime of the 2.90-MeV state.

theory and experiment is provided by the experimental results of the lifetime measurements.

The $7^- \rightarrow 6^-$ $M1$ transition in competition with the 0.545-MeV $E2$ transition from the 7^- to the 5^- level in Sn^{116} makes the lifetime of the 7^- level difficult to measure experimentally, so that no experimental determination is available for comparison. However, the lifetimes of the two $E2$ transitions between the 7^- and 5^- levels in Sn^{118} and Sn^{120} were previously measured and discussed in terms of the pairing-force calculations.[6,7] The significant point concerning these transitions is their retardation with respect to single-particle estimates (Table IV).[26] According to the simple shell model, these would be expected to proceed with a single-particle speed on the basis of the two-quasiparticle configurations assigned to these states. The pairing calculations[1] do predict retardations for these transitions, although of incorrect magnitude. However, as discussed in the earlier paper,[6] a small change in some of the parameters adopted for the Sn isotopes by Kisslinger and Sorensen could easily bring these predicted retardation factors into line with experiment without materially affecting other characteristics predicted by their calculations. Some change in such parameters may be warranted by the fact that, at the time of their calculations, the 5^- level in Sn^{120} was incorrectly designated experimentally as a 6^+ state and it was partially from this 7^- to "6^+" energy difference that the particular value of the strength parameter used by Kisslinger and Sorensen was chosen. On the other hand, if one takes the $(h_{11/2}, d_{3/2})$ and $(h_{11/2}, s_{1/2})$ admixture strengths that Arvieu attributes to the 5^- states in Sn^{118} and Sn^{120} and recalculates the reduction factors of these $E2$ transitions, these factors come closer to the experimental findings. Although no information is available on the corresponding $E2$ transition in Sn^{116}, the prediction of retardation based on the pairing effects for Sn^{118} and Sn^{120} indicates the successful attributes of the pairing-force approach.

The 0.099-MeV $E2$ transition between the 5^- and 3^- levels in Sn^{116} proceeds with very close to single-particle speed (Table IV). On the basis of collective nature of the 3^- state, this $E2$ transition (if not completely forbidden) would be expected to be substantially retarded. To allow it to proceed at all, and to the extent it does, one may either assume some particular admixture of two-quasiparticle configurations in the 3^- state, or one can attribute some contribution of collective excitation to the constitution of the 5^- level. These possibilities could help to explain the single-particle speed of the $E3(5^- \rightarrow 2^+)$ transitions in Sn^{116} and Sn^{118}, which otherwise would be forbidden or retarded.

The $E1$ transition between the 5^- and 4^+ states in Sn^{118} and Sn^{120} are absolutely forbidden, in agreement with the large retardations measured. Again some mixture of other configurations or collective dipole excitation could be invoked in the 5^- levels to permit the $E1$ transitions to proceed. As was pointed out earlier,[6] the practically identical retardation factors found for these transitions may pose the question as to whether this is only accidental or has some subtle significance.

The enhancement of the $E2$ $2^+ \rightarrow 0^+$ transitions in all the even-A Sn isotopes is explained simply and predicted quite well by Kisslinger and Sorensen, Arvieu, and others.

An additional point which seems to have escaped discussion previously, and to which some significance must be assigned, is that of the measured values of the gyromagnetic ratios of the 5^- levels in Sn^{118} and Sn^{120}. Two sets of measurements[38] of the g values of each of these levels have been reported in the literature; these are in good agreement with each other, and in remarkable agreement with the value obtained for this quantity from a theoretical calculation using the Schmidt values

[38] E. Bodenstedt, H. J. Korner, E. Gerdau, J. Radeloff, K. Auerbach, L. Mayer, and A. Roggenbuck, Z. Physik **168**, 103 (1962); M. Deutsch, A. Buyrn, and L. Grodzins, *Perturbed Angular Correlations*, edited by E. Karlsson, E. Matthias, and K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1964), p. 186.

for the two-neutron configuration $(h_{11/2}, s_{1/2})_{5^-}$. The experimental values for Sn^{118} and Sn^{120} are practically the same (~ -0.06), and the Schmidt value is -0.058. The g factor (-0.32) for the $(h_{11/2}, d_{3/2})_{5^-}$ configuration is in much poorer agreement with the experimental values. Perhaps no particular significance can be attributed to the experimental agreement with the Schmidt values; such excellent agreement is usually not obtained or expected. What is of significance is that the latest pairing-force calculations of Arvieu[2] predict that this 5^- level is a mixture of two-quasiparticle configurations made up of the $(h_{11/2}, s_{1/2})$ and $(h_{11/2}, d_{3/2})$ configurations, the former constituting $\sim 35\%$ of the 5^- level in Sn^{118} and 10% in Sn^{120} and the rest being contributed by the second configuration. On the basis of the constitution of these states given by Arvieu, the g factors for the 5^- levels in Sn^{118} and Sn^{120} could be expected to differ. This is counter to experimental findings and may be an important point to consider when single-particle energies are estimated and applied in any pairing-model calculation of the Sn isotopes.

The calculated parentage[2] of the 5^- level in Sn^{116} is $\sim 77\%$ $(h_{11/2}, s_{1/2})$ and $\sim 23\%$ $(h_{11/2}, d_{3/2})$. In view of the above considerations, an experimental determination of the g value for this level (now in progress) could be expected to be significantly different from those obtained for this level in the heavier isotopes and would be a serious test of certain facets of the Arvieu calculations.

One additional point which might be considered here is that on the basis of single-particle estimates[26] (however valid they may be in this case) the ratios of the γ-ray transition probability of the 0.545-MeV $E2$ to that of the 0.406-MeV $M1$ is $\sim 10^{-3}$, while the same ratio for the 0.545-MeV gamma ray to the 0.140-$M1$ gamma ray is $\sim 3\times 10^{-2}$. Both ratios are in disagreement with the observed branching ratio of the 2.90-MeV state, regardless of which $M1$ transition proceeds from it. However, on the basis of the proposed configuration assignments for the 7^- and 6^- levels in Sn^{116}, the $M1$ transition between these states would be expected to be l forbidden. If a retardation factor of 100, normal for l-forbidden $M1$ transitions,[26] is taken and applied to both transitions, then the 0.140-MeV $M1$ gamma-ray transition probability would be ~ 0.4 of that of the 0.545-MeV $E2$, in satisfactory agreement with experiment, while the strength of the 0.406-MeV gamma ray would still be ~ 10 times that of the 0.545-MeV $E2$ and thus ~ 20 times that observed. Since an enhancement of the $E2$ transition by a factor $\gtrsim 20$ seems unreasonable here (especially since the corresponding $E2$ transitions in Sn^{118} and Sn^{120} were found to be severely retarded), or a retardation of 2000 for the 0.406-MeV $M1$ (which would be needed to bring the intensities in agreement with experiment) seems equally unlikely, the most reasonable choice for the time ordering of these $M1$ transitions (based on this argument in the absence of other evidence) seems to be that proposed in the decay scheme of Fig. 13.

This work and those investigations of the decay of 54-min In^{116} show[9,10,12] that, with the exception of the 1.29-MeV first excited 2^+ state, all levels and transitions seen from the decay of 1-h Sb^{116} and 54-min In^{116} are separate and unique and that these differences can be wholly accounted for by the great difference in spin of the parent levels (8^- and 5^+, respectively).[12]

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