Nuclear Levels of Even Sn Isotopes Populated in the Decay of In Isomers*

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The decay of the following neutron-rich indium isomers produced by 14–15-MeV neutron bombardments of isotopically enriched tin samples have been studied with beta and gamma scintillation techniques: 5.0±0.5-sec and 4.35±0.05-min In^{118}, 3.2±0.4-sec and 44.3±1.5-sec In^{120}, and 7.5±0.8 sec-In^{122}. The disintegration of the 3.5-min Sb^{118} isomer has been investigated by using a highly mass-separated Te^{118} source. Numerous levels in the corresponding tin isotopes were found to be populated, and the level schemes are compared with the theoretical calculations of Kisslinger and Sorensen and of Arvieu *et al.* The systematics of odd-odd In isomers is discussed in light of the spectroscopic data and the nuclear-shell model. The isomeric cross-section ratios of the (n,p) reaction forming the In^{116}, In^{118}, and In^{120} isomers were measured and are briefly discussed.

I. INTRODUCTION

DURING the past few years, the level structure of even Sn isotopes has been the subject of many theoretical and experimental investigations. Since the tin nuclei with the closed proton shell $Z=50$ are very nearly spherical, their structure can be expected to exhibit features characteristic of the "classical" collective vibrational model.[1–3] In particular, in the even Sn isotopes, one would expect to find the 2^+ and 3^- states corresponding to one-quadrupole- and one-octupole-phonon excitations, respectively, and the almost degenerate 0^+, 2^+, 4^+ triplet due to two quadrupole phonons. So far, the existence of the one-phonon (2^+ and 3^-) states in all stable even tin isotopes has been established, but the situation with the two-phonon excitations has remained rather unclear.

On the other hand, it has been possible to perform essentially quantitative calculations of the levels of the Sn isotopes, based on the application of the theory of superconductivity to nuclear structure as suggested by Bohr, Mottelson, and Pines.[4] Using the pairing model developed by Belyaev,[5] Kisslinger and Sorensen[6] have performed calculations on single closed-shell nuclei including the tin isotopes. The residual interaction in their shell-model-type calculations consists of a pairing force and a long-range quadrupole force, which are treated separately. A perhaps more realistic approach to the Sn level calculation, which also is based on the superconductivity model, is that of Ariveu *et al.*[7] According to the ideas worked out by many authors,[8] they apply the treatment of the pairing correlations to the tin isotopes, assuming a general nuclear force and treating the interaction between quasiparticles by the method of linearized equations of motion. The results yielded by this method are qualitatively similar to those obtained by KS. Yoshida[9] has used the pairing force plus quadrupole-quadrupole and octupole-octupole interactions in a study of vibrational states of spherical nuclei, including a detailed calculation of the level structure of Sn^{118}. From the point of view of a systematic comparison between the experimental level schemes and the predictions of the pairing model, the calculations of KS and of Arvieu *et al.* are the most important ones. Other models do not seem to apply equally well to the structure of the even Sn nuclei.

A large number of experimental data on the levels of the even tin isotopes has been gathered in recent years by different means, such as Coulomb excitation,[10] nuclear reaction,[11–13] and nuclear disintegration studies.[14–25] The decay studies which have furnished most of

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the data have been primarily concerned with the decay of the neutron-deficient antimony isomers.[14–18] Most of the work done on the neutron-rich indium isomers[19–25] has been only preliminary (excepting for the In^{116} isomers[19,20]); not even decay schemes have been proposed for most of them. On the other hand, since large amounts of disintegration energy is released in the decay of the heaviest In isomers, a number of new levels in the Sn isotopes could be expected to be populated in these decays.

The present work was initiated in order to fill this gap and to study the levels of the tin isotopes populated in the decay of the $In^{118,120,122}$ isomers. The short half-lives and small cross sections for formation of these isomers with fast neutron bombardments introduce great difficulties in their spectroscopic study. For example, angular correlation and internal conversion studies cannot be performed with the present techniques which, of course, limits the obtainable information. Therefore, our results principally consist of determining the positions of a number of new levels in Sn^{118}, Sn^{120}, and Sn^{122}; striking similarities in the decay of some of the In isomers studied and in the level structure of various Sn isotopes suggest in many cases fairly plausible spin assignments by analogy.

As a mass-separated Te^{118} source was also available, we could obtain some further information on the 3.5-min Sb^{118} decay and the level structure of Sn^{118}. The study of the In^{122} decay reported here is continuation to our earlier work on the isotope.[24]

We also discuss the systematic features of the odd-odd In isomers in light of the nucleon coupling rules presented by Brennan and Bernstein.[26]

II. EXPERIMENTAL PROCEDURES

The In activities were produced by irradiating metallic enriched Sn^{118}(96.6%), Sn^{120}(98.4%), and Sn^{122}(90.8%) samples[27] weighing several hundred milligrams with DT neutrons from the University of Arkansas 400-kV Cockcroft-Walton accelerator. The estimated mean neutron energy was 14.7 MeV and the useful flux typically about 10^{10} n/cm^{2}sec. A highly mass-separated 6.0-day Te^{118} source was available as a by-product from another work.[28] For fast transportation of some short-lived sources, a pneumatic system described earlier[24] was employed.

The gamma spectrometry was carried out with 3×3-in. NaI(Tl) crystals, which were used to obtain singles, ordinary coincidence, and sum-peak coincidence spectra.[29–31] (For further details see, for example, Ref. 28). In recording high-energy singles gamma spectra, 0.25- to 2-in.-thick lead absorbers were systematically used to reduce the summing of lower energy coincident gammas. The same method was also employed in some coincidence measurements, and the attenuation of the gammas in the Pb absorbers was corrected for with the aid of experimentally determined curves. Also, the effect of the absorbers on the gamma line profiles was carefully observed and taken into account.

For beta spectrometry, we employed a $1\frac{1}{2}$-in.-diam by 13/16-in.-high cylindrical plastic beta crystal. Since thick sources (at least 100 mg/cm^2) had to be used and the effects of the gammas associated with the decays studied could not be completely corrected for, the accuracy of the beta results is not very good. In particular, the summing of the beta and the Compton-electron energies was difficult to take into account, as the low intensity of the sources required a large-solid-angle geometry. The gamma and beta crystals were also used in coincidence to obtain (gamma) (beta) and (beta)(gamma) coincidence spectra. The summing effect mentioned caused the former spectra to be only qualitative, but it was possible in some cases to establish a beta component which is in coincidence with a selected gamma ray.

Possible contaminant activities in the sources were carefully looked for on the basis of the isotopic and chemical analyses of the samples irradiated, as well as with the aid of suitable activity lists.[32,33] None of the many weak gammas tentatively assigned to the activities studied are likely to be due to any contaminants. Since a very large total number of runs were needed to complete the measurements on each mass number, the 14-day Sn^{117m} activity (0.16-MeV gamma) was strongly accumulated in the course of the work. Whenever possible, the decay of the various spectra was carefully followed. The stability of the electronics was frequently

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TABLE I. Gamma-ray energies E_γ and relative intensities I_γ observed in the decay of the 4.35-min In^{118} and the 44.3-sec In^{120}.

4.35-min In^{118} E_γ(keV)	I_γ	44.3-sec In^{120} E_γ(keV)	I_γ
≈210−220	3.0±1.5	90±4	12±4
445±10	7±2	198±5	9±2
640±20 [a]	≈10	≈260[a]	≈1.4
685±10	42±8	340±15[a]	1.2±0.7
805±15	7±2	410±15[a]	1.6±1.0
1052±10	83±6	610±15[a]	2.7±1.0
1228±8	100	710±15	12±5
1250±25	6±2	862±10	34±5
1490±30	1.4±0.4	945±20	12±4
1540±30	1.0±0.4	1024±10	61±7
≈1730[a]	≈0.4	1173±8	100
2040±20	3.1±0.6	1190±30	7±3
		1285±15	14±4
		1470±25	6±2
		1870±40	7±4
		2010±30	6±3
		≈2100[a]	(?)
		2220±50	3.0±1.5
		2400±50[a]	1.3±0.6
		2630±40	2±1

[a] Assignment probable but uncertain.

checked during the lengthy experiments, and was found good.

III. MEASUREMENTS, RESULTS, AND DECAY SCHEMES

1. In [118] Isomers and the 3.5-Min Sb^{118}

The previous assignment of a 5.1-sec activity to In^{118} based on studies of fission products[22] was confirmed by observing a 5.0±0.5-sec activity in irradiations of enriched Sn^{118}. The present half-life was determined by following the gross-beta decay with the beta crystal and by analyzing the decay curve with a computer. In good agreement with the work of Gleit and Coryell,[22] we found that the highest end-point energy of the 5-sec. beta spectrum is 4.2±0.3 MeV. The lower energy beta branch to the first excited level of Sn^{118} at 1.23 MeV[34] was estimated to be 10–20%, by comparing the gamma and beta spectra of the two In^{118} isomers. The allowed beta decays to the 0^+ and 2^+ states in Sn^{118} clearly establish the spin and parity of the short-lived In^{118} isomer as 1^+ (see Fig. 2).

The half-life of the high-spin In^{118} isomer was measured as 4.35±0.05 min by following the decay through almost 10 half-lives with the sum-peak spectrometer (with an almost 4π geometry) biased at 0.6 MeV. The gamma energies and relative intensities which are found to belong to this decay in the various singles and coincidence spectra are listed in Table I.

A typical singles spectrum of the medium and low-energy region ($E_\gamma<1.4$ MeV) is shown in Fig. 1(a). As the decay of this spectrum was followed, a number of longer lived contaminants were identified, such as

[34] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences—National Research Council, Washington 25, D. C.), NCR 60-3-140.

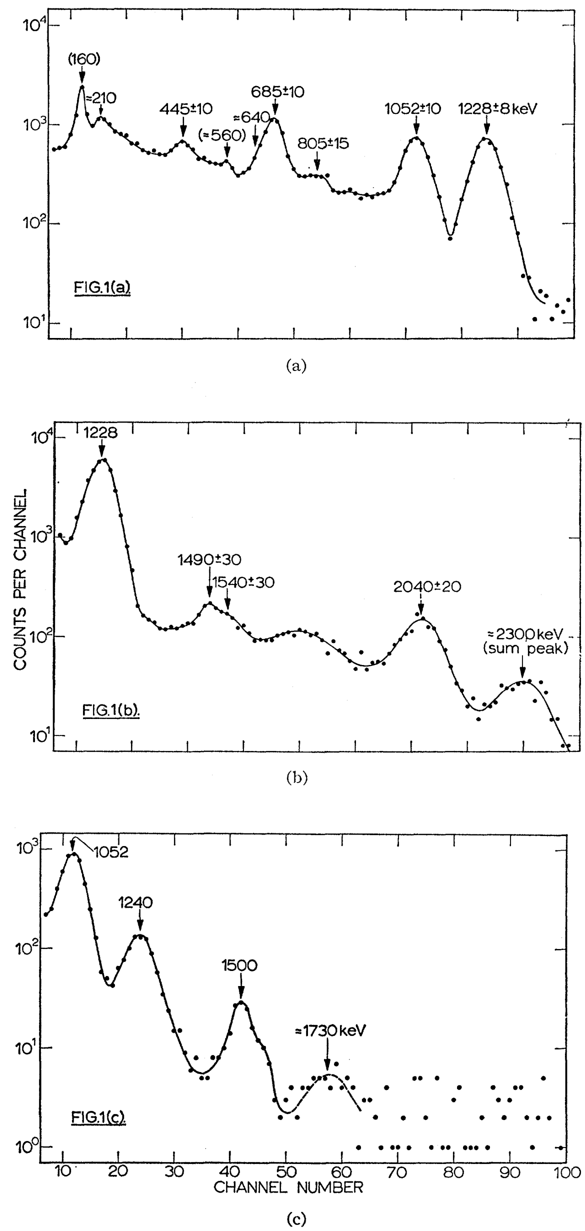

FIG. 1. Some typical gamma spectra of the high-spin isomer 4.35-min In^{118}: (a) Singles spectrum of the region $E_\gamma<1.4$ MeV, taken at a distance of 10 cm from a 3×3-in. NaI(Tl) crystal, with a 1-cm-thick Plexiglass beta absorber. The peaks at 160 and 560 keV are due to long-lived contaminants but the 210–220-keV peak probably to In^{118}. There is some unresolved complexity below about 0.6 MeV which may in part belong to the 4.35-min In^{118}. (b) Singles spectrum of the region $E_\gamma>1.1$ MeV obtained by using a 1.0-in. lead absorber to reduce the summing effects, with a source-to-detector distance of 3 cm. The complex peak at 1.7–1.8 MeV is due to Al^{28}, summing, and possibly to a weak gamma at 1.73 MeV [cf. Fig. 1(c)]. (c) High-energy coincidence spectrum, gated with a narrow (90 keV wide) window set on the 1.23-MeV peak. The lead absorbers in front of the spectrum and gating crystals were 1.0 and 0.25 in. thick, respectively. For this spectrum, 13 irradiations of 5-min duration with 40-min cooling-off periods were needed. The intensity of the 1.73-MeV peak is approximately three times as large as that estimated for the sum peak of the 0.68- and 1.05-MeV gammas; therefore, the observed peak can be considered as evidence for a 1.73-MeV gamma.

Sn^{117m}, Cu^{62}, and In^{117} (cf. Ref. 34). There also seems to be an unresolved group of lines below 0.6 MeV, which may in part be due to In^{118}. The high-energy part of the singles spectrum was studied by using suitable lead absorbers. In Fig. 1(b), a spectrum taken with a 1.0-in. absorber is illustrated, showing two gammas around 1.5 MeV and one at 2.040 MeV.

In the singles gamma spectrum as well as in spectra coincident with the 1.23-MeV gamma and with the beta spectrum, a reproducible asymmetry of the 0.68-MeV peak was observed. This can be attributed to a gamma at about 620–660 keV having an intensity of 10–30% of that of the 685-keV gamma. Since the "640-keV gamma" cannot belong to any contaminant expected on the basis of the isotopic and chemical analyses of the enriched Sn^{118} sample, it is probable that this gamma is associated with the 4.35-min In^{118} decay.

The coincidence relationships of the gammas were investigated by means of ordinary and sum-peak coincidence spectrometry.[31] The low-energy spectrum in coincidence with the 1.2-MeV line showed that all the gammas with $E_\gamma \leqq 1.2$ MeV are coincident with the 1.23-MeV gamma, as expected. A clear peak at 1.24 MeV in this coincidence spectrum indicates that the 1.2-MeV gamma actually is double. This was confirmed by the coincidence spectrum of the region above 1 MeV gated with the same line, with a 1-in. lead absorber in front of the spectrum crystal [Fig. 1(c)]. From the energy of the 1.24-MeV peak in the latter spectrum, one obtains 1250 ± 20 keV for the other gamma. The relative intensity of this new gamma was determined from the area of the 1.2-MeV peak, noting that the coincidence efficiency for the (1.2 MeV)(1.2 MeV) coincidence in this spectrum is twice that for the other coincidences, and correcting for summing and Compton tails in the gate channel. Furthermore, this spectrum shows that the 2.04-MeV gamma is not in coincidence with the 1.23-MeV one and, therefore, leads directly to the ground state. The 1730-keV peak is very weak, but since its intensity is about three times that estimated in various ways for the sum peak of the 685- and 1052-keV gammas, it can be considered as evidence for a 1.73-MeV gamma. The 1.49- and 1.54-MeV gammas are apparently also present, the sum of their relative intensities being very close to the same quantity in the singles spectrum.

The high-efficiency sum-peak spectrometry carried out showed unambiguously that the three strongest gammas in the 4.35-min In^{118} decay, viz., the 685-, 1052-, and 1228-keV gammas, form a triple cascade. The intense triple sum peak observed at 3.0 MeV establishes a level at 2.96 MeV in Sn^{118} and, since this triple sum peak is the highest energy peak observed, the 2.96-MeV level is probably the highest one populated in the In^{118} decay. The relative intensity data indicate that these gammas occur in the following order: The 685-keV gamma is the uppermost one and is followed by the 1052- and 1228-keV gammas. The peak observed at 2.5 MeV in the sum-peak spectra confirms the (1.23-MeV)(1.25-MeV) coincidence. Due to the low intensity of the other gammas, the coincidence relationships between them cannot be conclusively established. However, the sum-peak spectra show that there are no (445-keV)(685-keV) or (445-keV)(1052-keV) coincidences, which can be considered to support the otherwise weak evidence for the (445-keV)(805-keV) coincidence (see Fig. 2). All the sum-peak results seem to agree with the other coincidence data obtained. An example of the sum-peak method is illustrated in the more complicated case of the 44.3-sec In^{120} decay (see Fig. 4). That there definitely is no (445-keV)(1052-keV) coincidence was further confirmed by obtaining a coincidence spectrum gated by the (1052+1228)-keV sum line.

The singles beta spectrum of In^{118} exhibits two major components with end-point energies of 1.3 ± 0.1 and 2.0 ± 0.1 MeV, the intensity of the lower energy branch being almost twice that of the higher energy one. By taking the beta spectrum in coincidence with the 0.68-MeV gamma line and by subtracting the part of the spectrum due to the Compton tails of the higher energy gammas, it was found that the 1.3-MeV beta component is in coincidence with the 685-keV gamma. The beta and gamma intensity relations as well as the fact that no level above 3 MeV in Sn^{118} was found to be populated, prove that the 1.3-MeV beta branch must directly populate the 2.96-MeV level in Sn^{118}, which is the initial level of the 685-keV gamma. This result was further confirmed by gamma spectra recorded in coincidence with the beta crystal biased integrally at various energies.

On the basis of the above results, the rest of the decay scheme of the 4.35-min In^{118} can readily be constructed. The principal threefold cascade establishes in Sn^{118} levels at 1228, 2280, and 2965 keV. Since the 2.04-MeV gamma is not in coincidence with the 1.23-MeV one, there must also be a level near 2.04 MeV. The present coincidence measurements and the energy fit suggest that this level is depopulated by the 805-keV gamma, too. The fact that the 3-MeV sum peak is the highest energy one and the lack of any low-energy gammas of suitable intensity show that the 1250-keV transition apparently populates the 1228-keV level. The same is probably true of the 1490- and 1540-keV gammas also. Again, the energy fit and the weak coincidence evidence suggest that the 445-keV gamma connects the 2480- and 2040-keV states (see the decay scheme in Fig. 2). Furthermore, the 445-keV gamma is needed here in order to explain the population of the 2.04-MeV state. (This level is not observed to be directly fed by betas, which is consistent with the fact that the 2.04-MeV level must have a low spin.)

The probable 1.73-MeV gamma represents most naturally the 2965-keV $\rightarrow$ 1228-keV transition. Our re-

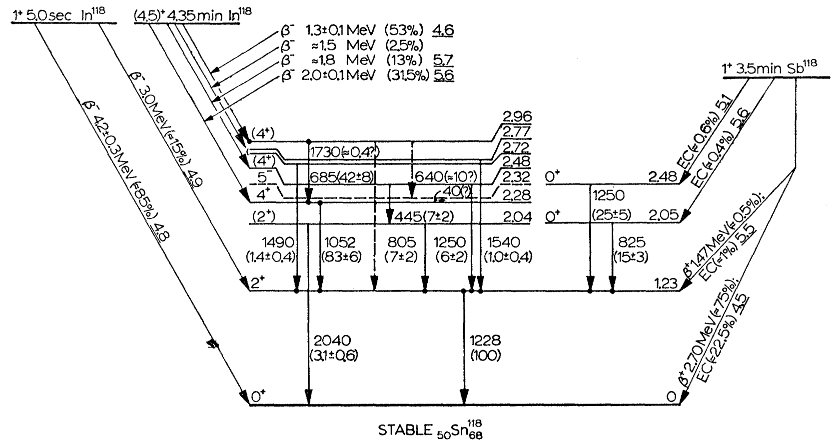

FIG. 2. Decay scheme proposed for the In^{118} isomers and the 3.5-min Sb^{118} isomer. The level energies are given in MeV, the gamma energies in keV, and the gamma-ray relative intensities as well as the beta-decay branchings are in parentheses. The log *ft* values of the beta-decay branches are underlined. The beta energies for which the limits of error are given have been measured in the present work. There is no definite information available concerning the relative positions of the In^{118} isomeric states.

sults do not definitely establish the position of the 640-keV gamma, but the intensity data indicate that it should be placed above the 2.28-MeV level. The energy fit would then suggest that this transition takes place between the 2.96-MeV level and the 5^- level established at 2.32 MeV.[17,18] The 41-keV gamma transition depopulating this level[17] was not observed in our work probably owing to the weakness of the transition, to absorption effects, and to internal conversion.

To summarize, our analysis establishes the 1.23-, 2.04-, 2.28-, 2.48-, and 2.96-MeV levels and suggests levels also at 2.72 and 2.77 MeV. The beta branching ratios and log *ft* values in the 4.35-min In^{118} decay have been computed from the gamma intensities and are indicated in the decay scheme in Fig. 2.

Since the 0^+ ground state and the 2^+ first excited state in Sn^{118} are not directly populated by betas from the 4.35-min In^{118}, it is likely that the initial In state is of high spin (probably $\geqq 4$) and that the higher levels populated in Sn^{118} have also high spins. Therefore, it is reasonable to identify the 2.28-MeV level with the 4^+ state observed at the same energy in the high-spin Sb^{118} decay.[17,18] Conversely, this assumption and the allowed beta decay to the 2.28-MeV level would then restrict the spin-parity of the longer-lived In^{118} isomer to 4^+ or 5^+.

The decay scheme of the 4.35-min In^{118} is strikingly similar to that of the 54-min In^{116} isomer.[19] The analogy would suggest that the initial In^{118} state is of 5^+ character and the high-lying levels in Sn^{118} are 4^+. As expected, the 2.96- and 2.48-MeV levels, which are populated by allowed beta branches from In^{118} and probably are connected to the 2^+ first excited state, would most likely have spin parity 4^+. Moreover, since the 2.96-MeV level seems to decay to the 5^- state at 2.32 MeV also, the 4^+ assignment would be even more favored for it. The 2.04-MeV level must be assigned a spin of 1 or 2, since this state decays by the 805- and 2040-keV transitions to the first excited state and to the ground state, respectively. The fact that this level probably is populated from the high-spin 2.48-MeV level would strongly favor spin 2. As a 2^- state at about 2 MeV would be highly improbable in view of the populating and depopulating transitions of this level, we prefer the assignment 2^+ for the 2.04-MeV state.

In summary, we suggest spins of 4^+, 4^+, and 2^+ for the 2.96-, 2.48-, and 2.04-MeV levels in Sn^{118}. However, if the In^{118} spin is 4^+, we cannot experimentally exclude the possibilities 3^+ and 1^+, respectively, for the 2.48- and 2.04-MeV levels.

On the basis of our data, most of the transitions occurring in Sn^{118} seem to be of $M1$, $E2$, or $M1+E2$ character. The only exception is probably the 640-keV gamma, which can be an $E1$ transition, if correctly placed. At least the intensity of the 640-keV gamma represents an upper limit for the $E1$ transition occurring between the 2.96- and 2.32-MeV levels. Since the 685-keV $M1$ or $E2$ transition is much more intense than the 640-keV gamma, it is clear that this $E1$ transition is strongly hindered.

In the mass-separated 6.0-day Te^{118} source (in equilibrium with the daughter, 3.5-min Sb^{118}), no trace of an expected 4.7-day Te^{119} contaminant could be observed (cf. Ref. 28). In the singles spectra, gammas were observed only at 1230 and 825±15 keV, in addition to the strong annihilation radiation. Any possible gammas above 1.2 MeV cannot have intensities of more than 2% of the 1.23-MeV gamma intensity. Neither could we substantiate the existence of a weak gamma at 0.4 MeV tentatively suggested by Fink *et al.*[15] The gamma spectrum in coincidence with the 1.2-MeV line showed gammas at 0.82 and 1.24 MeV, which indicates that the 1.2-MeV gamma also in this case is double, in accord with earlier work.[15] This was further confirmed with the aid of sum-peak spectra (taken at 10-cm source-detector distances by using an antiscattering shield), from which an energy value of 1250±25 keV was obtained for the other 1.2-MeV gamma. A comparison of the singles and coincidence spectra gave the following relative intensities for the 1.25-, 1.23-, and 0.83-MeV gammas: $I_{1.25}/I_{1.23}/I_{0.83}=(25\pm5)/100/(15\pm3)$.

With the aid of a technique described previously,[28] it was found that the ratio of the total number of positrons to the total number of 1.2-MeV quanta (i.e., 1.23- and 1.25-MeV quanta) was $I_{\beta^+}/(I_{1.23}+I_{1.25})=24\pm3$. The gamma spectrum taken in coincidence with the K x rays exhibited both the 0.8 and the 1.2-MeV gammas, but only the 1.2-MeV peak was seen in the spectrum coincident with the positrons obtained with a triple coincidence technique.[28]

On the basis of these results, it is clear that the ground state and the levels at 1.23, 2.05, and 2.48 MeV in Sn^{118} are populated in the 3.5-min Sb^{118} decay, as shown in the decay scheme in Fig. 2, in which the end-point energy of the ground-state positron branch is taken from the literature.[35] Using the relative intensities of the 1.25-, 1.23-, and 0.83-MeV gammas, the $I_{\beta^+}/(I_{1.23}+I_{1.25})$ ratio, and the theoretical total captures-to-positrons ratios[36,37] for the transitions to the ground state and to the 1.23-MeV state, one obtains the branching values indicated in Fig. 2. The log ft values of the transitions to the ground state, the 1.23-, 2.05-, and 2.48-MeV states are 4.5, 5.5, 5.6, and 5.1, respectively.

The fact that the levels at 2.04 and 2.48 MeV in Sn^{118} are populated in the decay of the 4.35-min In^{118} and the levels at 2.05 and 2.48 MeV are populated in the 3.5-min Sb^{118} decay would seem to suggest that the same pair of levels in Sn^{118} is involved in both decays. This is, however, not the case; instead, four separate levels are in question, as is clear for the following reasons: (1) Both levels populated in the high-spin In^{118} decay have a spin most likely $\geqq 2$. On the contrary, the 2.48- and 2.05-MeV levels observed in the decay of the 1^+ Sb^{118} isomer are both of 0^+ character, as shown by Käld[38] and Ikegami *et al.*,[18] respectively. (2) The different energies of the 0.8-MeV gammas, 805 ± 15 and 825 ± 15 keV, observed in the In and Sb decays, respectively, point to two separate levels around 2.04 MeV. However, this argument is not conclusive, although the limits of error given are conservative. (3) The 2040-keV level observed in the In decay is directly connected to the ground state, the relative intensities of the 805- and 2040-keV gammas being $I_{805}/I_{2040}=(7\pm2)/(3.1\pm0.6)$. In the antimony case, no 2-MeV gamma was observed, an upper limit of $I_{825}/I_{2050}>20$ being set on its relative intensity. Again, this supports the existence of two levels at 2.04–2.05 MeV. (4) According to our decay scheme for In^{118}, the high-spin 2.48-MeV level is depopulated by approximately equally intense 0.45- and 1.25-MeV gammas. On the other hand, in the Sb^{118} decay we have the ratio $I_{0.4}/I_{1.25}\ll0.5$, and no 0.4-MeV gamma was observed. (That no 0.4- or 2-MeV gammas were found in the decay of Sb^{118} is in accord with the well-known selection rule that no $0^+\rightarrow0^+$ gamma transitions can occur.)

On the basis of the angular distribution results of the (d,p) reaction on Sn^{117}, Cohen and Price[11] report 0^+ or 1^+ states in Sn^{118} at 1.75, 2.03, and 2.48 MeV. The 1.75-MeV level is not observed in the present work, but is reported by Ikegami *et al.*[18] as a result of a study of electric monopole transitions following the decay of the 3.5-min Sb^{118}. (Therefore, the 1.75-MeV level is of 0^+ character.) Ikegami *et al.* also report a 0^+ state at 2.06 MeV, which apparently is the same state as that found in our work at 2.05 MeV and corresponds to the "2.03-MeV level" of Cohen and Price. Our 2.48-MeV 0^+ state obviously has been observed in Ref. 11 at the same energy. Of the many levels reported for Sn^{118} from the (d,d') reaction,[12] the 2.06-, 2.47-, 2.71-, and 2.92-MeV ones may be tentatively identified with our levels at 2.04–2.05, 2.48, 2.72, and 2.96 MeV, respectively, purely on grounds of the energy fit.

2. In^{120} Isomers

Poularikas *et al.*[23] have assigned a 3.0 ± 0.8-sec hard beta-emitting activity to In^{120}, on the basis of cross bombardments with 14.8-MeV neutrons. This assignment is confirmed in our work in which the half-life of 3.2 ± 0.4 sec for this In^{120} isomer was measured with the beta crystal biased integrally at 2 MeV, the indium activity having been produced by irradiating enriched Sn^{120}. The highest end-point energy of the beta spectrum was measured as 5.6 ± 0.6 MeV; the uncertainty in this value is mainly due to the N^{16} contaminant.

Gamma rays in the 3.2-sec In^{120} decay were looked for by recording several successive two-second singles spectra after thirty 2-sec irradiations of Sn^{120}. In the decay of the 1.17-MeV photopeak which represents[34] the ground-state transition from the first excited state of Sn^{120}, a few-second component was observed, in addition to the 44-sec In^{120} decay. The shorter lived component can be attributed most naturally to the 3.2-sec In^{120} isomer. From the relative intensities of the 3.2- and 44-sec components of the 1.17-MeV gamma and from the isomeric cross-section ratio (see below, subsection III.4.), one can estimate that about 15% of the 3.2-sec In^{120} decay goes via the 1.17-MeV level in Sn^{120}. This figure may be high by a factor of 3 or low by a factor of 2.

The allowed beta branch (log $ft=5.1$) of the 3.2-sec In^{120} to the ground state of Sn^{120} restricts the spin-parity of this In^{120} isomer to 0^+ or 1^+, the probable beta branch to the 1.17-MeV 2^+ state in Sn^{120} supporting the latter alternative.

The half-life of the high-spin In^{120} isomer was measured to be 44.3 ± 1.5 sec by scintillation coincidence counting. This measurement was made with a nearly 4π geometry, having both the 3×3-in. NaI(Tl) detectors set to record pulses corresponding to the gamma-energy region of 0.83 to 1.2 MeV. The same result was

[35] A. A. Sorokin, A. Bedyesku, M. V. Klimentovskaya, L. N. Kryukova, K. P. Mitrofanov, *et al.*, Izv. Akad. Nauk. SSSR Ser. Fiz. **24**, 1484 (1960); C. W. Kocher, A. C. G. Mitchell, C. B. Creager, and T. D. Nainan, Phys. Rev. **120**, 1348 (1960).

[36] M. L. Perlman and M. Wolfsburg, U. S. Atomic Energy Commission Report BNL 485 (T-110), 1958 (unpublished).

[37] H. Brysk and M. Rose, Rev. Mod. Phys. **30**, 1169 (1958).

[38] L. Käld, Helsinki, 1963 (private communication).

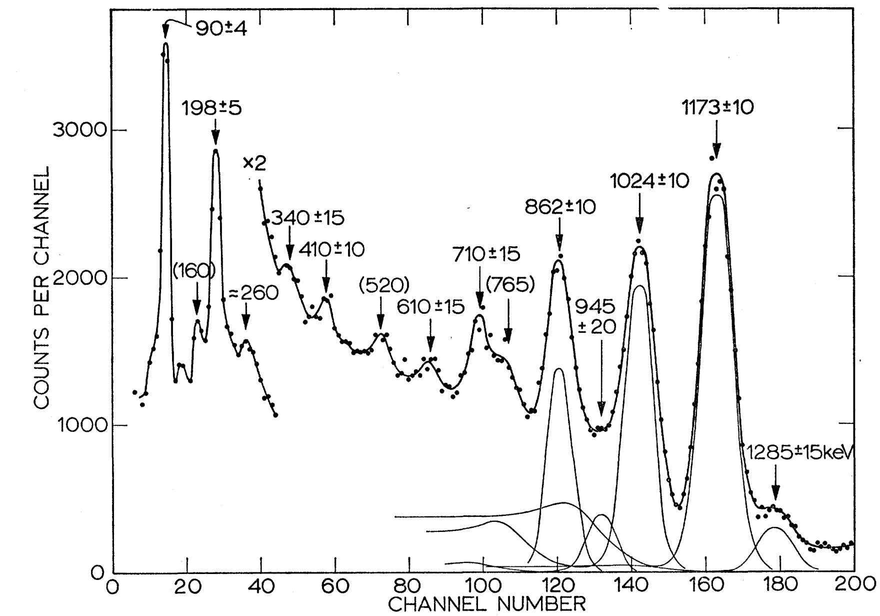

FIG. 3. A linear scale plot of the single-crystal gamma spectrum (below 1.4 MeV) of the 44.3-sec In^{120}, illustrating the peeling-off method employed in the analysis of the spectra. A 3×3-in. NaI(Tl) crystal with 10-cm source-to-detector distance was used. The peaks at 160, 520, and 765 keV are due at least in part to contaminants.

obtained by following the decay of the 1.17-MeV gamma photopeak (see Fig. 3) in several successive singles spectra. Our result for the half-life is somewhat smaller than the values[23] 50 and[16] 55 sec reported previously, which is probably due to the fact that disturbing longer lived activities are most effectively rejected in the present measurements.

The energies and relative intensities of the gamma rays associated with the 44.3-sec In^{120} decay are presented in Table I, in which the values listed are mostly weighted averages of the singles and coincidence spectra. A singles gamma spectrum of the energy region below 1.4 MeV is shown in Fig. 3. The decay of the weak gammas between 0.26 and 0.61 MeV could not be followed very well, but it is likely that they all belong to the 44-sec decay. The energy region above 1 MeV was studied with the lead absorber techniques, which showed that a large number of high-energy gammas belong to this decay (see Table I). All these gammas were observed also in the coincidence spectrum gated with the 1.17-MeV line, except perhaps a weak line at about 2.1 MeV (which thus would be evidence for a high-energy ground-state transition). These experiments also established the existence of a 1.19-MeV gamma, in the same way as the 1.25-MeV gamma was found in the decay of the 4.35-min In^{118} isomer.

The low- and medium-energy ($E<1.6$ MeV) spectrum in coincidence with the 1.17-MeV line (without Pb absorbers) exhibited all the gammas up to the 1.47-MeV one, although the statistics did not allow conclusive observations in the region of 0.26–0.61 MeV. In this spectrum, the relative intensity of the 0.71-MeV gamma was almost twice that in the singles spectrum, which hints at the existence of the triple coincidence of the 710-, 1173-, and 1190-keV gammas.

The sum (total absorption) and sum-peak spectra (with bias just above the Sn K x-ray peak) were obtained in this case in an almost 4π geometry,[31] in order to attain the largest possible detection efficiency for the weakest sum peaks. The most important portions of the two spectra are illustrated in Fig. 4, and the sum peaks with probable explanations are listed in Table II. These

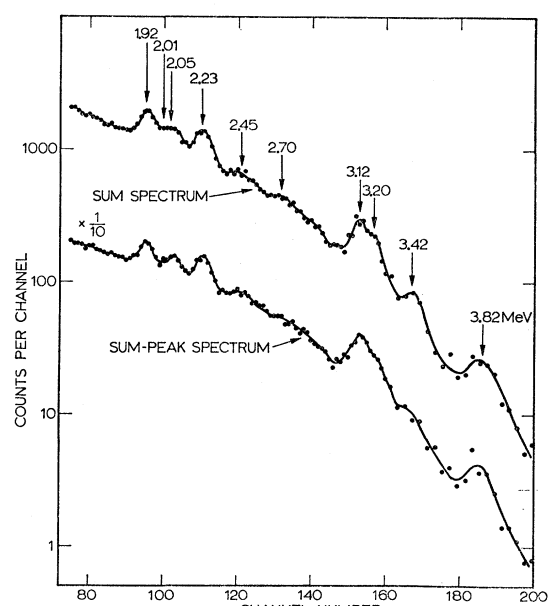

FIG. 4. The high-energy portions of the sum (total absorption) and low-bias sum-peak spectra of the 44.3-sec In^{120}, taken in an almost 4π geometry. The two spectra are not normalized for quantitative comparison. All the peaks observed are sum peaks, except the 2.01-MeV peak which is due to a 2-MeV gamma. From channel 160 on, the average counts of two adjacent channels are plotted. For the interpretation of the spectra, see Table II.

TABLE II. Energies and interpretations of high-energy sum peaks observed in the 4π sum and sum-peak spectra of the 44.3-sec In^{120} isomer. [Due to the well-known nonlinear response of NaI(Tl) to photons, the energies of the sum peaks are slightly larger than the corresponding sums of the gamma energies.]

Energy of sum peak (keV)	Interpretation: sums of gammas (keV)
1920	862+1024; 710+1173
2050	862+1173
2230	1024+1173
2450	1173+1190; 1173+1285
2680	1173+1470
3120	862+1024+1173; 1173+1870
3200	1173+2010
3420	1173+2220
3820	1173+2630

spectra were taken after different irradiations and are not normalized for quantitative comparison (cf. Ref. 31). However, it is clear that the 3.12-MeV sum peak is mostly to the (862)(1024)(1173 keV) triple cascade while all the other peaks seem to be mainly sums of two gammas. The sum-peak results confirm most of the other coincidence data, although all the sum peaks are not resolved because of the complexity of the spectrum. In addition to the results listed in Table II, one concludes from the sum-peak spectra that the following coincidences do not exist: (710)(862), (710)(1024), and (90)(198) keV.

The intensities of the 862-, 1024-, and 1173-keV gammas together with the sum-peak results establish the following levels in Sn^{120}: 3.06, 2.20, and 1.17 MeV. Since no sum peaks could be observed above the 3.82-MeV one, it is apparent that the highest level populated in Sn^{120} lies near 3.8-MeV. Similarly, it is likely that the other sum peaks above 3.2 MeV come from levels at 3.57, 3.39, and 3.18 MeV (see the decay scheme in Fig. 5). On the basis of the energy fit, the 1870-keV gamma can be placed between the 3.06- and 1.17-MeV levels.

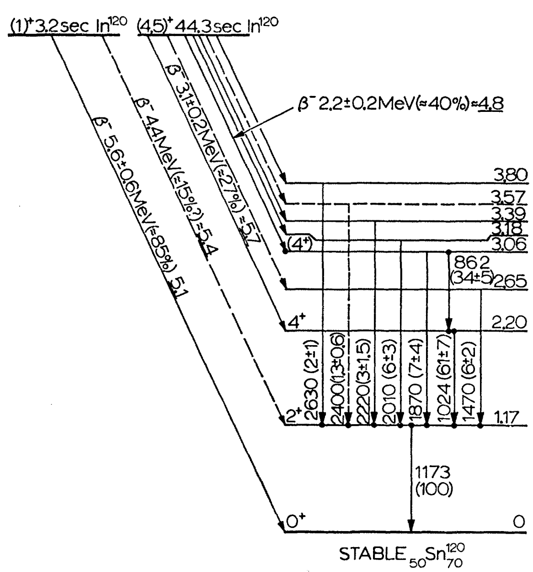

FIG. 5. A partial decay scheme suggested for the In^{120} isomers. In addition to the levels shown, it is probable that two or three of the following four levels exist in Sn^{120}: 1.88, 2.12, 2.36, and 2.46 MeV. (For notation, see caption of Fig. 2.)

The beta spectrum of the 44.3-sec In^{120} is by far too complex to be resolved into components with a scintillation spectrometer. The end-point energy of the most intense beta branch was measured as 2.2 ± 0.2 MeV and that of the highest energy branch as 3.1 ± 0.2 MeV. The beta component in coincidence with the intense 862-keV gamma was investigated by the method used in the study of the 4.35-min In^{118} decay. It was found that the 2.2-MeV beta branch is in coincidence with this gamma, and consequently feeds the 3.06-MeV level in Sn^{120}. The energy fit would then suggest that the 3.1-MeV beta component leads to the 2.20-MeV level.

Additional information as to the positions of the various gammas in the decay scheme was obtained by taking a gamma spectrum of the region below 1.6 MeV in coincidence with the part of the beta spectrum above 1.8 MeV. Since a geometry with large solid angles had to be used (which involved some summing of events due to betas and gammas in the beta detector), the results must be considered as qualitative only. The spectrum obtained showed clearly that the 0.72-, 0.83-, 0.94-, and 1.29-MeV peaks were noticeably attenuated with respect to the 1.02- and 1.47-MeV peaks, as compared with the singles gamma spectrum. Consequently, either the attenuated gammas originate from high-lying levels, or their initial levels are populated principally from such levels. This result is in accord with the position of the 862 keV gamma inferred from the sum-peak data. Since the 1470-keV gamma cannot originate from the highest levels, it very likely feeds the first excited state and thus establishes a level at 2.64 MeV, which apparently is fed by betas from the In^{120} decay.

For lack of many important coincidence results, which could not be obtained, our data on the 710-, 945-, 1190-, and 1285-keV gammas are not sufficient for placing the corresponding transitions uniquely in the decay scheme. On the basis of our results, it is likely that two or three of the following four levels exist in Sn^{120}: 1.88, 2.12, 2.36, and 2.46 MeV. There is no basis for placing the lower energy gammas in the decay scheme.

In studies of the 5.8-day Sb^{120} decay[17,18] an 11-μsec isomeric 7^- state has been observed in Sn^{120}, which is depopulated by cascading 200- and 90-keV gammas leading to the 2.29- and 2.20-MeV levels, respectively. This would seem to suggest positions for the 198 ± 5- and 90 ± 4-keV gammas found in our work, but since these gammas are not in coincidence, the 7^- state cannot be populated in the 44.3-sec In^{120} decay. Consequently, the 198-keV gamma observed in the In^{120} decay does not correspond to the same transition in Sn^{120} as the 200-keV gamma in the Sb^{120} decay. On the other hand, the two 90-keV gammas may be the same, which would mean that approximately 12% of the 44.3-sec In^{120} decay proceeds via the 2.29-MeV 5^- state in Sn^{120}.

With very similar reasoning as was used in the In^{118}–Sn^{118} case, one concludes that the spin-parity of the 44.3-sec In^{120} is 4^+ or 5^+ and that of the 2.20-MeV level in Sn^{120} 4^+. This level is very likely the same as the one found in the Sb^{120} decay.[17,18] Like the 2.96-MeV level in Sn^{118}, the 3.06-MeV level in Sn^{120} is probably of 4^+ nature. The other levels indicated in the decay scheme have high spins ($\geqq 3$), as they are directly populated from the high-spin In^{120}. Possible lower spin states (such as 2^+ states expected on the basis of level systematics and theoretical calculations) might be found in the region 1.88–2.46 MeV, which contains some unidentified levels.

If our spin assignment 4^+ for the 3.06-MeV level is correct, then the 862-keV gamma is of $M1$ and/or $E2$ and the 1870-keV gamma of $E2$ multipolarity. To obtain information on the possible reduction of $E1$ transition probabilities (see discussion), we estimated the relative intensity of a 770-keV gamma, which would connect the 4^+ 3.06-MeV state to the 5^- 2.29-MeV state, and found an upper limit of $I_{770}/I_{862} \lesssim 0.1$.

From (d,p) reaction data, Cohen and Price[11] report low-spin (0^+ or 1^+) levels in Sn^{120} at 1.89, 2.16, and 2.62 MeV. Purely energetically, these could correspond to our (possible) levels at 1.88 and 2.64 MeV. The (d,d') data[12] include level energies of 1.90, 2.09, 2.21, 2.46, 3.04, 3.16, and 3.72 MeV, which are close to our energies 1.88, 2.12, 2.20, 2.46, 3.06, and 3.80 MeV. Whether or not some of our levels coincide with those observed in the deuteron inelastic scattering remains to be studied.

3. In^{122}

We have previously reported[24] the decay characteristics of the new isotope In^{122} as follows: half-life 7.5 ± 0.8 sec, beta end-point energy 4.5 ± 0.8 MeV, and two coincident gammas having energies (and relative intensities) of 1140 ± 10 (1.8 ± 0.3) and 995 ± 10 keV (1). Later experiments have confirmed and supplemented these results.

In a sum-peak spectrum biased at 0.6 MeV, we observed sum peaks at 2160 ± 30 and 2330 ± 40 keV with relative intensities approximately 3:1. The former peak must be due to the summing of the 995- and 1140-keV gammas, while the latter one is interpreted to correspond to the sum of the 1140-keV gamma plus another gamma at 1160 ± 40 keV. Since no other gammas were found to belong to the 7.5-sec decay, these coincidence results suggest energy levels in Sn^{122} at 1.14, 2.14, and 2.30 MeV (see Fig. 6 for a tentative decay scheme).

Further measurements of the beta spectrum by a scintillation method involving the use of a Plexiglas beta absorber[39] showed that the highest end-point energy of the In^{122} beta spectrum is ≈ 5 MeV (i.e., about the same as that of P^{34} used as a standard). The N^{16} contaminant was particularly strong in this experiment and is responsible for most of the uncertainty in the energy value. It is not clear which levels in Sn^{122} are fed by the In^{122} betas, but according to the gamma-ray results, it is likely that only the levels above 2 MeV are populated by the betas. Consequently, the total beta disintegration energy of the 7.5-sec In^{122} would be ≈ 7 MeV.

Information as to the spin and parity of In^{122} and of the levels observed in Sn^{122} is meager. According to Coulomb-excitation results[10] and level systematics, it is practically certain that the 1.14-MeV level is the first excited state with a spin-parity of 2^+. A comparison with the level schemes of Sn^{116}, Sn^{118}, and Sn^{120} (see below) would suggest that the 2.14-MeV level is the lowest 4^+ state in Sn^{122}. On the basis of this and the fact that the 1.14-MeV 2^+ state does not seem to be connected with the 7.5-sec In^{122} isomer, one can tentatively restrict the spin of In^{122} to 4^+ or 5^+. Since a 1^+, 5^+ isomeric doublet probably exists in Sn^{116}, Sn^{118}, and Sn^{120}, one would expect a low-spin isomer in In^{122}, too. We therefore searched for a very short-lived hard beta-emitting isomer but were not able to see any trace of such an activity.

4. Isomeric Activation Cross-Section Ratios

To obtain information on the structure of the In isomers and the Sn isotopes as well as on the (n,p) reaction mechanism leading to the former ones from the latter ones, we measured the isomeric activation cross-section ratios for the production of the In^{116}, In^{118}, and In^{120} isomers. Enriched isotopes Sn^{116}(95.74%), Sn^{118}(96.6%), and Sn^{120}(98.4%) were irradiated, and a large number of short runs were necessary in all cases for any acceptable statistics. The accumulation of the

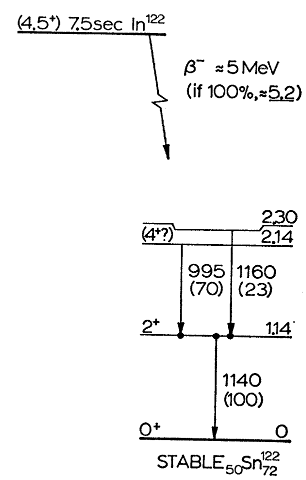

FIG. 6. Tentative partial decay scheme of the 7.5-sec In^{122} isomer.

[39] M. Karras and J. Kantele, Phys. Letters 6, 98 (1963).

TABLE III. Summary of the literature and present data on the odd-odd In isomers.

Mass number	Half-life	Spin and parity	Proposed neutron configuration[a]	β^--disintegration energy E (MeV) Measured	systematics[b]	Cross-section ratio[c] $\sigma_{5^+}/\sigma_{1^+}$	Energy difference $E_{4^+,5^+}-E_{1^+}$	References
106	5.3 min				<0			d
108	40 min	(2)	$d_{5/2}$		<0			f
	58 min	(7)	$d_{5/2}$					
110	4.9 h	7	$d_{5/2}$		<0			f,g
	66 min	2^+	$d_{5/2}$					
	42 msec	(7^-)	$h_{11/2}$					f,h
112	21 min	(4^+)	$s_{1/2}$				0.155	
	12 min	1^+	$g_{7/2}$	0.656	0.66[e]			
	2.5 sec	(8)						f
114	50 day	5^+	$s_{1/2}$				0.192	
	72 sec	1^+	$g_{7/2}$	1.984	1.98[e]			
	2.2 sec	$(5,6)^-$	$h_{11/2}$					i,j,k,l
116	54 min	5^+	$s_{1/2}$	3.36		1.3±0.3	≈0.070	
	13 sec	1^+	$g_{7/2}$	3.29	3.29[e]			
118	4.4 min	$(4,5)^+$	$s_{1/2}$	4.3±0.1	≈4.40	3.8±2	0.1±0.3	l
	5.0 sec	1^+	$g_{7/2}$	4.2±0.3				
120	44 sec	$(4,5)^+$	$s_{1/2}$	5.3±0.2	≈5.50	3±2	−0.3±0.6	l
	3.2 sec	$(1)^+$	$g_{7/2}$	5.6±0.6				
122	7.5 sec	$(4,5^+)$	$s_{1/2}$	≈7	≈6.50			l
124	3.6 sec	(high)		≈7.4	≈7.42			m

[a] The proton configuration is probably $g_{9/2}^{-1}$ in all cases. Therefore, only the neutron (quasiparticle) configurations are listed.
[b] M. Yamada and Z. Matumoto (Ref. 41), ground-state energies.
[c] Ratio of activation cross sections for formation of the In isomers from the Sn isotopes with 14.7-MeV neutrons by the (n,p) reaction.
[d] R. C. Catura and J. R. Richardson, Phys. Rev. **126**, 646 (1962).
[e] Measured value.
[f] Nuclear Data Sheets (Ref. 34).
[g] T. Katoh *et al.* (Ref. 42).
[h] J. Ruan, Y. Yoshizawa, and Y. Koh, Nucl. Phys. **36**, 431 (1962).
[i] P. G. Hansen *et al.* (Ref. 19).
[j] K. F. Alexander *et al.* (Ref. 46).
[k] P. Fettweis and J. Vervier (Ref. 20).
[l] Present work.
[m] M. Karras (to be published).

longer-lived isomer, which took place in spite of the cooling-off periods between the bombardments, was always corrected for. The measured ratios of the (n,p)-activation cross sections for formation of the high-spin and low-spin In isomers with 14–15 MeV neutrons are summarized in Table III.

The isomeric cross-section ratios for the mass numbers 116 and 118 could be measured by following the decay of the 1.29- and 1.23-MeV gamma photopeaks, respectively, in several successive spectra. In the 116 case, the gamma-branching values of Fettweis and Vervier[20] (for the 13-sec In^{116}) and of Hansen *et al.*[19] (for the 54-min In^{116}) were used in calculating the cross-section ratio $\sigma(54\text{ min})/(13\text{ sec})=1.3\pm0.3$. By following the beta decay with the integrally biased plastic crystal, we confirmed the order of magnitude of the result. Recently, Brzosko *et al.*[40] have measured this ratio for 14.2-MeV neutrons as 1.0 (with an uncertainty of about 50%), in agreement with our work. Our result on the isomeric cross-section ratio for the formation of the 4.35-min and 5.0-sec In^{118} isomers is rendered uncertain mainly because of the uncertainty of the 5.0-sec gamma branch employed.[22] Again, the study of successive beta spectra confirmed the order of magnitude of the gamma-ray result.

[40] J. Brzosko, P. Decowski, and Z. Wilhelmi, Nucl. Phys. **45**, 579 (1963).

In the case of the mass number 120, the activities of the 44.3- and 3.2-sec isomers could be compared only with the aid of the beta detector. Therefore, owing to the uncertainties in correcting for the beta absorption in the source and in the capsule, and to the finite detection efficiency of the beta crystal for gammas, this result must be assigned wide limits of error.

In summary, the present results on the isomeric activation cross sections of the (n,p) reaction show that in all cases the high-spin isomer is favored, and it is more favored at the higher mass numbers than in the case of the mass number 116.

IV. DISCUSSION

1. Isomerism of Odd-Odd Indium Isotopes

A summary of the literature and present data on the odd-odd indium isomers is presented in Table III. The ground-state energies from the beta-decay systematics of Yamada and Matumoto[41] are included for comparison with the present disintegration energies of the In isomers. Agreement within experimental limits between these two sets of values is evident.

Interpretation of the systematic features of the In isomers can be attempted in terms of the known shell-

[41] M. Yamada and Z. Matumoto, J. Phys. Soc. Japan **16**, 1497 (1961).

model single-particle configurations available. The low-lying configurations for the last odd proton are $g_{9/2}^{-1}$, $p_{1/2}^{-1}$, $f_{5/2}^{-1}$, $p_{3/2}^{-1}$, and for the last odd neutron $s_{1/2}$, $d_{3/2}$, $h_{11/2}$, $g_{7/2}^{-1}$, $d_{5/2}^{-1}$. The $g_{9/2}$ proton hole occurs systematically as the ground state of the odd-mass In isotopes, the $p_{1/2}^{-1}$ level being the first excited state at about 0.3 MeV above the ground state.[34] The order given for the odd-neutron orbitals is typical in the region under consideration, on the basis of compilations of odd-mass Cd ($Z=48$) levels by Katoh *et al.*[42] and of odd-mass Sn ($Z=50$) levels by Price.[11] The most likely proton-neutron configurations for a number of odd-odd In isomers have been proposed by Brennan and Bernstein, and the coupling schemes are found to follow the so-called modified Nordheim rules[26] which are theoretically based on the jj-coupling model.[43] In Table III, these earlier results are supplemented with the aid of the modified coupling rules. It should be noted that the proton states are actual single-hole states, but that it would be more appropriate to use the term quasiparticle for the neutron states. (For example, there probably is no pure $g_{7/2}^{-1}$ state in the In or Sn nuclei although the $g_{7/2}$ quasiparticle can mainly consists of a $g_{7/2}$ neutron hole.) Therefore, in the study of the coupling of the various states, this should be kept in mind, although for simplicity we consider mainly pure single-particle or single-hole states in the following.

The 2,7 doublet found in In^{108} and In^{110} apparently arises from two different couplings of the configuration ($g_{7/2}^{-1}$, $d_{5/2}^{-1}$), as predicted by the "weak" rule.[26] This is in accord with the fact that the $d_{5/2}^{-1}$ neutron state lies close to the ground state in Sn^{109} and Sn^{111}. The rise of this state occurring in Sn^{113} and in heavier Sn isotopes explains the disappearance of low-energy 2^+ or 7^+ states after In^{110}.

In In^{112}, In^{114}, and In^{116}, a 1^+ state is the ground state; in In^{118} and In^{120} it is either the ground state or a low-lying state. Among the available configurations, only the ($g_{9/2}^{-1}$,$g_{7/2}^{-1}$) proton-neutron configuration can produce a 1^+ state, which, according to the "strong" rule, should be an isolated low-lying ground state of this configuration.[43] In view of the single-neutron level systematics,[11] this is rather surprising, since in Sn^{115} and in higher odd-mass Sn isotopes, the $7/2^+$ level lies at about 0.6 MeV and rises monotonically with mass number exceeding 1 MeV in Sn^{123}. On the other hand, the single neutron levels $s_{1/2}$, $d_{3/2}$, and $h_{11/2}$ lie at much lower energies in Sn^{117} and in the heavier Sn isotopes. Therefore, these states could be expected to couple with the lowest odd-proton state $g_{9/2}^{-1}$ to form the lowest states in the odd-odd indium isotopes. Since the "strong" rule applies to the ($g_{9/2}^{-1}$,$g_{7/2}^{-1}$) configuration and does not apply to the other likely configurations, the odd-odd In isomerism can be understood as a striking example of the strength of the "strong" rule. The most natural explanation for this is offered by the fact that each of the coupled states has the same orbital angular momentum ($l=4$), and the antiparallel coupling between these is particularly strong.[43] The trend in the odd-odd In level energy difference $E_{4^+\,5^+}-E_{1^+}$ indicated in Table III (which seems to decrease toward higher mass numbers) may be caused by the observed increase of the energy of the $g_{7/2}^{-1}$ (or $g_{7/2}$ quasiparticle) state in heavier odd-mass Sn isotopes.

TABLE IV. Logft values of beta transitions from some of the 1^+ In isomers to the ground states of the tin isotopes, the theoretical (Ref. 6) (KS) and experimental (Ref. 44) quantities $U^2(g_{7/2})$ for the tin ground states, and logft values for the corresponding hypothetical single-particle beta transitions.

Mass number	logft	$U^2(g_{7/2})$ KS	$U^2(g_{7/2})$ Exp.	$\log(ft)_{\text{s.p.}} \approx \log ft - \log(1/U^2)_{\text{KS}}$	$\log(ft)_{\text{s.p.}} \approx \log ft - \log(1/U^2)_{\text{Exp.}}$
112	4.1	0.25		3.8	
114	4.4	0.13		3.5	
116	4.6	0.085	0.22	3.5	3.9
118	4.8	0.069	0.14	3.6	3.9
120	5.1	0.056	0.11	3.8	4.1

The log ft values of the beta decay of the 1^+ In isomers to the ground state of the Sn isotopes support nicely the configuration suggested above for the 1^+ In states. According to the pairing model calculations of KS and the (d,p) and (d,t) reaction data of Cohen and Price,[44] the various single-particle orbitals are being gradually filled in the ground states of the even Sn isotopes. This means that the quantities U^2 and V^2 (which characterize the nonoccupany and occupancy of the single-particle orbitals, respectively, and follow the equation $U^2+V^2=1$) are smoothly changing from isotope to isotope. With increasing mass number, U^2 decreases and, consequently, V^2 increases.[44] In the decay of the 1^+ In states, a neutron (probably a $g_{7/2}$ one) is transformed into a $g_{9/2}$ proton so that a $g_{7/2}$ neutron hole is created. Therefore, the beta transition should be the more likely the less occupied the $g_{7/2}$ single-particle state is in the corresponding tin ground state. One would thus expect[45] that in this case

$$ft\approx\frac{1}{U^2(g_{7/2})}(ft)_{\text{s.p.}}.$$

In Table IV, we list the log ft values of the beta decay of some of the 1^+ In states to the Sn ground states, together with the $U^2(g_{7/2})$ values calculated on the basis of the KS theory, and the experimental $U^2(g_{7/2})$ values.[44] The subtraction of the quantities $\log(1/U^2)$ from the observed log ft values seems to yield almost constant log ft values for the corresponding hypothetical pure single-particle transitions, as one would expect in view of the assumed In configuration and the pairing theory.

[42] T. Katoh, M. Nozawa, and Y. Yoshizawa, Nucl. Phys. **32**, 25 (1962).
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The only available configuration that gives high-spin odd-parity states is $(g_{9/2}^{-1},h_{11/2})$, which therefore can be uniquely assigned to a number of states (see Table III). The 5^+ state that may be present in all even-mass indiums from 114 to 124 can be produced by the three low lying configurations $(g_{9/2}^{-1},s_{1/2})$, $(g_{9/2}^{-1},d_{3/2})$, $(p_{1/2}^{-1},h_{11/2})$. The measured magnetic moments of the 5^+ levels in In^{114} and In^{116} agree with the semiempirical ones calculated on the basis of the first of these configurations,[26] which would support the first alternative (at least for In^{114} and In^{116}). Some mixing with the second type probably occurs, in particular at the highest mass numbers, since the $d_{3/2}$ neutron state lies at low energies and even becomes the ground state in Sn^{121}. The fact that only slight changes in the relative positions of the single-particle proton or neutron states occur at higher mass numbers would suggest that the same configurations dominate at the lowest levels in In^{116}, In^{118},$\cdots$, and In^{124}. This is in agreement with the findings of the present work, although no low-spin levels have been observed in In^{122} and In^{124}.

In our work, no evidence was found for isomeric transitions in In^{118}, In^{120}, or In^{122}, which is what one would expect since possible low-energy transitions with multipolarities consistent with the proposed spins and parities would be rather slow (particularly if they were $E4$ transitions). This result would thus be in agreement with the assumption that the high-spin isomers in In^{118}, In^{120}, In^{122}, and In^{124} are of 5^+ nature as are the corresponding In^{114} and In^{116} isomers.

2. The (*n,p*)-Reaction Isomeric Cross-Section Ratios

In general, isomeric cross-section ratios of the (n,p) reaction with fast neutrons cannot give such definite information about the spins of the produced isomers as is sometimes possible in the case of thermal neutron capture.[46] Furthermore, the large experimental uncertainties of our cross-section ratios (see Table III) allow only qualitative conclusions in this case.

As the ground states of the even Sn nuclei are 0^+ and the 5^+ or 4^+ state in the final nucleus is favored in all cases, a high-spin intermediate state is likely to be involved in the reaction. This means that on the average a large angular momentum must be transferred by the neutron to the target nucleus, which is typical of reactions proceeding mainly through compound-nucleus formation.[47] On the other hand, only relatively small amounts of angular momentum are transferred in direct interaction processes, which, therefore, would give low $\sigma_{\text{high}}/\sigma_{\text{low}}$ cross-section ratios.[48] Consequently, it is likely that the (n,p) reaction at 14–15 MeV producing the odd-odd In isomers mainly proceeds via compound nucleus formation.

Chursin *er al.*[49] have recently measured the (n,p) cross sections at 14.5 MeV of $Sn^{112,116,118,119,120}$ leading to the longer lived In isomers. They find no clear decrease of the cross sections with increasing mass number as predicted by the semiempirical systematics of Gardner,[50] and attribute this result to changes occurring from isotope to isotope in strongly competing reaction channels and in the nuclear shell structure. This may also be the explanation of the behavior of the isomeric cross-section ratios measured in the present work.

3. Levels in Even Sn Nuclei Populated in the Decay of In Isomers

There is a clear similarity in the decay of the In^{116}, In^{118}, and In^{120} isomers, which also points to expected similarity of the level structure of the corresponding Sn isotopes. Unfortunately the present data do not allow many definite conclusions to be drawn, neither is the comparison with the theoretical calculations very fruitful.

Hansen *et al.*[19] have proposed four 4^+ levels in Sn^{116}. According to our results, it is possible that the corresponding levels exist in Sn^{118} and Sn^{120}, too. Most clearly analogous 4^+ levels in these three nuclei are the lowest ones [referred to as the (a) levels in the following], which lie at 2.39, 2.28, and 2.20 MeV in Sn^{116}, Sn^{118}, and Sn^{120}, respectively. (A smooth continuation of this "systematics" towards higher mass numbers would suggest that the levels observed[24,25] in Sn^{122} and Sn^{124} at 2.13 MeV belong to the same group.) The (a) levels are populated by betas and gammas in a very similar fashion, and they decay predominantly to the first excited 2^+ states. The ratio of the energy of the (a) level to that of the first excited state is very close to 1.86 in all cases from Sn^{116} to Sn^{124}.

The (likely 4^+) levels in Sn^{116}, Sn^{118}, and Sn^{120} at 3.04, 2.95, and 3.05 MeV, respectively, are the most favored ones in the decay of the high-spin In isomers, which indicates the greatest overlap of the wave functions of the parent and the daughter levels. [These Sn levels will be referred to as the (b) levels below.] As the most likely high-spin In configurations are $(g_{9/2}^{-1},s_{1/2})$ and $(g_{9/2}^{-1},d_{3/2})$, the principal two-quasiparticle configurations of the (b) levels are probably $(g_{7/2},s_{1/2})$ and $(g_{7/2},d_{3/2})$. Consequently, the beta transition in question would correspond to the transformation of a $g_{7/2}$ neutron into a $g_{9/2}$ proton.

Other possible structural similarities of high-lying levels in Sn^{116}, Sn^{118}, and Sn^{120} are less pronounced. One might look for members of the expected two-phonon

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quadrupole vibrational triplet at 2–2.20 times the energy of the first excited state. There is a number of levels in this energy region, e.g., a high-spin (probably 4^+) state at 2.20 times the energy of the lowest 2^+ state in Sn^{116}, Sn^{118}, and Sn^{120}, but the data are at present too meager to solve the problem of the existence of the two-phonon states or triplets in the Sn nuclei.

In comparing the observed level structure to the calculations of KS, one cannot expect a good quantitative fit, since the breakup of the degeneracy of the two-quasiparticle states caused by the long-range force has not been included for the Sn isotopes. Also, there are indications[17,18] that the parameters used by KS do not give the best fit with the experimental results. The level energies of KS seem to be generally higher than the experimental ones.

In the KS picture, the (a) levels are most likely produced by the configuration $(h_{11/2})^2$ which also can qualitatively explain the observed trend in the energies of these levels. The (b) levels can be generated by a number of configurations, including $(g_{7/2},s_{1/2})$ and $(g_{7/2},d_{3/2})$ which are also suggested by the beta decay data.

Arvieu *et al.*[7] have calculated the positions of the lowest 0^+, 2^+, 4^+, 5^-, and 7^- levels in the even Sn isotopes. It is of particular interest that the lowest theoretical 4^+ energies are in fair quantitative agreement with the experimental (a) energies. In these calculations, the lowest 4^+ level is due to the $(h_{11/2})^2$ configuration in Sn^{116} and in heavier Sn isotopes, whereas it belongs to mixed configurations in the lighter isotopes.[51] From the point of view of further developments of the model of Arvieu *et al.*, it may be of interest to note that the same set of parameters which gives good agreement for the lowest 4^+ states, also yields the best fit for the lowest 2^+ levels.

The calculations of Yoshida[9] on Sn^{118} have yielded fairly good results on certain cross sections. However, the quantitative agreement between the calculated and and theoretical level energies is not very good.

A closer examination of some of the observed relative transition rates and the likely configurations involved reveals apparent inconsistencies in the interpretation of the decay of the high-spin In^{118} and In^{120} isomers. As is evident from Figs. 2 and 5, the parent In states decay with allowed beta transitions to the 4^+ (b) and (a) levels which also are strongly internally connected. If the In states are of $(g_{9/2}^{-1},s_{1/2})$ or $(g_{9/2}^{-1},d_{3/2})$, the (b) levels of $(g_{7/2},s_{1/2})$ or $(g_{7/2},d_{3/2})$, and the (a) levels of $(h_{11/2})^2$ nature, as is likely in view of the above discussion and the theoretical calculations,[6,7] then both the (In) $\rightarrow$ (a) and (b) $\rightarrow$ (a) transitions ought to be strongly j- and l-forbidden and by no means favored as observed. This "discrepancy" might be explained most naturally by assuming a strong interconfiguration mixing which is expected to be present.

Another interesting fact is that the 4^+ (b) $\rightarrow 5^-$ $E1$ transitions are strongly hindered with respect to the (b) $\rightarrow$ (a) $M1$ and/or $E2$ transitions, although the apparent configuration change would presumably not cause such large relative retardation. If the configuration of the 5^- level is $(h_{11/2},s_{1/2})$ as suggested by Ikegami and Udagawa,[18] then the (b) $\rightarrow 5^-$ transition might be interpreted to represent the single-quasiparticle transition[18] $g_{7/2} \rightarrow h_{11/2}$ that strictly rules out an $E1$ transition.

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