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States of ^{122}In and ^{124}In†

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The $(t, ^3He)$ reactions on ^{122}Sn and ^{124}Sn have been used to study the masses and the low-lying excited states of ^{122}In and ^{124}In. The ground state Q values as measured here for these two reactions are -6350(50) and -7590(50) keV, respectively, leading to masses of 121.91028(5) and 123.91344(5) u for ^{122}In and ^{124}In. Fourteen excited states of ^{122}In with E_x<1.2 MeV and four excited states of ^{124}In with E_x<0.6 MeV are also reported. Comparisons are made with β-decay data.

[NUCLEAR REACTIONS ^{122}Sn$(t, ^3He)$, ^{124}Sn$(t, ^3He)$, E=23.0 MeV; measured $\sigma(\theta)$. ^{122}In, ^{124}In deduced levels. New masses of ^{122}In, ^{124}In.]

I. INTRODUCTION

Because of the stability of the closed proton shell Z = 50, the Sn isotopes have permitted the study of the β^- decay of many isotopes of In produced by (n,p) reactions. The masses of the In isotopes, when obtained from β-decay measurements, are often poorly known, and there is generally limited knowledge of excited states in these In isotopes. The $(t, ^3He)$ reaction can be used to provide much more accurate ground state masses and to populate excited states with a large range of spin values.

The isotope ^{122}In has been previously[1] observed in the (n,p) reaction[2] on ^{122}Sn and in the β^- decay[3,4] of ^{122}Cd. One of the ^{122}In states has a half life of ~1.5 sec and a probable $J^\pi = 1^+$ and is observed[2,3] to decay both to the ground and the first excited states of ^{122}Sn at E_x = 1.14 MeV $[J^\pi = 2^+]$ by β^- decay with a log ft = 5.1 for both transitions based on Q_{β^-}(max) = 6.3 MeV. An additional isomeric state has been reported by Takahashi *et al.*[2] and by Grapengiesser *et al.*[4] with a half life of 9.2 ± 0.2 sec and a probable $J^\pi = (4,5)^+$. This state appears to decay predominantly to higher excited states of ^{122}Sn. The excitation energy of this isomeric state in ^{122}In is not known but the values for Q_{β^-}(max) for the 1.5 and 9 sec states are given[2] as 6.4 ± 0.2 and 6.5 ± 0.2 MeV, respectively. Aleklett *et al.*[5] have recently reported Q_{β^-} = 6.25 ± 0.16 MeV and[6] $J^\pi = 4^+$ for the ground state of ^{122}In.

Most of the information regarding ^{124}In comes[7] from studies of the β-decay of ^{124}Cd, particularly from the work of Fogelberg *et al.*[8] γ rays with E_γ = 36.50 ± 0.05, 62.80 ± 0.10, 143.33 ± 0.05, and 179.91 ± 0.05 keV (the first of these an $M1$ transition, the others $E1$ transitions) were observed in a coincidence arrangement. In addition to the ground state with $J^\pi = 2^+$,[6] $\tau_{1/2}$ = 3.17 ± 0.05 sec,[4] Fogelberg *et al.*[8] suggest an isomeric state in ^{124}In of unknown energy with $J^\pi = 6^-$ and $\tau_{1/2}$ = 2.4 ± 0.3 sec. A recent measurement by Aleklett *et al.*[5] reports Q_{β^-} = 7.14 ± 0.09 MeV.

II. EXPERIMENTAL PROCEDURES AND RESULTS

The $(t, ^3He)$ reactions on ^{122}Sn and ^{124}Sn were studied using a 23 MeV triton beam from the LASL three-stage Van de Graaff facility and a magnetic spectrometer of the quadrupole-dipole-dipole-dipole (Q3D) type. ^{3}He ions were detected with a 1 m helical cathode focal plane detector having 0.8 mm spatial resolution.[9]

The Sn targets were self-supported and were oriented at 30° to the incident triton beam. The ^{122}Sn targets were 100 to 280 μg/cm^2 thick and were enriched[10] to 92.25% ^{122}Sn (other isotopes were 4.72% ^{120}Sn, 1.12% ^{124}Sn). The ^{124}Sn targets were 100–210 μg/cm^2 thick and were enriched[10] to 94.74% ^{124}Sn (other isotopes were 1.21% ^{122}Sn, 1.75% ^{120}Sn, 1.17% ^{118}Sn) and to 96.96% ^{124}Sn (1.04% ^{122}Sn). Data were taken with ^{122}Sn at θ = 20°, 25° (three runs, one with the 100 μg/cm^2 target), 30° and 35° (one run with the thin target), and total integrated beam currents of 1.8 to 13.1 mC. With the ^{124}Sn targets, runs were made at θ = 25° (two runs, one with the thin target) and 35° and integrated beam currents of 2.4 to 3.5 mC. Runs were also made with an enriched ^{24}Mg target, under identical conditions and preceding or following each of the runs with a Sn target, to calibrate[11] the channel number versus the energy of the outgoing ^{3}He ions.

A. States of ^{122}In

Figure 1 shows the spectra observed at $\theta = 25°$ and $35°$ with the 100 $\mu g/cm^2$ target, while Table I displays the results. The group corresponding to the ground state of ^{122}In, group 0, has a width of ~35 keV full width at half maximum (FWHM). This is consistent with the energy resolution expected from the thickness of the target. The very small cross section for the $(t, {}^3\text{He})$ reaction (see Table I) necessitated a target thicker than desirable from the standpoint of resolution. All states shown in Fig. 1 are bound so levels with widths larger than 35 keV correspond to unresolved states; group 11 belongs to this category.

The ground state group has $Q_0 = -6.35 \pm 0.05$ MeV. Using the masses of Wapstra and Bos[12] for ^{122}Sn, t, and ^{3}He, this leads to an atomic mass excess of $-83\,580 \pm 50$ keV for ^{122}In and to a mass of 121.91028(5) u. The corresponding β-decay energy is then $Q_{\beta^-} = 6.37 \pm 0.05$ MeV, consistent with but far more accurate than the previous value[5] of 6.25 ± 0.16 MeV.

We cannot determine unambiguously whether the state which we call the ground state of ^{122}In is the 1^+ state ($\tau_{1/2} = 1.5$ sec) or the $(4, 5)^+$ state ($\tau_{1/2} = 9.2$ sec), or whether group 0 is a composite

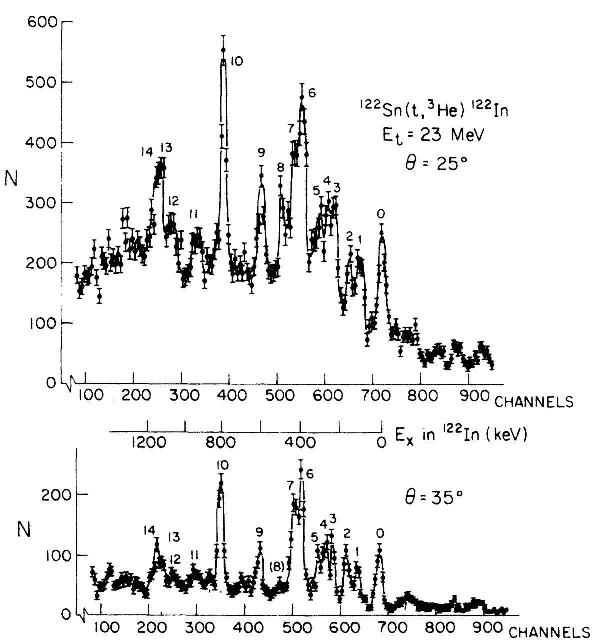

FIG. 1. Spectra of the ^{3}He ions from the ^{122}Sn$(t, {}^3\text{He})^{122}$In reaction at $E_t = 23.0$ MeV, $\theta_{lab} = 25°$ and $35°$, $B = 5.4527$ kG. The ordinates show the total number of counts recorded in a five-channel bin. The abscissas show the channel number and the excitation energy in ^{122}In, in keV. The numbered groups are due to states in ^{122}In: See Table I.

TABLE I. Energy levels of ^{122}In.

Group No.[a]	E_x in ^{122}In (keV)	$d\sigma/d\Omega$[b] (μb/sr)
0	≡0[c]	1.1
1	103 ± 15	0.9
2	157 ± 15	0.6
3	229 ± 15	0.9
4	262 ± 15	1.0
5	299 ± 15	1.0
6	383 ± 15	2.1
7	415 ± 20	1.6
8	(495 ± 20)	(0.7)
9	598 ± 15	1.0
10	801 ± 15	1.9
11	942 ± 25[d]	0.6
12	(1070 ± 25)	(0.8)
13	(1120 ± 25)	0.8
14	1150 ± 25	0.9

[a]See Fig. 1.
[b]$\theta_{lab} = 25°$; ±30%.
[c]Q_0 measured in this experiment is -6350 ± 50 keV.
[d]The width of this group shows that it corresponds to unresolved states.

of both states. If the ground state of ^{122}In is 4^+, as has been suggested by Aleklett *et al.*[6] then the transition between the 1^+ state and the ground state is an $M3$ transition. The excitation energy of the 1^+ state could then be as high as ~250 keV before[13] γ decay would compete with the β-decay half life of 1.5 sec. (If the ground state were 1^+, then $E_x \lesssim 200$ keV for a 4^+ excited state before the γ-decay lifetime becomes less than 9 sec.)

It is therefore suggested that the two isomeric states are the ground state of ^{122}In and the excited state at 103 keV (group 1), and following Aleklett *et al.*,[6] that these are 4^+ and 1^+, respectively. Evidence obtained in other $(t, {}^3\text{He})$ experiments[14] shows that states with relatively high angular momenta (i.e., 4, 5, and 6) are populated with cross sections which are entirely consistent with those observed for groups 0 and 1, taking into account differences in Q values and in mass numbers.

B. States of ^{124}In

Figure 2 shows the spectra observed at $\theta = 35°$ with the thicker target and at $25°$ with the thinner target. Table II displays the results, including the data of Fogelberg *et al.*[8] The FWHM of the ground state peak at $\theta = 25°$ (~35 keV) is consistent with that for a single state. Group 3, however, appears to correspond to unresolved states.

The Q value of the ground state group is -7.59 ± 0.05 MeV which corresponds to an atomic mass excess of $-80\,630(50)$ keV for ^{124}In and to a mass of 123.91344(5) u. The β-decay energy is Q_{β^-}

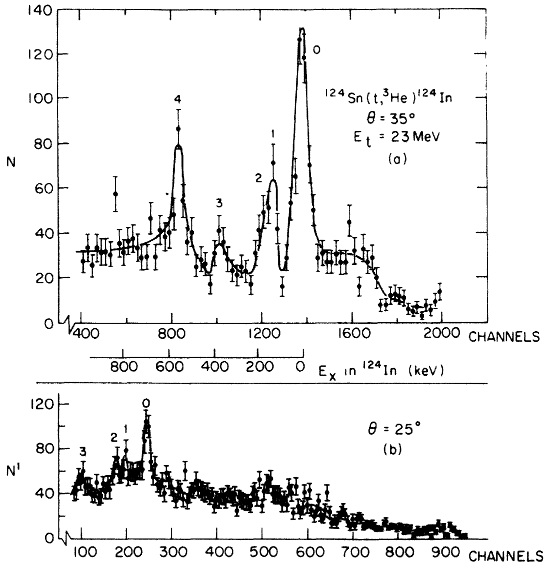

FIG. 2. Spectra of the ^{3}He ions from the ^{124}Sn(t, ^{3}He)^{124}In reaction at E_t = 23.0 MeV. (a) shows the results at $\theta = 35°$, B = 5.2717 kG, where N is the total number of counts recorded in a twenty-channel bin. The abscissa shows the channel number and the excitation energy in ^{124}In, in keV, based on group 0 being the ground state group. (b) shows the results with a thinner target at $\theta = 25°$, B = 5.4427 kG, where N' is the total number of counts recorded in a five-channel bin. The predicted mass of ^{124}In (see text) would lead to a group at about channel 400.

= 7.61 ± 0.05 MeV. The one measurement of Q_{β^-}, by Aleklett *et al.*,[5] reports a value of 7.14 ± 0.09 MeV. If this value of the decay energy is correct we should observe a group at approximately channel 400 in the 25° data shown in Fig. 1. There is no indication of such a group. There are occasional data points in the three ^{124}Sn runs which lie somewhat outside the statistical error flags, but there are no structures, other than the ones listed in Table II, which occur in more than one run.

Fogelberg *et al.*[8] have strong evidence for an excited state at E_x = 36.5 keV, and its γ decay to the ground state [$J^\pi = 2^+$ (Ref. 6)] is probably $M1$, suggesting $J^\pi = 1^+$ (see Table II). While we do not have any evidence for the state at 36.5 keV, our results do not contradict it, as can be seen from Fig. 2. Another problem arises in connection with the location of the isomeric state suggested by Fogelberg with $J^\pi = 6^-$ and $\tau_{1/2}$ = 2.4 ± 0.3 sec. As we have mentioned earlier, the (t, ^{3}He) reactions we have studied do not appear to discriminate against high J states. If we consider a $6^- \rightarrow 2^+$ $M4$ γ decay, the two states would have to be separated[13] by at least ~1 MeV before γ decay could compete with a β^- decay half life of ~2.4 sec. Thus *a priori* any of the excited states we observe could be the 6^- state reported by Fogelberg *et al.*[8]: It does not have to lie close to the ground state.

In the ^{124}Cd β^- γ-γ work of Fogelberg *et al.*[8] strong evidence is shown for a state at 179.87 keV whose main decay is via a crossover transition to the ^{124}In ground state. Our energy for that state is 178 ± 15 keV. They also observe a 143.33 keV γ ray, coincident with the 36.5 keV γ (from the decay of the first excited state) and with a 62.8 keV γ ray which is also coincident with the 180 keV γ ray. They attribute the 143 keV γ decay to the cascade transition 180 → 37 → 0, and the 62.8 keV γ to the cascade γ decay of a state at E_x = 242.67 keV via the 180 keV state (see Table II). Fogelberg *et al.*[8] suggest $J^\pi = 1^+$ for the 243 keV state. They add, however, that it is not observed to γ decay to either the ground or the first excited state of ^{124}In which indicates a complex structure for the state. We find no evidence for a state at 243 keV: The corresponding group would occur at channel 1140 in Fig. 2(a).

Finally, we shall comment on the states we report and which were not observed in the ^{124}Cd decay.[8] The second excited state at 122 keV, populated in this reaction, may possibly be the 6^- isomer suggested by Fogelberg *et al.*,[8] who also point out that the configuration $(\pi g_{9/2}^{-1}, \nu h_{11/2})$ would

TABLE II. Energy levels of ^{124}In.

	Present results		Results from β decay of ^{124}Cd[c]	
Group No.[a]	E_x in ^{124}In (keV)	$d\sigma/d\Omega$[b] (μb/sr)	E_x (keV)	J^π
0	≡0[d]	1.8	0	2^+[g]
			36.50 ± 0.05	(1^+)
1	122 ± 15	0.5		
2	178 ± 15	0.3	179.87 ± 0.05[e]	(1^-)
			242.67 ± 0.07[f]	(1^+)
3	365 ± 20[h]	0.3		
4	555 ± 20	0.8		

[a]See Fig. 2.

[b]$\theta_{lab} = 35°$; ±30%. At $\theta_{lab} = 25°$ [see Fig. 2(b)] the values for groups 0, 1, and 2 are, respectively, 0.5, 0.3, and 0.3 μb/sr.

[c]Level scheme proposed by Fogelberg *et al.* (Ref. 8) on the basis of γ-γ coincidence measurements in the β^- decay of ^{124}Cd.

[d]Q_0 measured in this experiment is −7590 ± 50 keV.

[e]Decays by γ transitions to both the ground and the 36.5 keV states.

[f]Decays by a cascade transition via the 180 keV state.

[g]An isomeric state with $J^\pi = 6^+$ is also observed by Fogelberg *et al.* (Ref. 8): Its excitation energy is not known.

[h]Broad group: may correspond to unresolved states.

lead to a set of low-lying excited states with $J^\pi = 1^-$ to 10^-. The excited states we report at 365 and 555 keV could be other states of that configuration with relatively large J values which would make their direct population in the β decay of ^{124}Cd [$J^\pi = 0^+$] unlikely. In both the 25° and 35° runs there is some evidence for other excited states of ^{124}In above $E_x = 600$ keV but it is not statistically significant. We could clearly also be failing to observe relatively weakly populated states below 500 keV because of the problems associated with the low cross section for this reaction.

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