^{112}Cd from ^{110}Cd(t,p)

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The level structure of ^{112}Cd has been investigated with the reaction ^{110}Cd(t,p), at $E_t = 15.0$ MeV. Twenty-nine angular distributions have been measured and compared to predictions of distorted-wave Born-approximation calculations to extract L, and hence J^π, values.

I. INTRODUCTION

Low-lying levels of even-even nuclei near closed shells are commonly described in terms of the vibrational model. The presence of "intruder" states at low excitation energies in the Cd isotopes has, therefore, generated substantial experimental and theoretical interest.[1,2] In ^{112}Cd, for example, the basic vibrational character is disturbed at the energy of the $N=2$ vibrational triplet near 1.4 MeV.[2] In this energy region, two extra levels with $J^\pi=0^+$ and 2^+ are observed, forming a quintuplet of states with the spin sequence 0_2^+, 2_2^+, 4_1^+, 0_3^+, and 2_3^+. Recently, Heyde *et al.*[3] have been successful in explaining these states in terms of specific mixtures of vibration-like and intruder rotation-like states. The intruder levels are assumed to be mainly 2p-2h states resulting from the excitation of a pair of protons across the $Z=50$ closed shell. Calculations with comparable success were done both in a particle-core coupling model and in the interacting boson approximation (IBA).[3]

While a number of particle transfer experiments have been carried out to study various structural aspects of these states,[1] no reactions involving two-neutron stripping have been performed to investigate the 2n parentage of the Cd levels. In the present study, the (t,p) reaction has been employed for this purpose. One might expect, for example, that if the intruder states do arise from the excitation of two protons across the $Z=50$ closed shell, these states will be weakly populated in the (t,p) reaction, assuming, of course, a weak admixture between the 2p-2h proton configurations and the ground states of ^{110,112}Cd.

II. EXPERIMENTAL PROCEDURE

The ^{110}Cd(t,p) reaction was performed at the University of Pennsylvania tandem accelerator using a tritium ion source. A 15-MeV triton beam bombarded a gold-backed ^{110}Cd target, approximately 100 μg/cm^2 in areal density and enriched to 97.2%. Protons from the reaction were momentum analyzed in a multiangle spectrograph and detected in nuclear emulsions. Absorbers stopped all particles except protons. Spectra were obtained in 7.5° steps starting at 3.75°, and the one measured at 11.25° is displayed in Fig. 1. The energy resolution was about 25 keV full width at half maximum (FWHM). Contaminant peaks due to Au and small amounts of ^{112}Cd and ^{111}Cd in the target were identified. The absolute cross section scale was determined from the elastic scattering which was recorded with a monitor counter, the uncertainty in the absolute scale being about 30%. At forward angles, the peak from ^{197}Au(t,p) ^{199}Au(g.s.) comes at 2.23 MeV in the ^{110}Cd(t,p) spectrum. It is the only strongly excited Au state in our region of interest, but weak ^{112}Cd states above 2.23 MeV may be slightly contaminated by the "grass" of weak Au peaks.

III. DISTORTED-WAVE BORN APPROXIMATION ANALYSIS AND RESULTS

Thirty-three peaks, including at least eleven doublets, were assigned to the ^{110}Cd(t,p) ^{112}Cd reaction. Angular distributions were obtained for all but four of these groups. The excitation energies obtained in the present work are compared with those listed in the Nuclear Data Sheets (NDS) (Ref. 1) and in the ^{111}Cd(d,p) reaction (Ref. 4) in Table I. Generally, the energies are in good agreement. However, above about 2.6 MeV many more states are known than we see, and, in many cases, the level density is so high that several states lie within our experimental resolution. Hence, at these higher energies, our angular distributions will frequently contain contributions from more than one state. The experimental results are shown in Figs. 2–9 along with curves calculated using the zero-range microscopic two-nucleon transfer code DWUCK.[5] The triton optical-model parameters were those of Flynn *et al.*[6] and were also used successfully by Anderson *et al.*[7] in their study of ^{108}Pd(t,p). The proton parameters were those from the work of Perey.[8] Both are listed in Table II. No shell-model calculations for states in ^{112}Cd were available, so pure configurations were assumed for the purpose of calculat-

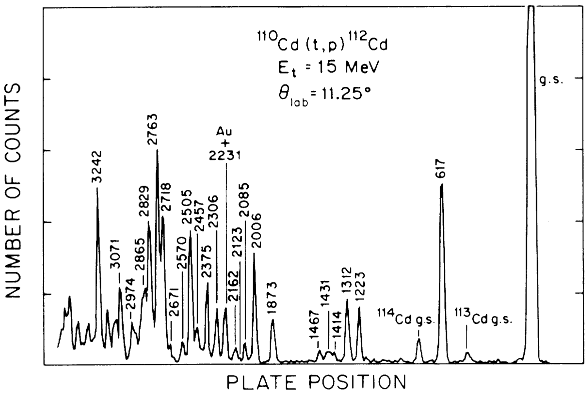

FIG. 1. Proton spectrum of the ^{110}Cd(t,p)^{112}Cd reaction at a bombarding energy of 15.0 MeV and a laboratory angle of 11.25°.

ing angular-distribution shapes. The characteristic L-dependent shapes were compared with the data in order to determine L transfers and to make spin and parity assignments. The results are given in Table I and discussed below.

Below an excitation energy of 2310 keV, we observe all previously reported levels, except for the 3^+ state at 2064 keV. That we do not observe this state is not

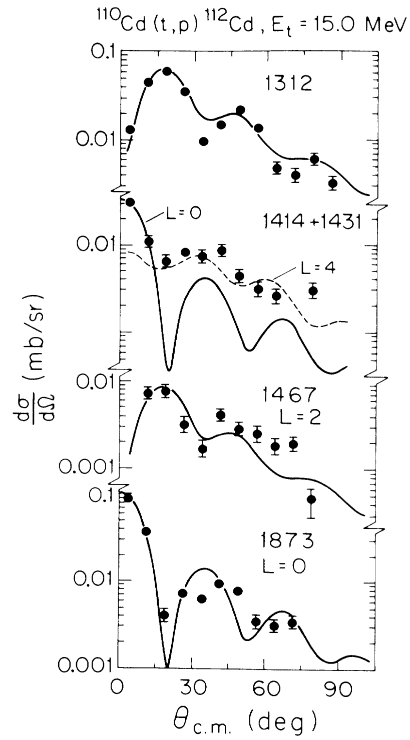

FIG. 3. Same as Fig. 2, but for $E_x = 1312-1873$ keV.

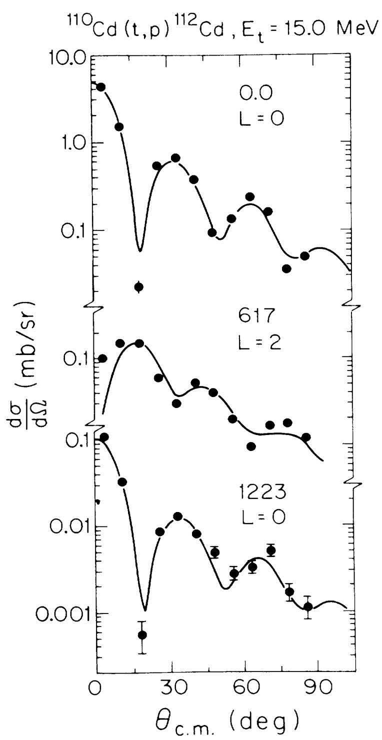

FIG. 2. Angular distributions from the ^{110}Cd(t,p)^{112}Cd reaction. The curves are the results of DWBA calculations for the indicated L values for $E_x = 0.0-1223$ keV.

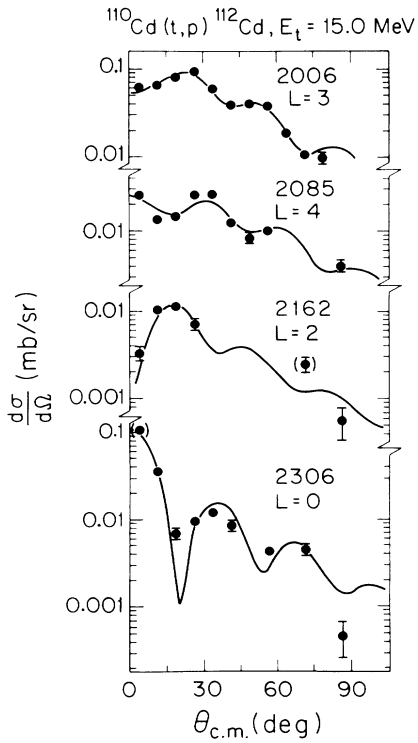

FIG. 4. Same as Fig. 2, but for $E_x = 2006-2306$ keV.

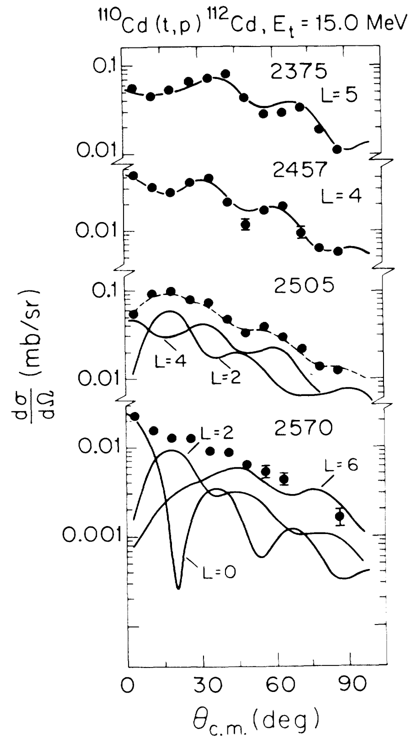

FIG. 5. Same as Fig. 2, but for $E_x = 2375-2570$ keV.

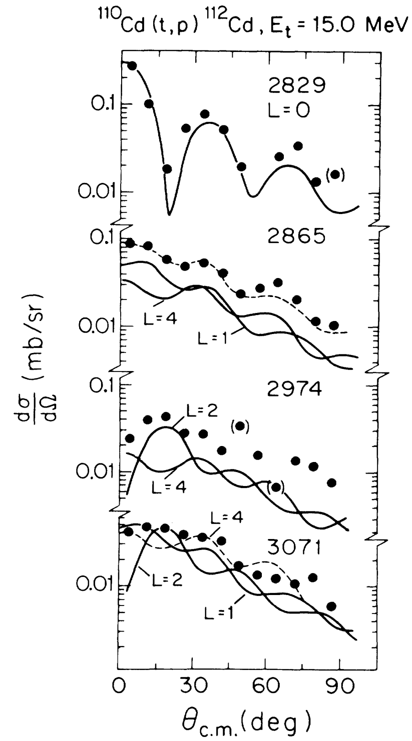

FIG. 7. Same as Fig. 2, but for $E_x = 2829-3071$ keV.

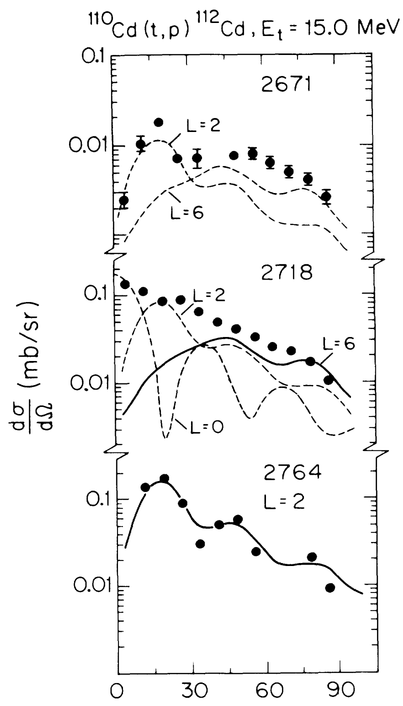

FIG. 6. Same as Fig. 2, but for $E_x = 2671-2764$ keV.

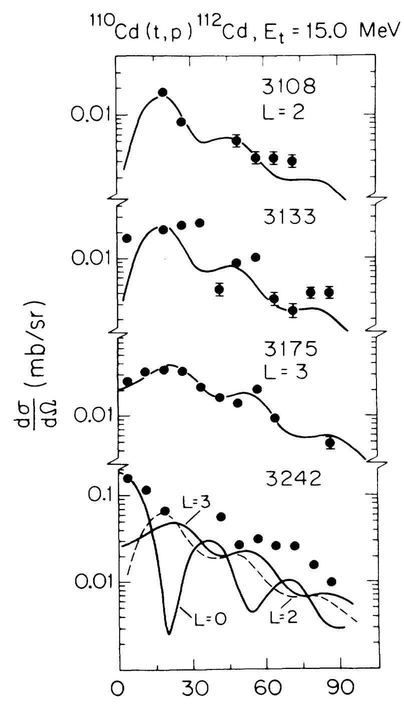

FIG. 8. Same as Fig. 2, but for $E_x = 3108-3242$ keV.

TABLE I. Present results for ^{112}Cd from the ^{110}Cd(t,p) reaction compared with previous information.

Nuclear Data Sheets[a]		^{111}Cd(d,p)[b]		^{110}Cd(t,p)[c]			
E_x (keV)	J^π	E_x (keV) (±8 keV)	l_n	E_x (keV) (±4 keV)	σ_{max} (μb/sr)	L	J^π
0	0^+	0	0	0	4504	0	0^+
617.494±0.097	2^+	619	2	617	152	2	2^+
1224.2±0.3	0^+	1228	0	1223	120	0	0^+
1312.3±0.3	2^+			1312	60	2	2^+
1415.3±0.3	4^+			1414	(8.1)	4	4^+
1433.2±0.4	0^+	1436	0	1431	(32)	0	0^+
1468.8±0.3	2^+	1474	2	1467	7.7	2	2^+
1870.8±0.3	0^+	1876	0	1873	88	0	0^+
2005.1±0.5	3^-	2009	(3)	2006	94	3	3^-
2064.1±0.4	3^+						
2081±1	4^+	2087		2085	27	4	4^+
2121.3±0.4	2^+	2123	2	(2123)		weak	
2156.4±0.6	2^+	2159	2	2162	11	2	2^+
2167±1	(6^+)						
2231.0±0.5	(2^+)	2235	(2,3)	2231	30–40	(2)	(2^+)
2301.1±0.8	0^+			2306	106	0	0^+
(2335±20)							
2372.8±0.4	$5^{(-)}$	2374		2375	80	5	5^-
2390±1	$(1,2^+)$						
2416.0±0.6	2^+						
2424±8	$(1,2^+)$	2424					
2464±20				2457	40	4	4^+
2506.7±0.5	(1^-)	2507	2	2505	(55)	2	2^+
					(40)	(4 or 1)	$(4^+$ or $1^-)$
2571±2	(6)				(6)	6	6^+
2572±2	(1,2)	2573		2570	(9)	2	2^+
					(21)	(0)	(0^+)
2607±2							
2637±8	(2)	2637	2				
2640	0^+						
2667±2	$(1,2^+)$	2657					
2668.8±0.5	(2^-)			2671	(6)	6	6^+
					(12)	2	2^+
2673.6±0.6	2^+	2678	2				
2723.6±0.6	2^+	2725	2	2718	(120)	(0)	(0^+)
					(83)	2	2^+
2765.5±0.6	$(2)^+$	2770	2	2763	170	2	2^+
2794±2	(7^-)						
2818		2822	(0,2)				
2829.2±0.3	$1^{(-)}$						
2832±3	0^+	2840	(0,2)	2829	283	0	0^+
2833±2	(>3)						
2850±2	2^+						
2866.7±0.9	(3)			2865	89	(4) and/or (1)	4^+ and/or (1^-)
2875±8		2875					
2880±2	(8^+)						
2901±8		2901					
(2932±2)		2936	2				
2936±2	(6,7)						
2961.9±1.2	2^+	2965	2				
						2	2^+
				2974	42	4	4^+
2988±8		2988					
						(2)	(2^+)
3067.7±1.2		3071		3071	46	(4)	(4^+)
3110±3	2^+	3113	2	3108	19	2	2^+
3130.7±0.9	2^+			3133	25	(2)	(2^+)
3169.1±0.6	(1^-)						

TABLE I. (*Continued*).

Nuclear Data Sheets[a]		^{111}Cd(d,p)[b]		^{110}Cd(t,p)[c]			
E_x (keV)	J^π	E_x (keV) (±8 keV)	l_n	E_x (keV) (±4 keV)	σ_{max} (μb/sr)	L	J^π
3175±2	(7.8)						
3176±2	(3,4)			3175	33	3	3^-
3184±8	$(2,3)^+$	3184	2				
3189±5	(1^-)						
3214±2							
3232±5							
3251±2	0	3240		3242	156	3 or 2	3^- or 2^+
						0	0^+
3303.2±0.7		3304	2	3302	28	(6)?,3(?)	(3^-)
3312±5	2^+						
3320±2	(9^-)						
						0	0^+
3344±8		3344		3335	41	4	4^+
3370.1±0.6	(2^-)			3365			
3393.0±1.2	$(1,2^+)$			3393			
3418±5				3415	23	4	4^+

[a]Reference 1.
[b]Reference 4.
[c]Present work.

surprising as unnatural-parity states are expected to be weak in (t,p) reactions.

In this low-lying part of the spectrum, there are five reported 0^+ levels, six 2^+ (though one is a tentative assignment), two 4^+, one (6^+), a 3^+, and a 3^- (Ref. 1). In the present work, the five observed 0^+ states all have angular distributions that are clearly characteristic of $L=0$ shape, even though the 1431-keV 0^+ state is not completely resolved from the nearby 4^+ level at 1414 keV.

For the 2^+ states, that at 2123 keV is too weak to allow extraction of an angular distribution and that at 2231 keV is obscured by the ^{197}Au(t,p) ^{199}Au(g.s.) peak at several forward angles. The other four are well fitted by $L=2$ curves, though the data do exhibit two slightly different types of shapes. The 617- and 1467-keV states have one shape; those at 1312 and 2162 keV have another. This difference is more clearly demonstrated in Fig. 10, where we compare data for the two lowest 2^+ states.

The angular distribution of the 4^+ state at 2085 keV has a forward-angle rise, but it is well fitted by an $L=4$ distorted-wave Born approximation (DWBA) curve. The other low-lying 4^+ level is unresolved from a 0^+ state, but the combined angular distribution is well fitted by a mixture of $L=0$ and 4 curves.

The probable (6^+) state at 2167 keV is not at all resolved from the 2156-keV 2^+ level, but the peak in the spectrum does appear to be slightly wider than other nearby ones—suggesting both states are populated. The peak is weak at all angles, and too weak at backward angles to allow an estimate of the $L=6$ cross section.

The angular distribution of the 3^- state at 2006 keV is well fitted by an $L=3$ curve, and that for the $5^{(-)}$ level at 2375 keV is in good agreement with an $L=5$ curve—allowing a definite assignment for the parity of the latter.

We find no evidence in our data for a state near 2335±20 keV, listed in the compilation,[1] but apparently previously observed only in (p,p′) (Ref. 9). Our spectra have a deep minimum between the 2306- and 2375-keV states, so that if the 2335-keV state exists, it is extremely weak in (t,p).

Above 2.4 MeV we begin to see fewer and fewer of the known states—undoubtedly due largely to the increased level density, but partially because several of them probably are of unnatural parity and hence weak in (t,p). Thus, for higher energies, we discuss only states (or groups of states) for which we have angular distributions.

TABLE II. Optical-model parameters used in the analysis of the ^{110}Cd(t,p) ^{112}Cd reaction.

	V_0 (MeV)	r_0 (fm)	a (fm)	W (MeV)	$W'=4W_D$ (MeV)	r'_0 (fm)	a' (fm)	λ	r_c (fm)
^{110}Cd+t	166.7	1.16	0.752	21.4		1.498	0.817		1.3
^{112}Cd+p	50.8	1.25	0.65		56.8	1.25	0.47		1.25
^{110}Cd+nn	a	1.27	0.67					32	

[a]Adjusted to give a binding energy to each particle of $0.5[Q(t,p)+8.482]$ MeV.

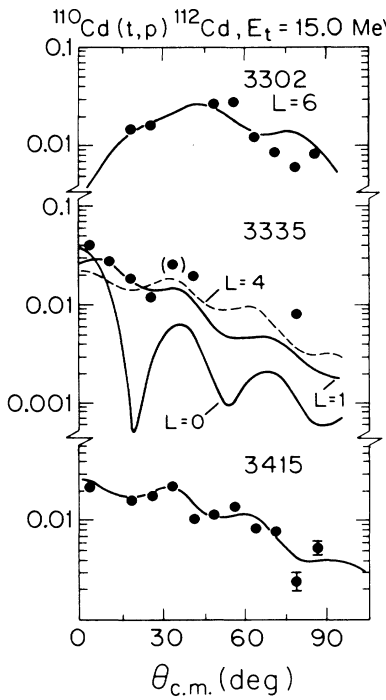

FIG. 9. Same as Fig. 2, but for $E_x = 3302-3415$ keV.

Our 2457-keV angular distribution is well fitted by $L=4$, allowing a 4^+ assignment. No nearby state in the compilation has either a definite or tentative 4^+ assignment. In fact, among the known states, it appears that only the one at 2464±20 keV is a candidate to correspond to our level.

Our 2505-keV state is reasonably strong, and its angular distribution clearly contains at least two L values. In the NDS, a (1^-) assignment for a state at 2507 keV is contradicted by observation of $l=2$ in ^{111}Cd(d,p).[4] We have fitted the data with a mixture of $L=4$ and 2, though 1 + 2 would do equally well.

Our 2570-keV angular distribution contains contributions from two or three L values. The compilation lists two nearby states—2571±2, $J=(6)$ and 2572±2, J $=(1,2)$. Our large-angle data are consistent with the presence of $L=6$, but neither $L=1+6$ nor 2 + 6 fits the full angular distribution. We show $L=0$, 2, and 6 curves with the data. We find no evidence of a 0^+ state at 2640 keV, assigned $L=0$ in (^{3}He,n) (Ref. 10). The uncertainty in their excitation energy is not known, so it may be that our 2570-keV group contains their 2640-keV 0^+ state.

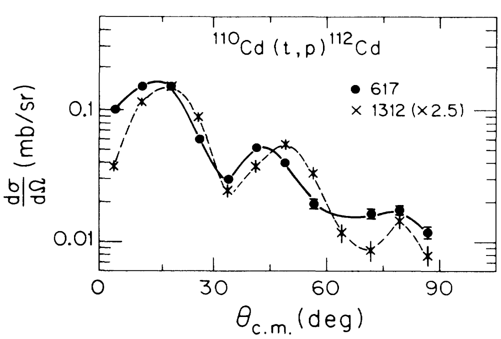

FIG. 10. Comparison of data for the first two 2^+ states of ^{112}Cd, populated in the ^{110}Cd(t,p) reaction. The lines have been drawn to help guide the eye.

Our 2671-keV state is quite weak. Its angular distribution appears to contain contributions from $L=2$ and some large L value, probably $L=6$ or 7. The NDS list a $(1,2^+)$ state at 2667 keV, (2^-) at 2669 keV, and 2^+ at 2674 keV. No high-J state is known near here.

Our 2718-keV angular distribution is indistinguishable from that at 2570 keV. We thus compare it with $L=0$, 2, and 6 DWBA curves. A 2^+ state is known at 2724 keV. The 2763-keV level is strong and has a clear $L=2$ angular distribution. The tentative $(2)^+$ assignment in the NDS for a state at 2766 keV can thus be made a definite 2^+.

Our strong $L=0$ angular distribution to a level at 2829 keV undoubtedly identifies it as the 0^+ state at 2832 keV in the NDS.

Our 2865-keV "state" clearly contains two or more levels. Its excitation energy varies from 2852 to 2892 keV at different angles. In this region, five states are known, but only one has a definite J^π assignment—a 2^+ at 2850 keV. Either $L=1$ or 4 gives a reasonable fit to the angular distribution and $L=1+4$ fits well.

The 2974-keV angular distribution appears to contain $L=2$ and 4. The width of the peak in the spectrum also suggests at least two states. A 2^+ state is known at 2962 keV, and a state at 2988±8 keV has no J^π assignment. If these are the two states we see, then the latter has $J^\pi=4^+$.

The 3071-keV angular distribution is not characteristic of any single L value, even though the NDS list only one state near here—at 3068 keV, with no J^π information. The peak in the spectrum for this level is no wider than that for single resolved states. The angular distribution appears to contain $L=1$ or 4 plus something else. We compare the data with $L=1$, 2, and 4 curves, but make no assignment.

Our 3108-keV angular distribution is well fitted by $L=2$. The NDS list a 2^+ level at 3110 keV. Our 3133-keV angular distribution has an unusual shape. Only a 2^+ state is known in the vicinity, at 3131 keV. We show an $L=2$ curve with the data.

Our 3175-keV state has an $L=3$ angular distribution. In this region five states are known, but none have definite J^π assignments. We are able to assign $J^\pi=3^-$ to one of them. If previous limits are correct, it must be the $J=(3,4)$ level at 3176±2 keV in the NDS.

Our 3242-keV state appears to be a doublet, one member populated with $L=0$, the other via $L=2$ or 3. Thus the $J=0$ level at 3251±2 keV in the NDS probably has $J^\pi=0^+$, and the state at 3232 keV has $J^\pi=2^+$ or 3^-.

The 3302-keV angular distribution is reasonably well fitted by $L=6$. A state at 3303 keV in the NDS has no J^π information, while a level at 3304 keV is populated with $l=2$ in (d,p).

The NDS list three states within our experimental resolution of our 3335-keV level. They are 3312±5 keV, $J^{\pi}=2^+$; 3320±2 keV, $J^{\pi}=(9^-)$; and 3344±8 keV, no J^{π} information. Only the latter is populated in (d,p). Our angular distribution is not characteristic of any single L value, though $L=1$ fits better than any other. We compare the data with $L=0$, 1, and 4 curves.

Our final angular distribution is for a state at 3415 keV, and it is well fitted by $L=4$. It may correspond to the level in the NDS at 3418±5 keV, with no J^{π} information.

TABLE III. Ratios of maximum cross sections relative to the ground state for excited 0^+ states below 2 MeV.

E_x (keV)	$10^2\sigma(E_x)/\sigma(\text{g.s.})$
1223	2.66
1431	0.70
1873	1.95

IV. DISCUSSION

Twenty-nine angular distributions for states populated in the ^{110}Cd(t,p) ^{112}Cd reaction have been measured. Comparison with DWBA curves has allowed L value assignments (and hence J^{π}) to most of the levels. States which were not observed were either of high J, unnatural parity, or unresolved from neighboring levels.

Of the three 0^+ states at 1223, 1431, and 1873 keV, one is undoubtedly the intruder 0^+ level that is commonly identified as the band head of a $K^{\pi}=0^+$ rotational band. The other two are then presumably members of the two- and three-phonon vibrational multiplets. As mentioned previously, the theoretical interpretation[3] of the intruder band is that of a set of states resulting from the excitation of a pair of protons across the $Z=50$ closed shell. In Table III the ratios of the maximum cross sections of the lowest three excited 0^+ states, taken relative to that of the ground state, are listed. Of course, a single-step direct (t,p) transfer reaction would not be expected to significantly excite either the two-phonon or 2p-2h configuration. That it excites one of them to the extent that it does suggests the importance of an admixture of the 2p-2h proton configuration in the ground-state wave function of ^{110}Cd, and/or mixture of the normal g.s. and intruder 0^+ states in ^{112}Cd. This point is discussed further in Ref. 11.

Finally, an interesting feature of the (p,t) reaction on the Cd nuclei has been reported by Comfort *et al.*[12] In their study, distinct differences in the shapes of the experimentally measured angular distributions for both the $L=0$ (zero- and two-phonon states; lowest 0^+ levels) and the $L=2$ (one- and two-phonon states; lowest 2^+ levels) transitions were observed. While no noticeable difference is apparent in the $L=0$ transitions in the present experiment, differences are observed in the (t,p) $L=2$ transfers to the first and second 2^+ states at 617 and 1312 keV (see Fig. 10). While less pronounced than those in the (p,t) work, these shape differences in the (t,p) reaction cannot be understood in terms of direct one-step distorted-wave Born-approximation calculations. As noted in the earlier (p,t) work, this difference in the shapes of the experimental angular distributions suggests the need to consider other reaction mechanisms. In (p,t) studies on other nuclei, two-step processes have been able to alter the angular distribution shape. Again, while smaller in the (t,p) case, the present data might suggest a similar requirement.

V. CONCLUSIONS

The angular distributions for 29 levels or multiplets have been extracted in the present ^{110}Cd(t,p)^{112}Cd study. Spin assignments determined from the (t,p) angular distributions for states below 2.4 MeV are in excellent agreement with those reported in the Nuclear Data Sheets. Above this excitation energy, a number of new spin assignments have been made in the present work.

Finally, phase differences in the angular distributions of the low-lying 2^+ states were observed. Similar results have been noted in earlier (p,t) studies of the Cd nuclei. As the authors of the (p,t) work stated, this difference may suggest the need for multistep processes in the reaction calculations.

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