^{114}Cd from ^{112}Cd(t,p)

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The reaction ^{112}Cd(t,p) has been used to investigate levels of ^{114}Cd up to an excitation energy of 3.7 MeV. Twenty-seven angular distributions were measured and compared with distorted-wave calculations to extract L and J^{π} information.

I. INTRODUCTION

The present work is part of a systematic investigation of the (t,p) reaction on even Cd isotopes. Data for ^{110}Cd(t,p) (Ref. 1) and ^{114}Cd(t,p) (Ref. 2) have already been published. Cross-section ratios for low-lying 0^+ states have been used[3] in a simple coexistence model[4] with mixing to estimate the magnitude of the mixing potential matrix element between intruder and normal ground state.

This paper concerns the reaction ^{112}Cd(t,p). The nucleus ^{114}Cd is well studied. The latest compilation (Ref. 5) lists 86 levels below 4.21 MeV excitation. Twenty three of them, all below 3.0 MeV, have had their J^{π} uniquely determined. For many additional levels, the possible value of J^{π} has been restricted to two or three values. A recent (n,γ) study[6] summarizes existing information and lists 81 states up to 3.46 MeV. Of these, 37 have J^{π} assignments—some of which, however, disagree with those in Ref. 5.

II. PROCEDURE AND RESULTS

A 15.0-MeV triton beam from the Penn tandem bombarded a gold-backed Cd target of approximately 85 μg/cm^2 areal density, and enriched to 98.5% in ^{112}Cd. The gold backing was nominally 100 μg/cm. Protons were detected with nuclear emulsions in a multiangle spectrograph, absorbers in the focal plane stopping all but protons. Data were collected in 7.5° steps, beginning at 3.75°. A monitor detector, placed at 40° to the beam, recorded elastically-scattered tritons and was used as a running check on the condition of the target. The gold and Cd peaks were not fully separated in the monitor spectrum, so the nominal target thickness has been used to calculate the absolute cross section scale. It should be accurate to about 15%.

A proton spectrum is displayed in Fig. 1. Resolution is about 22 keV (full width at half maximum). Impurity peaks arising from the (t,p) reaction on ^{197}Au, ^{12}C, ^{16}O, and other isotopes of cadmium were identified. For the other Cd isotopes, only the ground-state transitions are strong enough to be seen. In ^{197}Au(t,p), also, only the g.s. is strong.[7] However, the weaker excited states of ^{199}Au are strong enough to be a nuisance in extracting yields for ^{114}Cd peaks above $E_x = 2.0$ MeV. It is primarily for this reason that data points are sometimes missing for weak states.

Excitation energies from the present work are listed in Table I, where they are compared with values from the recent (n,γ) work and other literature. Our energies are in reasonable agreement—although as the excitation energy increases, the level density becomes so high that many of our groups clearly correspond to unresolved sets of states.

At least 15 peaks observed in the present work appear to correspond to single states. For those 15, the standard deviation between our excitation energies and those in Ref. 5 is 2.6 keV—quite good agreement considering that the minimum uncertainty we quote is 3.0 keV. Larger uncertainties in Table I correspond to the standard deviation of the mean excitation energy at angles for which the peak is observed. In many cases this standard deviation is as large as it is (8.6 keV in the worst case) because the peak contains two or more states with differing angular-distribution shapes. Table I also lists the maximum observed cross sections and the presently determined L values, to be discussed below.

III. ANALYSIS AND DISCUSSION

Theoretical angular distributions were calculated in distorted-wave Born approximation (DWBA) formalism, using the code DWUCK (Ref. 8) and standard optical-model parameters.[9,10] Calculations were performed for a wide variety of microscopic configurations and for a few other selected sets of optical-model parameters. These are displayed in Fig. 2 for $L = 0$ and 2. It is noted that the shapes of these angular distributions are quite stable—all the $L = 0$ curves are similar, as are all those for $L = 2$. This comparison was also made for other L values (not shown) with comparable conclusions. Hence, the remainder of the calculations were performed for pure configurations. Needless to state, theoretical 2n-transfer amplitudes are not available for the Cd nuclei.

Experimental angular distributions are displayed in Figs. 3–5. The error bars in the angular distribution figures are for the *relative* cross section only and result

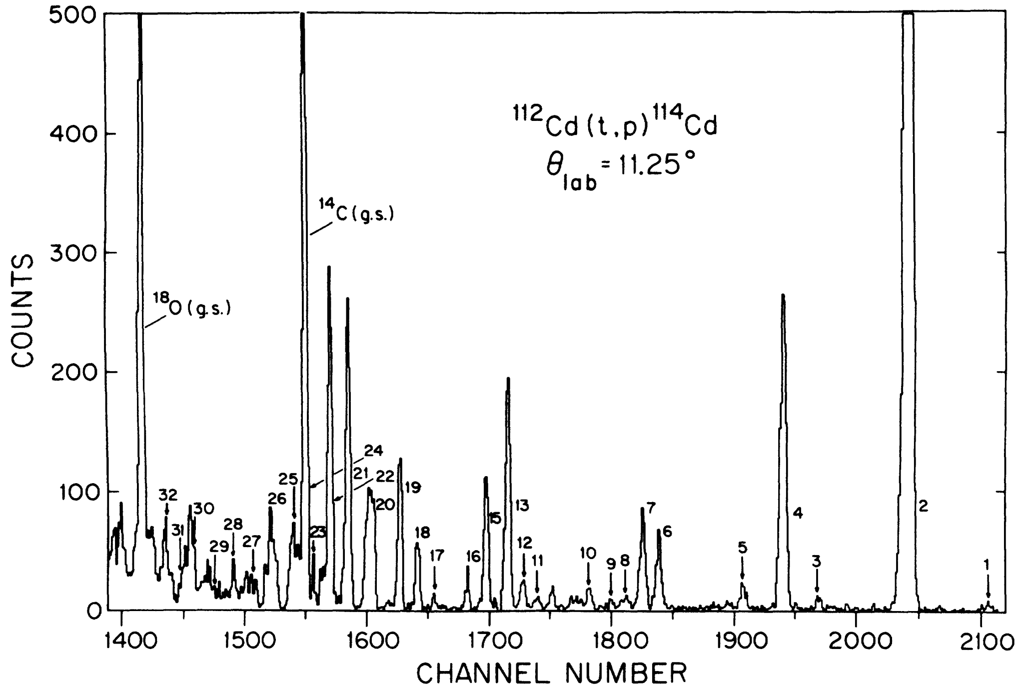

FIG. 1. Spectrum of protons from the reaction ^{112}Cd(t,p)^{114}Cd, at $E_t = 15.0$ MeV, and $\theta_{lab} = 11.25°$.

from counting statistics and/or uncertainties in separating close-lying levels. As mentioned earlier, we estimate that the *absolute* cross-section scale is accurate to 15%. For the ground state and the 2^+ level at 558 keV, we compare the data with the maximally different DWBA curves from Fig. 2. Despite the poor fit for the lowest 2^+ state [previously noted in ^{110}Cd(t,p) (Ref. 1)], the L value is obvious.

Up to an energy of 2219 keV, Ref. 6 lists 17 levels, all with their J^π known. Of these, all but one (a 4^+ state at 1932 keV) are listed in Ref. 5, and all but two others have unique J^π listed in Ref. 5. The 3^+ state at 1864.3 keV is listed in Ref. 5 as 0^+, 3^+ at 1863.6 keV; and the 2218.9-keV state has $J^\pi = 2^+$ in Ref. 6, $J^\pi = 0^+, 2^+$ in Ref. 5.

In this region of excitation, we observe 12 angular distributions, implying some levels are weak and/or part of unresolved doublets. We have already mentioned the two lowest states. The next two are 0^+ and 2^+ at 1134 keV and 1210 keV, respectively. Our results are in good agreement. The anomalous $L = 2$ shape observed in the data for the first 2^+ state does not appear to be present in most other 2^+ levels. The 0^+ state at 1134 keV is commonly thought[4,11] to be an intruder—probably the band head of a rotational band. Its (t,p) cross section is 139±7 μb/sr, i.e., 2.4% of the ground state. This value is of interest as input into an attempt[3] to assess the degree of mixing between intruder and normal states.

Our 1292-keV angular distribution undoubtedly contains contributions from two levels at 1284 and 1306 keV, with $J^\pi = 4^+$ and 0^+, respectively. However, our data are not fitted by a sum of $L = 0$ and 4. Hence, either the states are too weak for their angular distributions to be characterized by their L values, or there is also a 2^+ state present. This 0^+ level is commonly identified[4,11] as the two-phonon 0^+ state. The possible $L = 0$ contribution in our angular distribution limits $\sigma(0_3^+)$ to less than 10^{-3} of σ (g.s.).

Our next three states appear to have $L = 2$ angular distributions. Our 1368-keV level undoubtedly corresponds to the known 2^+ at 1364 keV. However, our 1736-keV state is very close to a known 4^+ at 1732 keV, and our data are not fitted by $L = 4$. Again, the cross section is quite small. Our 1784-keV level has an angular distribution similar to that of the lowest 2^+, but no state is listed near here in Refs. 5 or 6. A possible state at 1770 keV did appear in an earlier compilation.

Our 1854-keV state has a clear $L = 0$ angular distribution and probably corresponds to a known 0^+ level at 1860 keV. Nearby 2^+ (1842 keV) and 3^+ (1864 keV) states must be weakly populated.

The next two known states are at 1932 keV, $J^\pi = 4^+$ and 1958 keV, $J^\pi = 3^-$. Our 1959-keV angular distribution is characterized by $L = 3$, with perhaps a hint of a small $L = 4$ component.

Our 2^+ state at 2046 keV probably corresponds to the known 2^+ at 2048 keV. Our 2219-keV angular distribution also appears to have an $L = 2$ shape. Reference 6 lists a 2^+ state at 2219 keV.

Reference 6 lists a state at 2297 keV, with $J = 4,5,6$. Our 2301-keV angular distribution contains a large $L = 5$ component, with perhaps a small contribution from some other L value.

Our $L = 4$ state at 2390 keV is probably the known 4^+ level at 2392 keV. We see little or no evidence for the nearby 3^- at 2385 keV and 0^+ at 2438 keV.

Our 2537-keV angular distribution contains two (or three) different L values. Both $L = 0$ and 2 are clearly present, and $L = 5$ or 6 may also be contributing. States

TABLE I. Previous and present information concerning levels of ^{114}Cd.

Literature[a]			Present work		
E_x (keV)	J^{π}	Level number	E_x (keV)	σ_{max} (μb/sr)	L
0.0	0^+	2	-3.6 ± 3.0	5772 ± 289	0
558.5	2^+	4	560.5 ± 3.0	193.5 ± 9.7	2
1134.5	0^+	6	1137.1 ± 3.0	139 ± 7	0
1209.7	2^+	7	1211.2 ± 3.0	59.8 ± 3.0	2
1283.7 1305.6	4^+ 0^+	8	1291.7 ± 3.0	12 ± 1	$0+2$
1364.3	2^+	9	1368.1 ± 3.0	10 ± 1	2
1732.2	4^+	11	1736.4 ± 5.2	7.6 ± 1.0	(2)
[b]		12	1784.1 ± 4.8	16.6 ± 1.4	(2)
1841.9	2^+				
1859.7	0^+	13	1854.0 ± 3.0	321.9 ± 16.1	0
1864.3	3^+				
1932.1 1958.1	4^+ 3^-	15	1958.9 ± 3.4	101 ± 6	$3(+4)$
2048.0	2^+	16	2046.4 ± 3.2	18.7 ± 1.5	2
2152.3	4^+ [c]				
2204.6	3^+				
2218.9	2^+	17	2219.2 ± 3.0	13.7 ± 1.3	2
2296.8 2316.7[d]	4,5,6 2^+	18	2301.2 ± 3.6	71.3 ± 3.6	(5)
2384.8	3^-				
2391.5 2411.6	4^+	19	2389.5 ± 3.0	131 ± 7	$4(+0)$
2437.6	0^+				
2456.0	1^-				
2460.8	$3^-(4^-)$				
2503.4	$\geq4,3^-$				
2525.4 2535.2	2^+ $\geq4,3^-$	20	2537.3 ± 3.0	207.3 ± 10.4	$0+2(+5$ or $6)$
2553.9	0^+				
2580.4	2^-				
2636.5	$0^+(2^+)$				
2650.1	2^+	21	2657.2 ± 4.3	248.8 ± 12.4	2
2660.9	2^+				
2701.1	3^+				
2734.0 2749.3	$\geq4,3^-$ 2^+	22	2746.0 ± 3.6	209.8 ± 10.5	$2(+3)$
2756.9	$3^-,(4^-)$				
2767.8	1^-				
2771.0	≥3				
2788.5	$2^+,1^+$				
2800.0	$2^+,1^+$				
2806.6	3^+				
2812.0	2^+				
2820.2	4^+				
2828.1		23	2830.6 ± 4.8	16.0 ± 3.0	(4)
2872.8	≥3	24	2868.9 ± 4.1	63.6 ± 3.2	$4(+2)$
2901.2	$(3^+,0^+)$				
2910.3	$(0^+,2^+)$				
2915.8	≥3				
2936.1	(3^-)	25	2933.7 ± 4.5	109.2 ± 5.5	4
2943.7	$(0,1,2)^+$				
2953.3	2^+				
2957.3	$2^-,(1^-)$				
2991.8					
2999.6	1^-				
3002.2	2^+				
3024.6	≥3				
3052.9	$2^+,(1^+)$	26	3052.7 ± 5.4	243.6 ± 12.2	0

TABLE I. (*Continued.*)

Literature[a]		Present work			
E_x (keV)	J^π	Level number	E_x (keV)	σ_{max} (μb/sr)	L
3077.4	$1^+,2^+$				
3090.4	≥ 3				
3098.5	$(0\text{-}3)^+$				
3108.6	1^-				
3117.4	$(0^+,2^+)$				
3128.5	≥ 3				
3140.7	$(1^-,0^-,2^-)$	27	3142.3±6.0	66.8 ±3.3	(6 + 0)
3157.2	$1^-,(2^-)$				
3166.8	$(0\text{-}3)^+$				
3175.3	≥ 3				
3183.1	≥ 3				
3196.6	≥ 3				
3206.0	2^+				
3209.7					
3213.4	$\pi=-$				
3218.6	$1^-,(2^-)$				
3231.8	$\pi=+$				
3258.1	$1^-,2^-$	28	3253.9±6.1	41.0 ±3.0	[5 + (0)]
3260.1					
3264.8	$\pi=-$				
3285[d]	$1^+,2^+,3^+$				
3322.0	$\pi=-$	29	3342.5±8.6	39.8 ±3.0	(4)
3348[d]	$0^+,1^+$				
3365[d]					
3381[d]					
3383[d]					
3409.2	$\pi=-$				
3410[d]	$1^+,2^+,3^+$				
3446.9	$\pi=-$				
3464.2	$\pi=-$				
3461[d]	$1^+,2^+,3^+$	30	3460±5.8	47.5 ±3.0	1,(2)
3480[d]					
3499[d]					
3521[d]					
3557[d]		31	3566.2±6.4	13.2 ±3.0	(4,1)
3582[d]					
3613[d]		32	3603.8±6.9	68.0 ±3.4	(0)
3670[d]					
3690[d]					

[a]From Ref. 6 unless otherwise noted.
[b]No state listed in Refs. 5 or 6. Tentative state at 1770 was listed in an earlier compilation.
[c]Erroneously listed as 2^+ in Ref. 5.
[d]Reference 5.

with $J^\pi=2^+$ (2525 keV) and 0^+ (2554 keV) are nearby. The $L=5$ or 6 state could be the level at 2535 keV, with $J\geq 4,3^-$.

Our 2^+ angular distribution at 2657 keV probably contains both 2^+ states known at 2650 and 2661 keV.

Our 2746-keV angular distribution is dominated by $L=2$, with a possible weak $L=3$ mixture. A 2^+ state is known at 2749 keV.

The angular distribution for the weak state at 2830 keV is not characteristic of any single L value, though a tentative $L=(4)$ assignment is made. A 4^+ state is known at 2820 keV.

The 2869-keV angular distribution is dominated by $L=4$, with perhaps a small $L=2$ component. A state at 2873 keV in Ref. 2 has $J\geq 3$. The state at 2934 keV also appears to be populated with $L=4$, although the two most-forward data points are below the curve. It may be possible to produce an $L=4$ DWBA curve without a forward rise.

From its angular distribution, the 3053-keV state has $J^\pi=0^+$. No previously known state near here could have $J=0$, so our 0^+ level must be a state previously unreported. The 3142-keV angular distribution is well fitted by $L=0+6$, implying presence of states with $J^\pi=0^+$ and 6^+.

The 3254-keV state is well fitted by $L=5$ at all but the

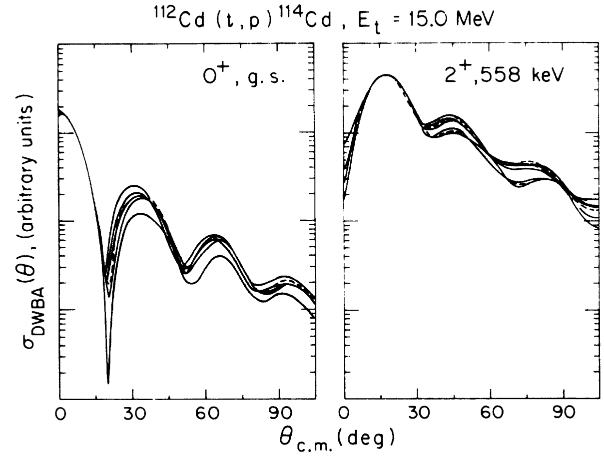

FIG. 2. Calculated DWBA curves for the g.s. and first excited state of ^{114}Cd in the reaction $^{112}Cd(t,p)$, using a variety of optical-model parameters and microscopic configurations.

most forward angle, where $L=0$ is suggested. At least four states are known to exist within the resolution width of this state, but none have known J^{π}. Our data suggest $J^{\pi}=5^-$ and (0^+) for two of them.

The 3342-keV angular distribution is not well fitted by any single L value, but $L=4$ does better than any other. Our (4^+) assignment is tentative.

The 3461-keV data appear to contain both $L=1$ and 2.

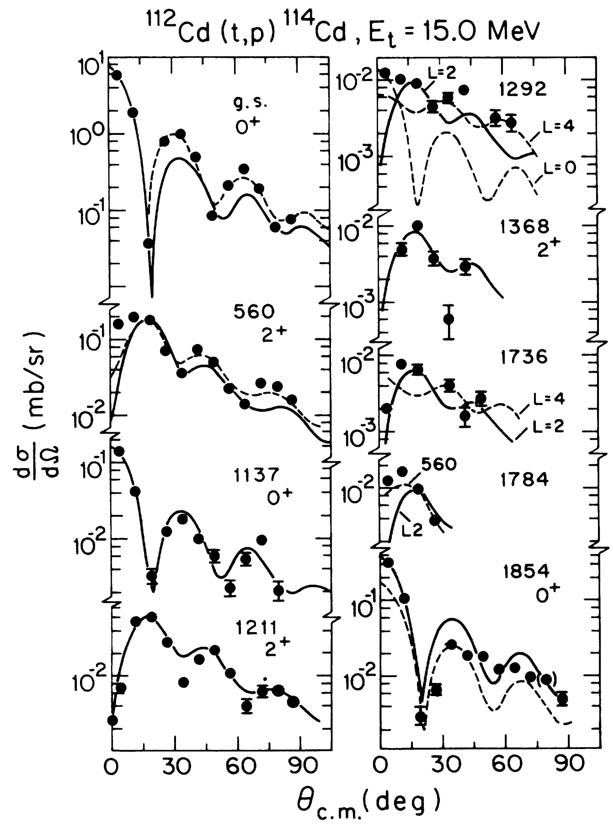

FIG. 3. Angular distributions for the reaction $^{112}Cd(t,p)$, compared with DWBA curves.

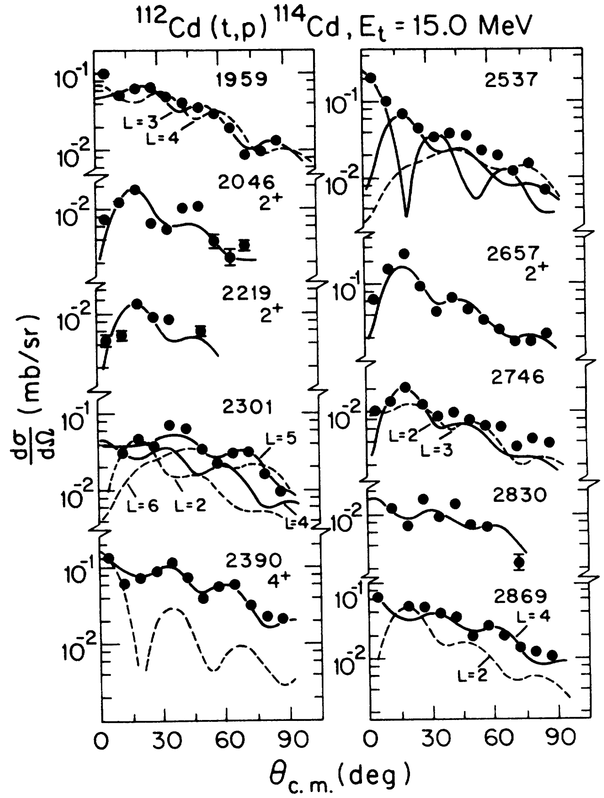

FIG. 4. Same as for Fig. 3, but $E_x=1975-2885$ keV.

The L value(s) for the 3566-keV state is not clear. The 3604-keV level appears to have $J^{\pi}=0^+$.

In summary, we have measured 27 angular distributions in the reaction $^{112}Cd(t,p)^{114}Cd$ and have compared all of them with results of DWBA calculations. Eighteen unique L assignments have been made, and several other

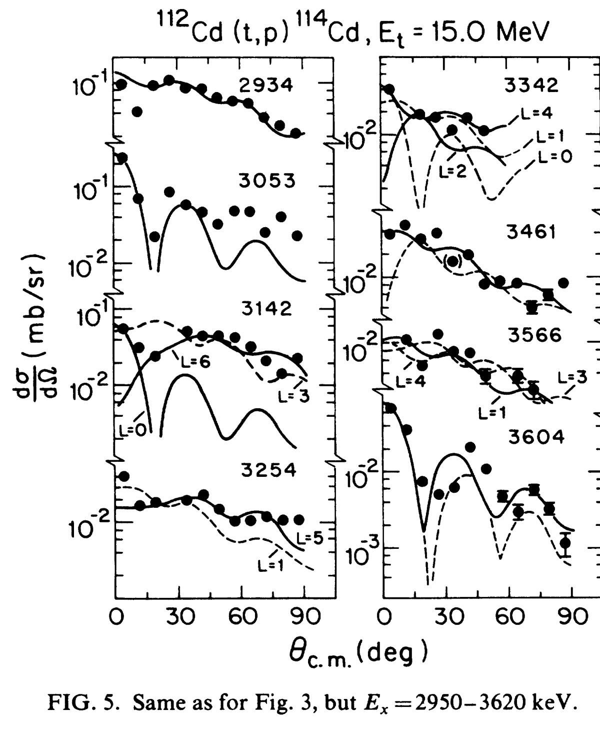

FIG. 5. Same as for Fig. 3, but $E_x=2950-3620$ keV.

possible or tentative ones. The definitiveness of the L assignment probably decreases with increasing L, but we believe they are firm for $L=0$–4, more tentative for $L=5$ and 6. Whenever the level density is low enough to compare, our energies agree well with those already known. But, above ~2.3 MeV, most of our angular distributions probably contain contributions from two or more states.

As mentioned earlier, no theoretical two-nucleon transfer amplitudes exist for this reaction. However, our measured cross sections should be useful if such amplitudes become available. The relative cross sections for low-lying 0^+ levels have already been used[3] to extract useful information. Heyde[12] has pointed out that the matrix element of 330 keV derived in Ref. 3 should be compared with the theoretical value of 0.4 MeV calculated in Ref. 4. The agreement is acceptable.

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