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Nuclear-Structure Studies with (d, p) and (d, t) Reactions on ^{106}Cd†

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Energy and angular distributions from (d,p) reactions induced by 12-MeV deuterons and (d,t) reactions induced by 16-MeV deuterons on ^{106}Cd were measured. Neutron l-transfer assignments, spin-parity assignments, and spectroscopic strengths were obtained for 25 of the 28 proton groups observed in ^{106}Cd(d,p) and for 3 of the 7 triton groups observed in ^{106}Cd-(d,t). The ground-state Q value of ^{106}Cd$(d,t)^{105}$Cd reaction was found to be -4.661 ± 0.05 MeV.

I. INTRODUCTION

The nuclear structure of Cd isotopes has been investigated previously by (p, t) and (p, d) studies on ^{111,112,113,114,116}Cd[1] and by (d,p) and (d,t) studies on ^{110,112,114,116}Cd.[2-4] Since ^{106}Cd and ^{108}Cd targets are rare, similar studies of lighter Cd isotopes have not yet been reported. This paper reports (d,p) and (d, t) studies on ^{106}Cd.

II. EXPERIMENTAL

A ^{106}Cd target was bombarded with 12- and 16-MeV deuterons from the University of Pittsburgh three stage Van de Graaff accelerator. Protons from (d,p) reactions and tritons from (d, t) reactions were magnetically analyzed and detected by photographic plates. The essentials of the magnetic analysis are discussed in Ref. 4. The (d, t) analysis was also done using position-sensitive detectors, the technique for which is described in Ref. 5.

Since the only ^{106}Cd target available was fairly thick (a self-supporting 1.24-mg/cm^2 foil) the energy resolution was 30 keV full width at half maximum (FWHM), considerably worse than usual for this type of experiment but still good enough to obtain useful data.

(d,p) measurements were made at 10 angles between 8 and 55°; (d, t) measurements were made at seven angles between 12 and 45°. The target thickness was measured by the energy loss of α particles from an ^{241}Am source. The integrated incident beam was measured with a Faraday cup and the relative product of the incident beam and the target thickness was determined by observing elastically scattered deuterons at ±38.7° with scintillation detector monitors as a cross check. The *magnet-entrance-slit solid angle* used was 1.3 msr.

The ^{106}Cd target was 85% isotopically pure. *Isotopic-contaminant peak positions* and approximate intensities were determined by using a natural Cd target, with due regard to differences in target thickness, integrated incident beam, and isotopic constituency.

Typical energy spectra of protons from ^{106}Cd(d,p) (12-MeV bombarding energy) and of tritons from ^{106}Cd(d, t) (16-MeV bombarding energy) are shown in Figs. 1 and 2, respectively. For the (d,p) measurements, stepped aluminum absorbers prevented all particles other than protons from being detected. For the (d, t) measurement with photographic plates, stepped absorbers prevented detection of particles heavier than tritons, while deuterons and protons had a magnetic rigidity too low to interfere with the reported triton peaks. Those peaks not labeled in Figs. 1 and 2 are those believed to be due to isotopic contaminants. The peak labeled ^{112}Cd(d,p) in Fig. 1 is the most clearly identified contaminant peak.

Excitation energies were determined with a precision of ±10 keV; cross sections were determined with an estimated accuracy of about 20% for well-defined peaks, and with somewhat poorer accuracy for less well-defined peaks.

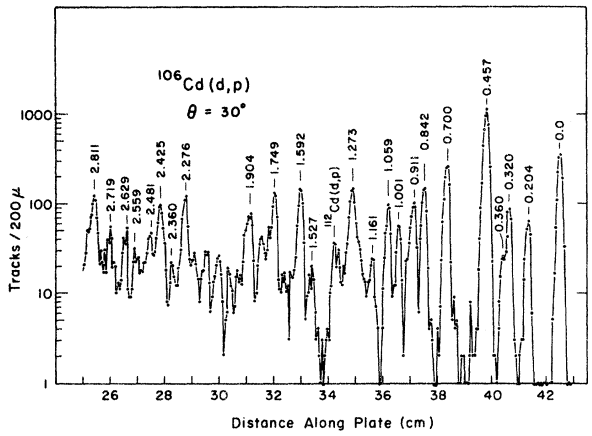

FIG. 1. Typical energy spectrum. This is energy spectrum of protons from ^{106}Cd(d,p) with protons detected at 30°. Numbers above peaks are excitation energies of corresponding levels in the residual nucleus ^{107}Cd in MeV. Unlabeled peaks are due to impurities.

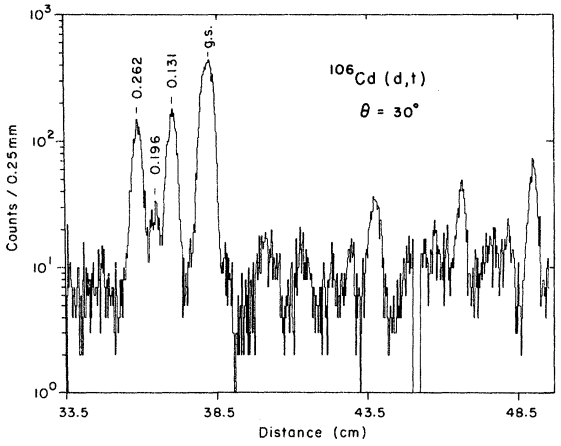

FIG. 2. Typical energy spectrum for ^{106}Cd(d,t) at a scattering angle of 30°. The numbers above the peaks are the excitation energies in MeV, of the levels in ^{105}Cd. The unlabeled peaks to the right of the ground state (g.s.) are due to heavier isotopic contaminants.

III. RESULTS AND ANALYSIS-^{106}Cd(d,p)

Some 28 proton groups were observed which are believed to be from ^{106}Cd(d,p) reactions. An additional nine proton groups observed are believed or suspected to be contaminant peaks. Quite possibly there may be some overlap of contaminant and genuine ^{106}Cd(d,p) peaks.

Figure 3 shows the angular distributions of 25 of the proton groups observed from the ^{106}Cd(d,p) reaction, grouped according to their l-value assignments. The l values were obtained from comparisons with distorted-wave Born-approximation (DWBA) calculations,[6] previous experi-

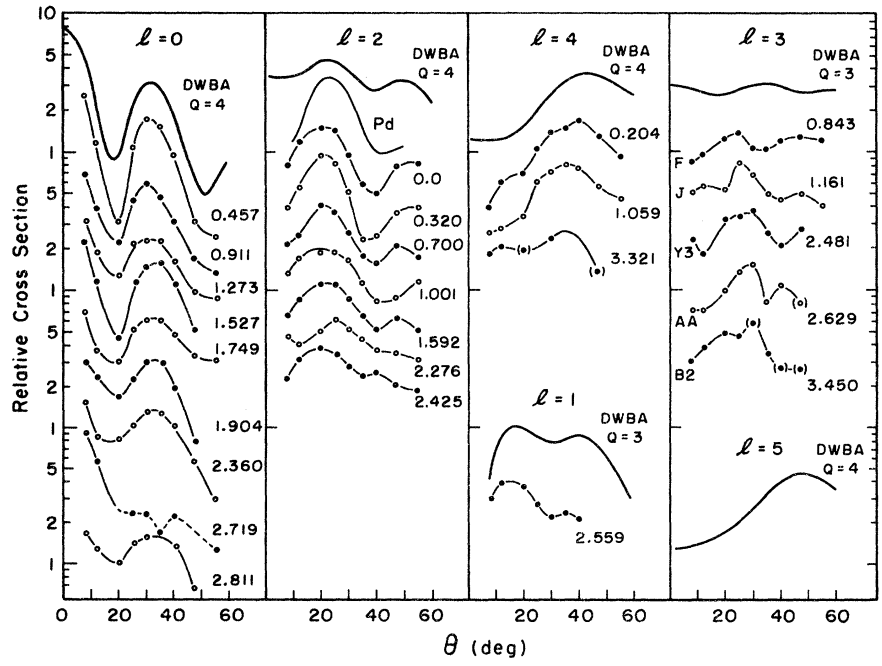

FIG. 3. Angular distributions of protons from ^{106}Cd(d,p), grouped according to l-value assignments.

TABLE I. Energy levels and spin assignments for ^{107}Cd and cross sections for the (d,p) reactions leading to them. The asterisk denotes that the value is probably a multiple peak.

Present work					Basu and Patro [a]		Reference 9, Ref. 8	
Excitation energy (MeV)	$\sigma(d,p)$ [b] (mb/sr)	l	J^π	S	Excitation energy (MeV)	J^π	Excitation energy (MeV)	J^π
0.0	1.44	2	$\frac{5}{2}^+$	0.25	0.0	$(\frac{5}{2}^+)$ [c]	0.0	$\frac{5}{2}^+$
0.204	0.24	4	$\frac{7}{2}^+$	0.40	0.220	$(\frac{7}{2}^+)$ [c]	0.2050	$(\frac{7}{2}^+)$
0.320	0.45	2	$\frac{3}{2}^+(\frac{5}{2}^+)$	0.14	0.320		0.3209	$(\frac{7}{2},\frac{9}{2})$
0.360	~0.1						0.3656	$(\leq\frac{5}{2})$
0.457	3.18	0	$\frac{1}{2}^+$	0.46			≈0.41	$(\frac{1}{2}^+)$
0.700	1.18	2	$\frac{3}{2}^+(\frac{5}{2}^+)$	0.35			≈0.68	$(\frac{3}{2}^+)$
0.843	0.53	3(?)	$(\frac{7}{2}^-)$	0.086				
0.911	0.33	0	$\frac{1}{2}^+$	0.046			(0.9215)	$(\frac{7}{2},\frac{9}{2})$
1.001	0.19	2	$\frac{3}{2}^+(\frac{5}{2}^+)$	0.054				
1.059	0.34	4	$\frac{7}{2}^+$	0.47	1.040			
1.161	0.10	3(?)	$(\frac{7}{2}^-)$	0.016				
*1.273	0.60	0	$\frac{1}{2}^+$	0.083	1.260		(1.2684)	$(\frac{7}{2}^+,\frac{9}{2}^+)$
*1.527	0.64	0	$\frac{1}{2}^+$	0.0086				
1.592	0.57	2	$\frac{3}{2}^+(\frac{5}{2}^+)$	0.15			(1.574, 1.6030)	(–), $(\frac{7}{2},\frac{9}{2})$
*1.749	0.48	0	$\frac{1}{2}^+$	0.063	1.800			
1.904	0.34	0	$\frac{1}{2}^+$	0.044			(1.9220)	$(\frac{7}{2}^+,\frac{9}{2}^+)$
2.276	0.42	(2)	$\frac{3}{2}^+(\frac{5}{2}^+)$	0.096	2.260		(2.2640, 2.2860)	$(\frac{1}{2}^+,\frac{9}{2}^+)$ $(\frac{7}{2}^+,\frac{9}{2}^+)$
2.360	~0.6	0	$\frac{1}{2}^+$	~0.075			(2.3754)	···
2.425	0.49	2	$\frac{3}{2}^+(\frac{5}{2}^+)$	0.108				
2.481	0.19	3(?)	$(\frac{7}{2}^-)$	0.027			(2.471)	···
2.559	0.21	1	$\frac{3}{2}^-$	0.012	2.580			
2.629	0.14	3(?)	$(\frac{7}{2}^-)$	0.019				
2.719	0.13	(0)	$(\frac{1}{2}^+)$	0.016			(2.7180)	$(\frac{7}{2}^+,\frac{9}{2}^+)$
2.811	0.53	(0)	$(\frac{1}{2}^+)$	0.065	2.860		(2.8160)	$(\frac{7}{2}^+,\frac{9}{2}^+)$
3.321	0.17	4(3)	$\frac{7}{2}^+(\frac{7}{2}^-)$	0.175(0.023)				
*3.383	0.33							
3.450	0.25	3(?)	$(\frac{7}{2}^-)$	0.032				
*3.516	~0.3							

[a] Nucl. Phys. 46, 59 (1963), ^{107}In→ ^{107}Cd + $\beta^+ + \nu$ studies.
[b] At first maximum past $\theta = 10°$.
[c] From logft and shell-model arguments (Ref. a).

ence,[4,7] and a known state of ^{107}Cd. Representative DWBA angular distributions and a previously[4,7] measured $l=2$ transfer (d,p) angular distribution are included in Fig. 3. The ground-state spin-parity of the ^{107}Cd nucleus is known (by optical double resonance)[8] to be $\frac{5}{2}^+$, which means its l transfer for formation by ^{106}Cd(d,p) is known to be $l=2$. The experimental $l=2$ angular distributions for ^{106}Cd(d,p) are more sharply peaked than predicted by DWBA claculations, as was noticed previously for (d,p) reactions with Pd and other Cd isotope targets.[4,7] The $l=3$ assignments are not very definite; they were made largely because other l values could not very well be assigned. The other l assignments are regarded as fairly definite except for the 2.276- (probably $l=2$) and the 3.321-MeV level (probably $l=4$, possibly $l=3$).

TABLE II. Previously reported (Refs. 8 and 9) energy levels not seen in present work.

Excitation energy (MeV)	J^π	Possible reason for not observing
0.5054	$(\frac{7}{2}, \frac{9}{2})$	
0.8090	$(\frac{7}{2}, \frac{9}{2})$	
0.9331	$(\frac{9}{2}, \frac{11}{2})$	Overlaps isotopic contaminant
1.3777	$(\frac{7}{2}, \frac{9}{2})$	Overlaps isotopic contaminant
1.4040	$(\frac{7}{2}, \frac{9}{2})$	Overlaps isotopic contaminant
1.6500	...	Overlaps isotopic contaminant
1.7777	$(\frac{7}{2}^+, \frac{9}{2}^+)$	Overlaps isotopic contaminant
1.8190	$(\frac{7}{2}, \frac{9}{2})$	Overlaps isotopic contaminant
1.8300	$(\frac{7}{2}, \frac{9}{2})$	Overlaps isotopic contaminant
1.8770	$(\frac{7}{2}^+, \frac{9}{2}^+)$	
1.9570	$(\frac{7}{2}, \frac{9}{2})$	Overlaps isotopic contaminant
2.0067	$(\frac{7}{2}^+, \frac{9}{2}^+)$	Overlaps isotopic contaminant
2.0470	$(\frac{7}{2}^+, \frac{9}{2}^+)$	Overlaps isotopic contaminant
2.0645	$(\frac{7}{2}^+, \frac{9}{2}^+)$	Overlaps isotopic contaminant
2.1840	$(\frac{7}{2}^+, \frac{9}{2}^+)$	Overlaps isotopic contaminant
2.2520	$(\frac{7}{2}, \frac{9}{2})$	Overlaps isotopic contaminant
2.3050	$(\frac{7}{2}^+, \frac{9}{2}^+)$	Resolution
2.4065	$(\frac{7}{2}^+, \frac{9}{2}^+)$	
2.5865	$(\frac{7}{2}^+, \frac{9}{2}^+)$	
2.6540	$(\frac{7}{2}^+, \frac{9}{2}^+)$	
2.6660	$(\frac{7}{2}^+, \frac{9}{2}^+)$	
2.6820	$(\frac{7}{2}^+, \frac{9}{2}^+)$	
2.7015	$(\frac{7}{2}^+, \frac{9}{2}^+)$	
2.7845	$(\frac{7}{2}^+, \frac{9}{2}^+)$	
2.863	...	
2.8750	$(\frac{7}{2}^+, \frac{9}{2}^+)$	
2.9860	$(\frac{7}{2}^+, \frac{9}{2}^+)$	

Table I lists the excitation energies, cross sections, l assignments, spin-parity assignments, and spectroscopic factors for the observed ^{107}Cd levels and comparisons with previous data. As is indicated, several of the levels are in all likelihood unresolved multiplets. For three of these probable multiplets one l value predominated. The three levels for which no l assignments are given were resolved sufficiently to be consistently observed, but not enough to obtain reliable angular distributions. The spin-parity assignments were made with the assistance of the shell model, which predicts that the ^{107}Cd levels populated in ^{106}Cd(d,p) are $2d_{5/2}$, $1g_{7/2}$, $3s_{1/2}$, $1h_{11/2}$, $2d_{3/2}$, $2f_{7/2}$, and $3p_{3/2}$. It was assumed that $l=0$, 1, 3, and 4 levels have spin-parity $J^\pi=\frac{1}{2}^+$, $\frac{3}{2}^-$, $\frac{7}{2}^-$, and $\frac{7}{2}^+$, respectively. No $l=5$ levels were observed. Levels with $l=2$ were assigned $J^\pi=\frac{3}{2}^+$ except for the ground state, which is known to have $J^\pi=\frac{5}{2}^+$,[8] because of sum-rule arguments which will be discussed below. The spectroscopic factors were obtained

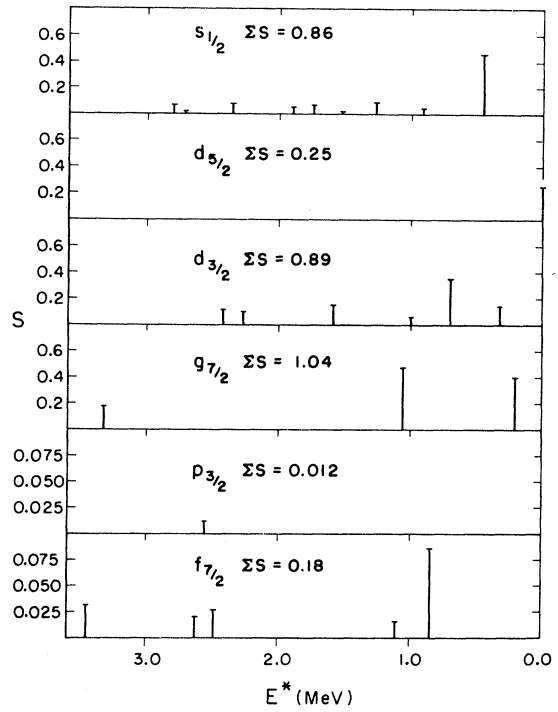

FIG. 4. Spectroscopic factors vs excitation energies for the various single-particle states.

from the relationship

$$\frac{d\sigma}{d\Omega} = 1.5\ (2J+1)\, S\sigma_{\mathrm{DWBA}} \quad \text{(even-even target)}, \tag{1}$$

where σ_{DWBA} is the (d,p) cross section calculated with code JULIE.[6] S was calculated from (1) at the first peak in the angular distribution past 10°.

The previous data compared with that reported here were obtained from studies of the β decay of ^{107}In to ^{107}Cd. Not all of the levels reported in Refs. 8 and 9 were seen in the work reported here, and those levels are listed in Table II along with possible reasons for not being seen. Of the 44 levels reported in Refs. 8 and 9, the first six are seen in this work and another 11 levels have energies close enough to levels reported here to be tentatively identified with them. Of the first six levels, there is one discrepancy in J^π: The 0.320-MeV level reported here has a definite $l=2$ angular distribution which implies a J^π of $\frac{3}{2}^+$ or $\frac{5}{2}^+$, while the 0.3209-MeV level reported in Refs. 8 and 9 is tentatively assigned a J of $\frac{7}{2}$ or $\frac{9}{2}$ from logft arguments. The fifth and sixth levels, reported in Ref. 8 as expected from isobaric analog resonance data, were observed at approximately the expected excitation energies, with the expected J^π's. 11 more previously observed levels are tentatively identified as nine of the levels reported here (two of which are double if this identification is correct, but these two are not obviously multiple experimentally) on the basis of similar excitation energies. Of these nine there are six disagreements of J^π assignments, and the remaining three are not definitely in agreement since J^π's were not previously assigned. Of the 27 previously reported levels not seen in this work, 13 are at excitation energies where isotopic contaminant peaks posed considerable problems and at least one is at an excitation energy where the poor energy resolution could explain its nonappearance. 13 of the levels reported here were not reported in Ref. 8 or 9.

TABLE III. Sum of spectroscopic factors $\sum S$; single-particle state energies E_j. Numbers in parentheses apply if 3.321-MeV level is $l=3$ instead of $l=4$.

Single-particle state nlj	$\sum S$	E_j (MeV)
$3s_{1/2}$	0.86	1.13
$2d_{5/2}$	0.25	0.0
$2d_{3/2}$	0.89	1.18
$1g_{7/2}$	1.04(0.86)	1.11(0.67)
$3p_{3/2}$	0.012	
$2f_{7/2}$	0.18(0.20)	

Since ^{106}Cd(d,p) preferentially forms low l states of ^{107}Cd and has small cross sections for forming $l \geq 4$ states, while the β decay of ^{107}In (ground state $J^\pi = \frac{9}{2}^+$) preferentially forms high l states of ^{107}Cd, it is perhaps not surprising that different states are observed in the two processes. Probably, the six apparent discrepancies at higher excitation energy are cases involving coincidentally close levels which are either unresolved in this work and/or the higher l state is too weakly formed by (d,p) to be readily detected in this work. The levels listed in Table II are perhaps too weakly formed by (d,p) to be readily detected by (d,p) measurements, particularly in those parts of the spectra where isotopic contaminants pose difficulties. It is difficult to see why the $l=4$ level with excitation energy 1.059 MeV was not observed in the work reported in Ref. 9; a 1.04-MeV level was reported considerably earlier by Basu and Patro. Their work involved the study of ^{107}In β decay with NaI detectors, which have poor energy resolution, so possibly this is the 1.059-MeV level reported here. To summarize the comparison of the 28 levels reported here and the 44 levels reported in Refs. 8 and 9, probably only the first six of each are the same levels with the only discrepancy in J^π that of the 0.320-MeV level.

Figure 4 shows spectroscopic factors vs excitation energies for the various single-particle states. Table III shows the sums of spectroscopic factors and single-particle state energies E_j, obtained by finding the "center of gravity" of all levels belonging to a given single-particle state, where each level is weighted by its spectroscopic factor.

TABLE IV. Energy levels and spin assignments for ^{105}Cd and cross sections for the (d,t) reactions leading to them. The asterisk indicates data using position-sensitive detectors.

Excitation energy (MeV)	$\sigma(d,t)$ (mb/sr)	l	J^π	S
0.0	0.870	2	$\frac{5}{2}^+$	1.54
0.131	0.176	4	$\frac{7}{2}^+$	4.69
0.196	0.036[a]	...	...	
0.262	0.215	2	$\frac{3}{2}^+$	0.50
0.759 ± 0.1*	...	...	...	...
0.867 ± 0.1*	...	...	...	...
0.940 ± 0.1*	...	...	...	...

[a] Calculated at 20°.

As was mentioned above, the spin assignments for the $l=2$ levels were made because of sum-rule arguments, with the assistance of the shell model and the knowledge of the ground-state spin. From previous work with Pd(d,p) and Cd(d,p)[4,7] it was expected that the sum of spectroscopic factors be about 0.25 for $d_{5/2}$ levels and about 0.8 for $d_{3/2}$ levels populated by ^{106}Cd(d,p). From the shell model one expects the $d_{5/2}$ single-particle energy to be lower than the $d_{3/2}$ energy. The ground state is known to have $J^\pi = \frac{5}{2}^+$ [8] and its spectroscopic factor is 0.25, so the remaining states were tentatively assigned $J^\pi = \frac{3}{2}^+$ which resulted in a sum of spectrographic factors for $d_{3/2}$ of 0.89. It is possible that one of the six levels assigned $J^\pi = \frac{3}{2}^+$ is $\frac{5}{2}^+$.

The $g_{7/2}$ total spectroscopic strength is close to unity while no $h_{11/2}$ levels were observed. An $h_{11/2}$ level with a spectroscopic strength near unity would be about 3 to 4 times as intense as the 0.204-MeV level at 40 to 50° and would have an angular distribution peaked at between 46 and 52°, depending on excitation energy. An $l=5$ ^{106}Cd(d,p) angular distribution calculated in the DWBA is shown in Fig. 3, although no experimental $l=5$ angular distributions were observed. While a case might be made that the 0.204-MeV level is an $h_{11/2}$ level, this is highly unlikely because if it were, it would be an isomeric state, which it is not.[8] While an $h_{11/2}$ level with a small spectroscopic factor could have easily been missed, it is unlikely that one with a large spectroscopic factor was missed. The absence of $h_{11/2}$ spectroscopic strength and presence of considerable $g_{7/2}$ spectroscopic strength in ^{106}Cd(d,p) is another example of the $g_{7/2}$-$h_{11/2}$ anomaly observed in (d,p) reactions with Pd, Cd, and In targets and discussed at length previously.[10]

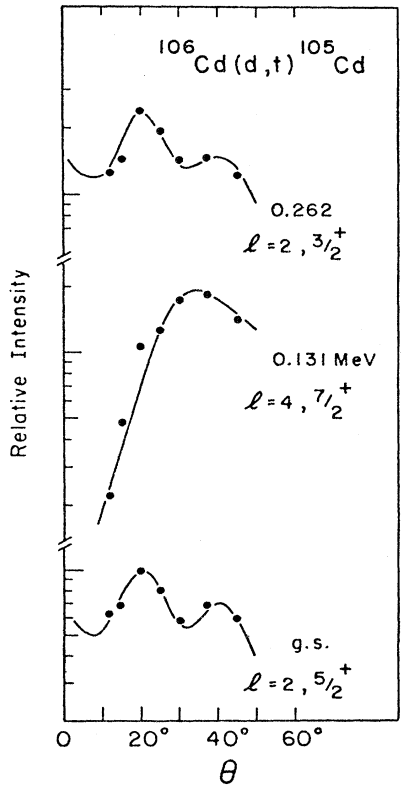

FIG. 5. Angular distributions of tritons from ^{106}Cd(d,t).

IV. RESULTS AND ANALYSIS-^{106}Cd(d,t)

A typical spectrum from ^{106}Cd$(d,t)^{105}$ reaction is shown in Fig. 2. The unlabeled peaks to the right of the peak marked g.s. are due to isotopic contaminants whose Q values for (d,t) are less negative. Some of these peaks were identified as due to ^{110}Cd(d,t) by taking a ^{110}Cd(d,t) spectrum and comparing with the ^{106}Cd(d,t) data.

Figure 5 shows the angular distributions for the three levels marked g.s., 0.131, and 0.262 MeV, respectively, fitted to the calculated angular distributions obtained from the DWBA code JULIE.[6] The ground-state angular distribution agrees with an l assignment of 2 and spin-parity assignment of $\frac{5}{2}^+$. Assistance of the shell model was used in assigning the spin-parities to the observed levels. The spin-parity assignment of the ground state agrees with that reported in earlier work.[11] The angular distribution for the peak labeled 0.196 MeV is not shown since the peak was weakly excited and it was not cleanly separable from the others at all angles. The useful range for the detection of tritons is small in this case on account of the large negative Q value (and hence, interference from deuterons). An attempt was made to study higher excitation energies by using position-sensitive detectors thus eliminating deuteron interference. At least three triton groups were observed. Energy calibration of the detectors was done by using elastically scattered deuterons of known energy. The data, however, had poor resolution and the only information extractable was the excitation energies. It is rather surprising that the $l=0$, $J^\pi = \frac{1}{2}^+$ state was not observed. However, there was an indication of a fairly strong peak very close to the deuteron elastic, but not separable from it.

Table IV shows the excitation energies, cross sections, l assignments, spin-parity assignments, and spectroscopic factors for the observed levels of ^{105}Cd. The spectroscopic factors S were obtained from

$$\frac{d\sigma}{d\Omega}(d,t) = 3.33\, S\sigma_{\mathrm{DWBA}} \quad \text{(even-even target)}, \quad (2)$$

where σ_{DWBA} is the (d,t) cross section calculated from the code JULIE.[6] Triton optical-model parameters were obtained from Ref. 12. A real-well radius of $1.16A^{1/3}$ fm was used. The spectroscopic factors were evaluated at the first peak in the angular distribution beyond 12°.

The previously known ground-state Q value for the ^{106}Cd(d,t) reaction was -4.670 ± 0.10 MeV.[13] From the present work we were able to establish the Q value as -4.661 ± 0.05 MeV.

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Gamma Decay of Excited States in ^{210}Bi and an Interpretation with the Shell Model

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The γ decay of excited states in ^{210}Bi up to 3250-keV excitation energy has been studied with the ^{209}Bi$(d,p\gamma)$ reaction at 8.0- and 10.0-MeV incident deuteron energies, using particle-γ and γ-γ coincidence techniques and a pulsed deuteron beam. For almost all of the states excited in this reaction, γ-decay branching ratios were obtained. The branched decay of states with a dominant configuration $(d_{5/2}^{\nu}\otimes h_{9/2}^{\pi})$ into states with a $(g_{9/2}^{\nu}\otimes h_{9/2}^{\pi})$ configuration was analyzed to determine experimentally the amount of configuration mixing between these two multiplets. The obtained mixing amplitudes are in remarkably good agreement with shell-model calculations. From the observed lifetimes of the $(g_{9/2}^{\nu}\otimes h_{9/2}^{\pi})_{5^-,7^-}$ states, a reduced matrix element of $\langle g_{9/2}^{\nu}\|E2\|g_{9/2}^{\nu}\rangle=-38\pm4\ e\,\mathrm{fm}^2$ has been extracted. This value is in good agreement with an intermediate coupling calculation which yields $-35\ e\,\mathrm{fm}^2$.

I. INTRODUCTION

The shell-model interpretation of the low-lying excited states of ^{210}Bi as states resulting from the coupling of one proton and one neutron to the inert core of the doubly magic nucleus ^{208}Pb has been the subject of various experimental[1-6] and theoretical[7-9] studies. The nucleus ^{210}Bi is of special theoretical interest since the simple two-particle character of the excited states provides an excellent example for studying the effective nucleon-nucleon interaction. Several shell-model calculations[7-9] have been performed to understand the spectrum of the excited states of ^{210}Bi in terms of two-particle multiplets. All calculations showed the necessity of introducing tensor forces besides the usual central forces. A remarkable result of these calculations is the prediction of generally very pure wave functions of the states with appreciable configuration mixing only in special cases.

The first high-resolution studies on the levels of ^{210}Bi have been made in 1962 by Erskine, Buechner, and Enge[1] who measured with a spectrograph angular distributions for the protons emitted in the ^{209}Bi(d,p) reaction. They showed that the first 10 levels excited in this reaction can be interpreted as the members of the $(g_{9/2}^{\nu}\otimes h_{9/2}^{\pi})_{0^-,\ldots,9^-}$ multiplet. In recent experi-