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^{108,106}Pd(p, t) reactions and the core-coupling model*

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The ^{108,106}Pd$(p,t)^{106,104}$Pd reactions were studied at 30 MeV proton energies using a quadrupole-dipole-dipole-dipole spectrograph together with a 60 cm wire proportional counter backed by a plastic scintillator. Closely spaced multiplets of states in ^{104}Pd of special interest were investigated at 5 keV energy resolution with a 5 cm solid state position sensitive detector. The (p,t) strength for population of levels in the even Pd isotopes is found to be close to the corresponding summed strength previously found for population of the core-coupled multiplets in the silver isotopes, a result in accord with a prediction of the weak coupling model.

[NUCLEAR REACTIONS ^{106,108}Pd(p,t), $E_p=30$ MeV, measured $\sigma(\theta)$ and level energies, DWBA analysis, deduced L, J^π. Enriched targets, 13 keV resolution, 5 keV for some multiplets.]

INTRODUCTION

In recent (p,t) reaction studies of the odd-A isotopes ^{107,105}Ag [1] and ^{101}Rh [2] doublets and singlets were selectively excited and interpreted as arising from coupling of the $2p_{1/2}$ proton to collective states in the corresponding even-even core nuclei. The $\frac{3}{2}^-$, $\frac{5}{2}^-$ doublets at approximately 500 keV associated with the one phonon excitation were populated with reasonable strength. States at about 900 keV, associated with the 2^+ and 4^+ members of the two phonon triplet were also identified. Nearby states tentatively assigned as the $\frac{1}{2}^-$ members of the two phonon quintet were very weakly populated. Strong doublets at about 2.2 MeV were associated with the coupling to the 3^- octupole vibration.

The even-even Pd nuclei, which may be taken as the cores of the Ag isotopes have not been previously investigated by (p, t) reactions at this proton energy. We have undertaken a study of the ^{108,106}Pd$(p, t)^{106,104}$Pd reactions in order to compare the reaction cross sections of corresponding levels in these odd and even nuclei.

EXPERIMENT

In this investigation the experimental procedures were similar to those of our previous study[1] of the odd-A silver isotopes. The ^{108}Pd target was prepared from 98% isotopically enriched Pd metal evaporated onto a 20 μg/cm^2 carbon backing. The ^{108}Pd thickness was 250 μg/cm^2. The ^{106}Pd target was also 250 μg/cm^2 thick and prepared from 96% enriched material.

The experiment was performed at a proton energy of 29.7 MeV; the triton spectra were recorded with the Princeton quadrupole-dipole-dipole-dipole (QDDD) spectrograph. The 60 cm wire proportional counter used was not capable of covering the whole energy range of interest (~3 MeV) simultaneously. Therefore, three overlapping sections of the spectra were recorded at different QDDD field settings. Examples of these spectra are shown in Figs. 1 and 2. The energy resolution obtained [full width at half maximum (FWHM) = 13 keV] was mainly limited by the target thickness.

For both nuclei data were taken at eight different angles (11°, 15°, 20°, 30°, 35°, 40°, 45°, 50°). Peak areas and relative energies were determined by the computer code AUTOFIT.[3] Level energies were derived at all angles investigated by first calibrating the QDDD focal plane using the energies of previously known levels in these Pd isotopes furnished mainly by γ spectroscopic studies.[4,5] Energies for new levels were determined for each angle; the averaged value is reported below. Relative cross sections were derived from the peak areas by normalizing the data taken at different angles and QDDD field settings to the measured charge collected during the run. Absolute cross sections were derived by normalizing the ground state intensity to elastic scattering data obtained from a separate scattering chamber experiment. Errors in the relative cross sections are almost entirely statistical. This is ±10% for the smallest analyzed peak and is typically ~±3% for most peaks of interest. The errors in absolute cross sections are larger; these errors are due primarily to the uncertainty of the target thickness as measured in the elastic scattering experiment. Absolute cross section errors are ~±15% and constant for a given reaction for all measured intensities. The angular distributions are shown in Figs. 3 and 4. Due to overlaps of spectra some of the cross sections have been determined twice; these values

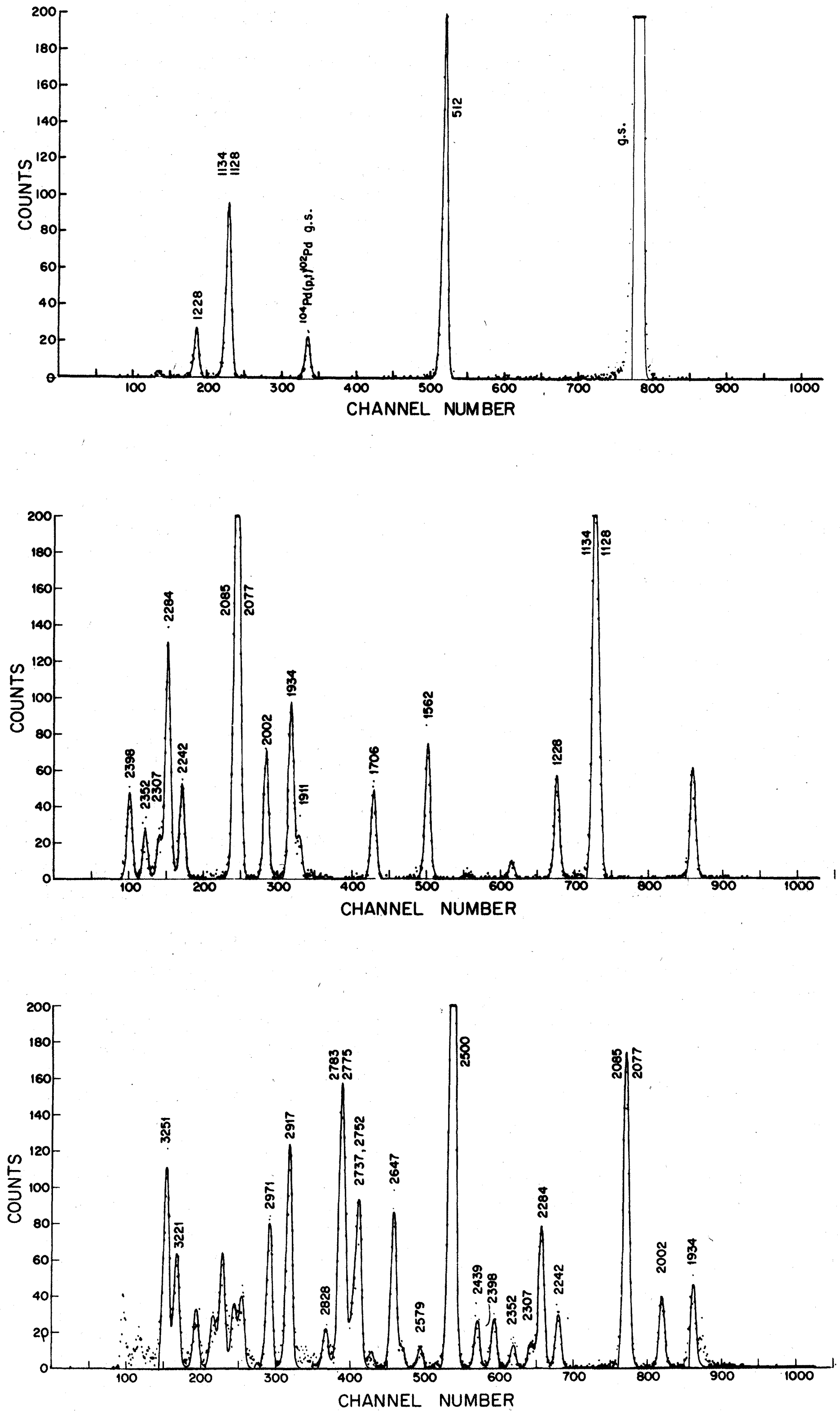

FIG. 1. ^{108}Pd$(p,t)^{106}$Pd triton spectra. $\theta_{c.m.}=15°$.

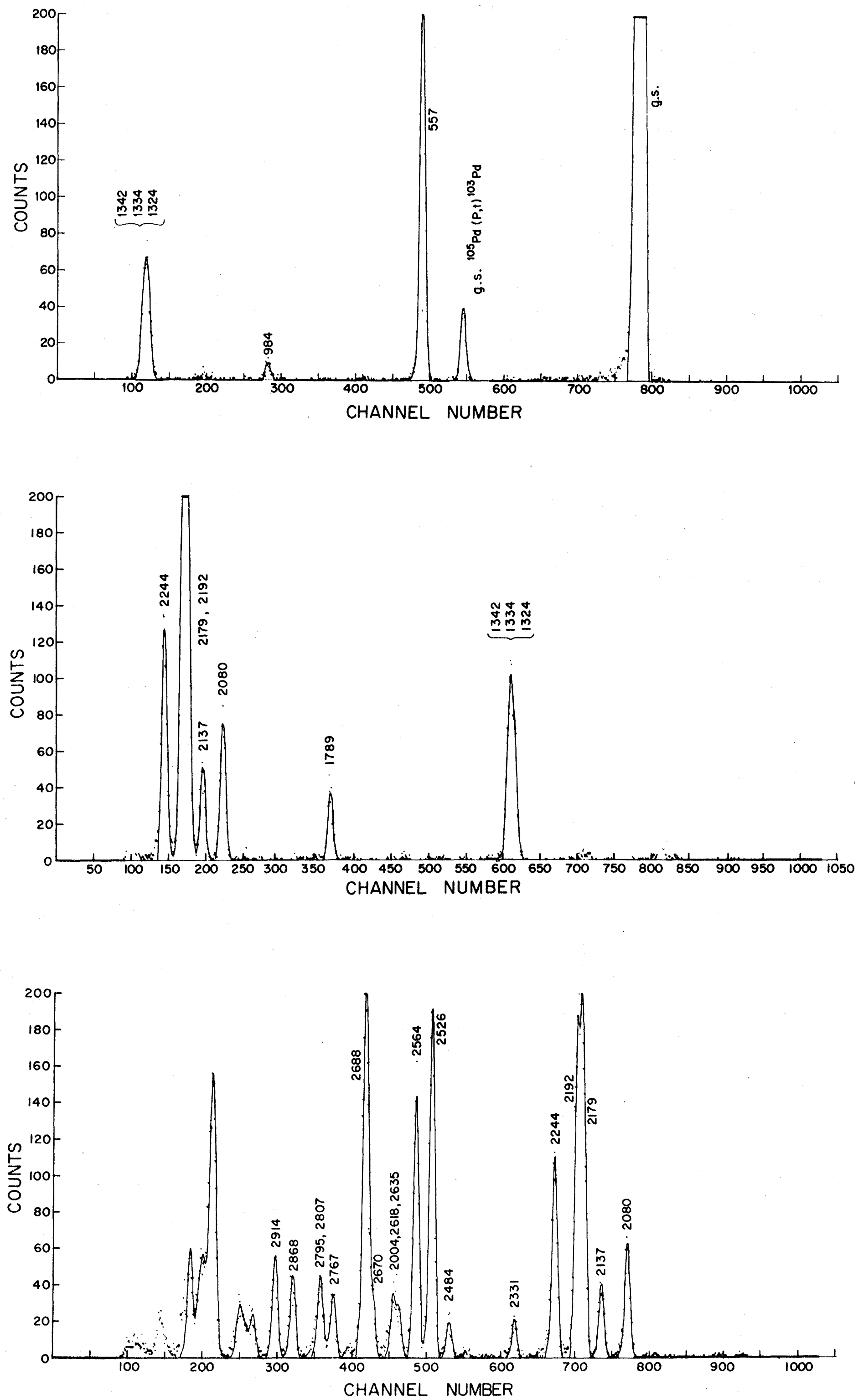

FIG. 2. ^{106}Pd$(p,t)^{104}$Pd triton spectra. $\theta_{c.m.} = 15°$.

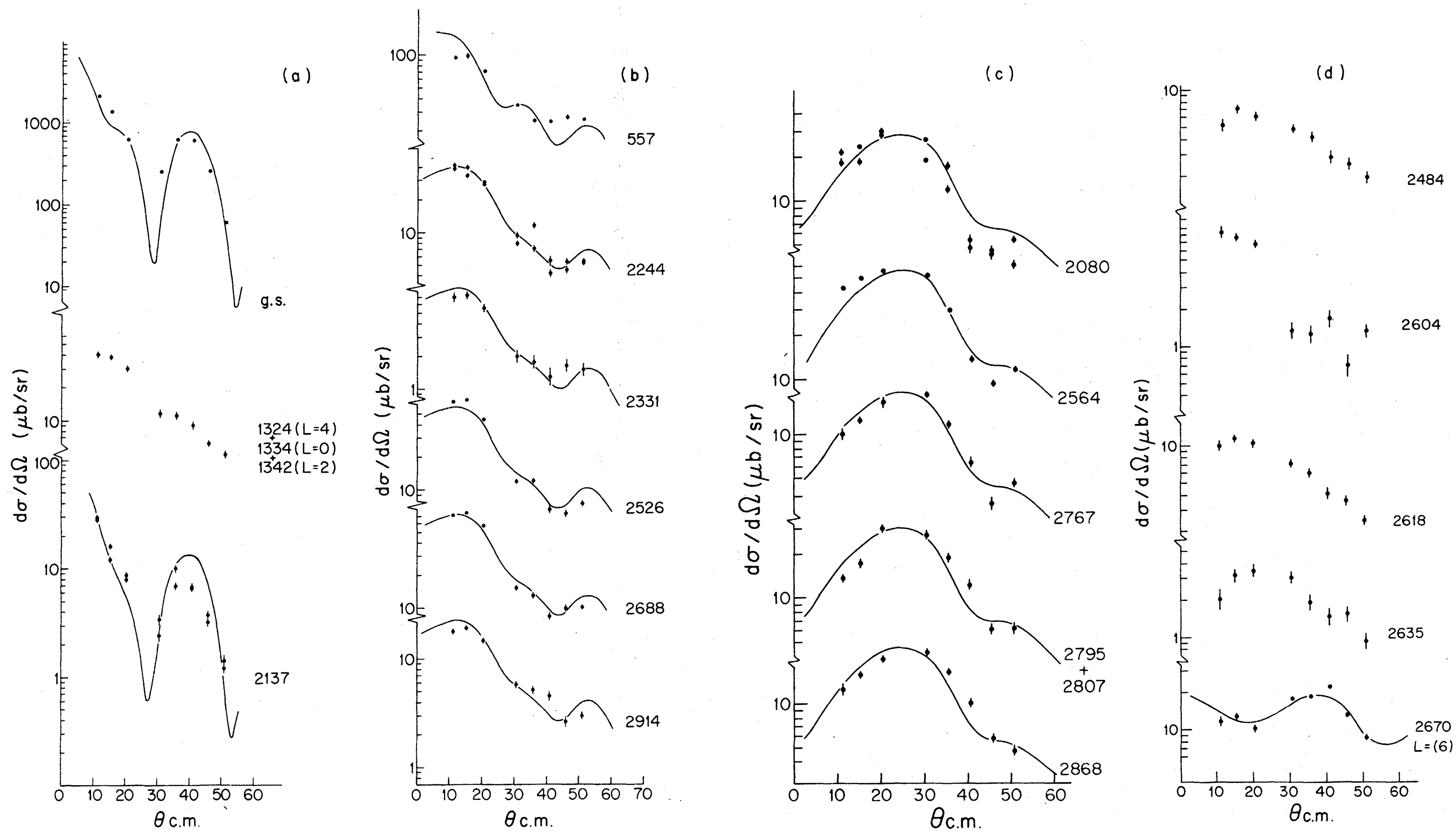

FIG. 3. ^{106}Pd$(p,t)^{104}$Pd angular distributions. The solid lines are DWBA calculations (a) $L=0$, (b) $L=2$, (c) $L=3$ and $L=4$ (d) $L=(6)$ and uncertain.

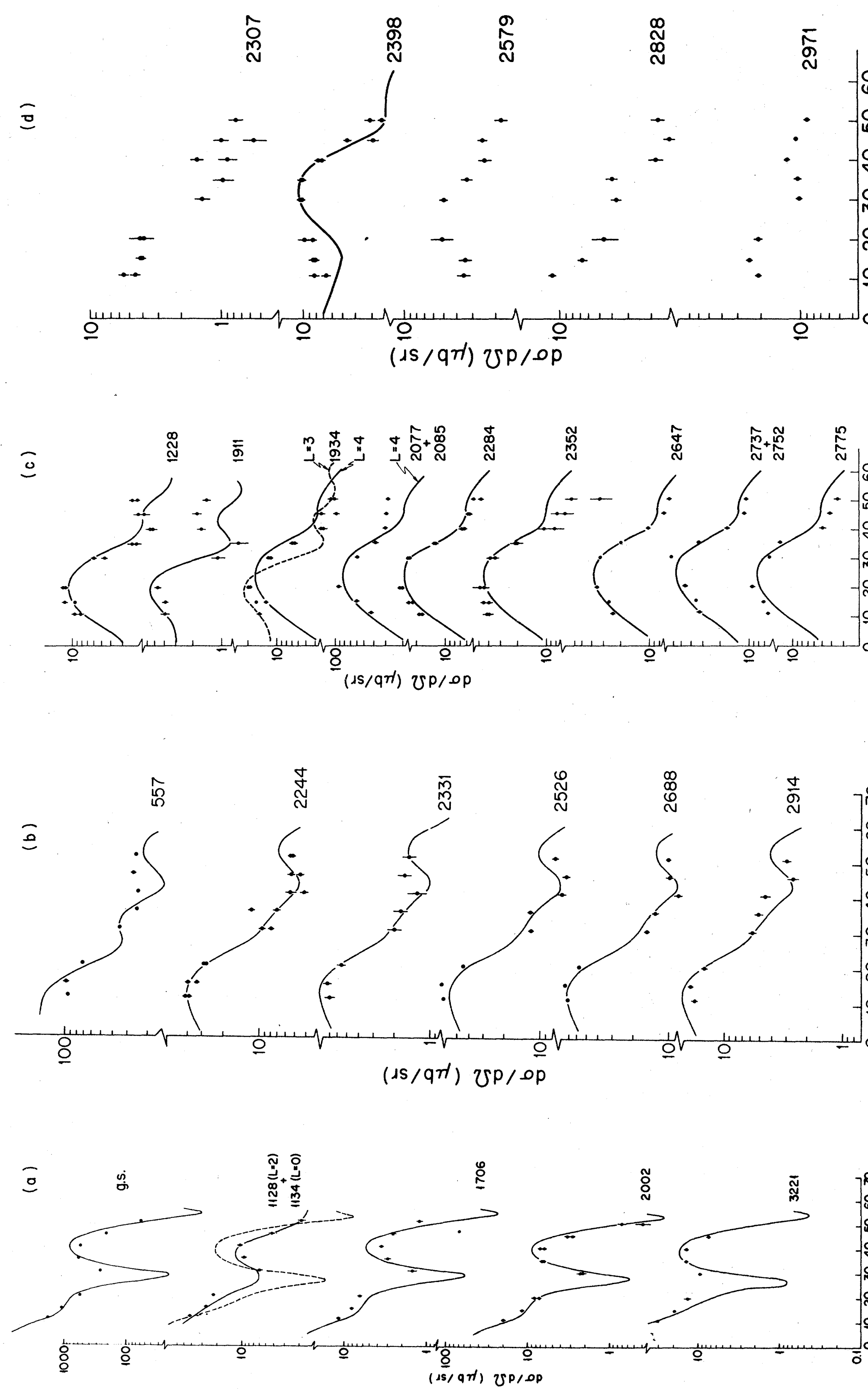

FIG. 4. ^{108}Pd$(p,t)^{106}$Pd angular distributions. The solid lines are DWBA curves (a) $L=0$, (b) $L=2$, (c) $L=3$ and $L=4$, (d) $L=(5)$ and uncertain.

are consistent within statistics. The error bars represent statistical errors only including uncertainties associated with the numerical resolution of overlapping peaks. The solid lines are the distorted wave Born approximation (DWBA) fits using the same DWBA calculations reported in our previous Rh and Ag investigations.[1,2] Effects of averaging over the 5° acceptance angle of the QDDD aperture have been included. The energies, cross sections at 20°, and deduced L-transfer values are listed in Tables I and II.

With the 13 keV resolution several states were not resolved. In ^{106}Pd these are the known 0^+ and 2^+ levels at 1128 and 1134 keV and the 3^- and 4^+ states near 2080 keV. Similarly in ^{104}Pd the 0^+, 2^+, 4^+ triplet at 1330 keV and the doublet at 2180 keV were not well resolved.

For ^{106}Pd relative contributions to the 0^+ and 2^+ 5 keV doublet were determined by a least squares fitting method that decomposed the angular distribution of the doublet into its $L=0$ and $L=2$ components. Typical shapes for the $L=0$ and $L=2$ distributions were taken from the experimental 0^+ ground state and the 2^+ first excited state in ^{106}Pd. The result of this procedure is indicated by the solid line shown in Fig. 4. For comparison a pure $L=0$ angular distribution is drawn as a broken line. We conclude that the 1134 keV 0^+ state carries most of the (p,t) strength into this doublet. The relative intensities derived for this doublet at the 20° reaction angle are given in Table I. These values may have large errors. A similar analysis for the triplet at 1330 keV in ^{104}Pd did not prove practical. Also, the similarities in the angular distributions between $L=3$ and $L=4$ prevented an application of this method in the case of the 3^-, 4^+ doublet at 2080 keV in ^{106}Pd.

TABLE I. ^{108}Pd(p,t)^{106}Pd. Energies are accurate to about 4 keV.

E (keV)	$\sigma(20°)$ (μb/sr)	L	J^π Ref. 4
0	557	0	0^+
512	78	2	2^+
1128	7.2 [a]	0+2	2^+
1134	27 [a]		0^+
1228	12.3	4	4^+
1562	7.7	2	2^+
1706	6.4	0	0^+
1911	4.6	(3)	(2, 3)
1934	19.1	(4, 3)	$(3,4)^+$
2002	7.9	0	0^+
2077			
	83	3+4	$(4^+)+(6^+)$ [c]
2085			3^-
2242	5.4	2	2^+
2284	29	4	(4^+)
2307	4.1	···	$(2)^+$
2352	4.6	4	$(4)^+$
2398	9.0	(5)	(3^-)
2439	6.1	2	2^+
2500	90	2	(2, 3) [c]
2579	5.1	···	c
2647	35	4	0^+-4^+
2737			···
	47	4	
2752			$(2^-,3^-)$
2775	(26) [b]	(4)	$2^+,3^+$
2783	(26) [b]	(2)	···
2828	4.6	···	(0)
2917	27	2	(2^+)
2971	21	···	···
d			
3221	13	(0)	···
3251	21	(2)	···

[a] Result of least squares fitting routine.
[b] Barely resolved levels.
[c] Doublet.
[d] Unresolved multiplet of 4–6 states.

TABLE II. ^{106}Pd(p,t)^{104}Pd. Energies are accurate to about 4 keV.

E (keV)	$\sigma(20°)$ (μb/sr)	L
0	645	0
557	72	2
1324 [a]	11.2 [b]	4
1334 [a]	13.3	0
1342 [a]	8.9	2
1789 [c]	5.8	···
2080	29	4
2137	8.3	0
2179	62 [b]	(3) [b]
2192	67.9 [b]	(4) [b]
2244	28	2
2331	5.6	2
2484	6.2	···
2526	45	2
2564	56	4
2604		···
2618	21	···
2635		···
2670 [d]	10	(6)
2688	57	2
2767	17	4
2795		
	30	4
2807		
2668		
	20	4
2914	15	2

[a] Energies from Ref. 5.
[b] Results of high resolution experiment.
[c] Doublet.
[d] Sits on tail of much stronger peak.

The unresolved states in ^{104}Pd were reexamined in a second experiment using a 60 $\mu g/cm^2$ thick target on a 20 $\mu g/cm^2$ carbon backing. In order to obtain the necessary energy resolution the angular and energy spread of the proton beam had to be narrowly restricted. The tritons were detected by a 5 cm long position sensitive silicon detector mounted in the focal plane of the QDDD spectrograph. With these improvements energy resolutions of 5 keV FWHM were achieved; this was sufficient to resolve the triplet of states at 1330 keV and the doublet at 2180 keV in ^{104}Pd. We show the triplet and doublet spectra at 20° in Figs. 5 and 6. Under these experimental conditions the event rate was very low. Therefore spectra for the ground state, the 1330 keV triplet, and the 2180 doublet were taken at 10°, 20°, and 40° only. The ground state line shapes measured at each angle were used to decompose the generally well resolved multiplets in order to determine individual peak areas. These individual areas were normalized to the collected charges. The three points of the experimental angular distribution are in good agreement with the experimentally observed shapes derived from other levels for the expected L transfers, but by themselves do not permit unique assignments. For the 2.2 MeV doublet we prefer the assignment $L=3$ for the 2179 keV state and $L=4$ for the 2192 keV state for the following reason: The first experiment using the wire proportional counter established that the whole angular distribution of this poorly resolved doublet had an $L=3$ or $L=4$ shape. Comparing the three data points obtained in the high resolution run with $L=3$ and $L=4$ transfer DWBA predictions (Fig. 7) better agreements are observed for the above mentioned assignments.

Absolute cross sections given in Table I for the high resolution experiment were deduced by normalizing to the ground state intensities recorded with the same experimental setup. The ratios of the summed intensities of the multiplets to the ground state agree for the high and low resolution.

COMPARISON WITH PREVIOUS EXPERIMENTS

A. ^{104}Pd

The level scheme of ^{104}Pd up to about 2.1 MeV excitation is well established from γ spectroscopy

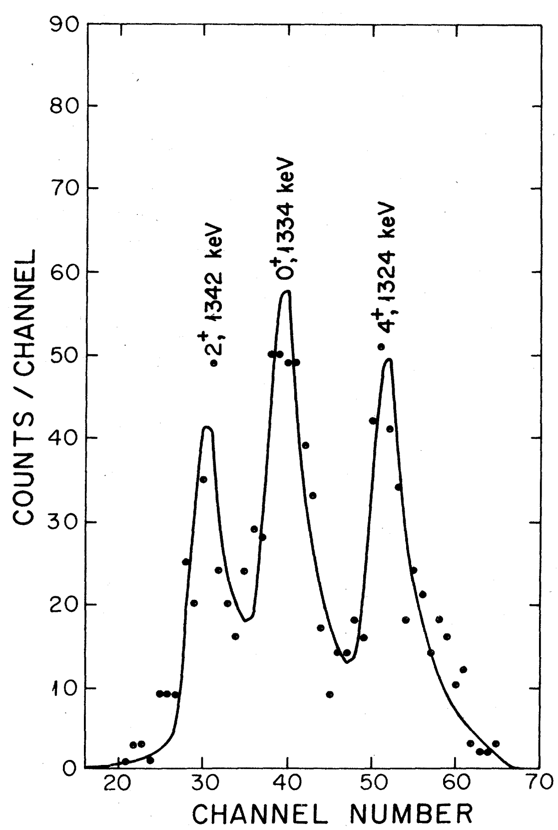

FIG. 5. High resolution spectrum of the 1330 keV triplet in the $^{106}Pd(p,t)^{104}Pd$ reaction.

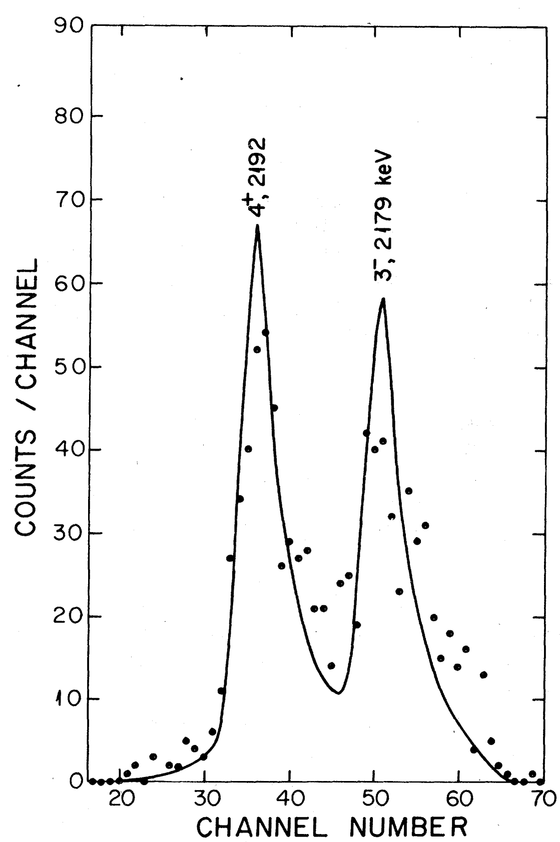

FIG. 6. High resolution spectrum of the 2180 keV doublet in the $^{106}Pd(p,t)^{104}Pd$ reaction.

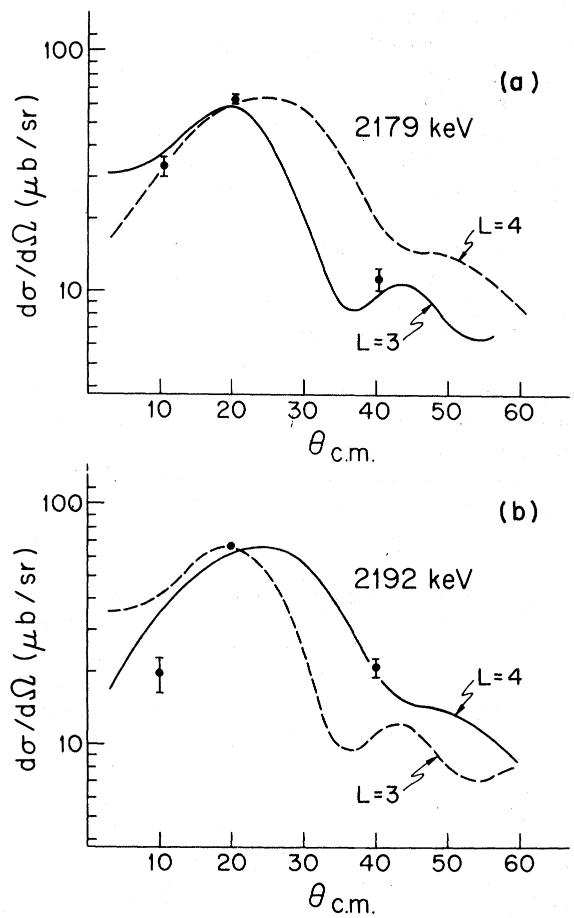

FIG. 7. Three point angular distributions from high resolution spectra of the 2180 keV doublet in ^{104}Pd. (a) 2179 keV level, the solid line is the preferred $L=3$ DWBA shape, the broken line is the $L=4$ DWBA shape. (b) 2192 keV level, the solid line is the preferred $L=4$ DWBA shape, the broken line is the $L=3$ DWBA shape.

of the decays of ^{104}Rh and ^{104}Ag[5] and the (p,t) L transfer values agree with previous assignments. As 2137 keV we find an additional 0^+ state not seen in decay[5] which probably corresponds to the 2126 keV state observed in the pickup reaction.[11]

B. ^{106}Pb

The levels in ^{106}Pd have been studied extensively before by γ-ray spectroscopy[4] and the ^{108}Pd(p,t) reaction.[13] Our energy and L transfer measurements are consistent with those of Ref. 13; the experiment described in Ref. 13 used protons of 19 MeV so that cross sections are not immediately comparable. For a survey of other works on ^{106}Pd see Ref. 4. The spin-parity assignments from Ref. 4 for levels also observed by the present (p,t) reaction are included in Table I. For states at 1911, 1934, 2002, 2284, 2352, 2500, 2647, and 2917 keV previous tentative assignments are now made definite by our present results. In particular the 1934 keV level is a 4^+ state; the parity is positive according to the conversion electron data[4] and the (p,t) reaction does not appreciably populate states with unnatural parity changes; $L=4$ is left as the only possible (p,t) L transfer value. This is in contradiction with a definite 3^+ assignment to a state at 1931.7 keV known from n-γ work.[6]

Discrepancies between the present and previous studies[4] exist only for the states at 2398 and 2775 keV; however, the assignments made here for these levels are considered tentative.

We have tentatively assigned the 2179 keV state to have spin and parity $J=3^-$. γ-ray angular correlation studies assign a level at 2181.5 keV as 4^+. We suggest that the 2181.5 keV level is distinct from the level we observe at 2179 keV. The β decay of the 1^+ ground state and the 5^+ isomeric state of ^{104}Rh could only weakly populate a 3^- state in ^{104}Pd due to its highly forbidden character. The same is true of the 5^+ ^{104}Ag ground state decay. The 2^+ isomeric state of ^{104}Ag decays primarily to the ^{104}Ag ground state[8] so that any feeding of a 3^- state may have remained unnoticed. In neighboring nuclei ^{107,105}Ag, ^{101}Rh, and ^{106}Pd strong (p,t) $L=3$ transitions are observed in this energy region; this would suggest that a 3^- state probably also exists in ^{104}Pd. The three point angular distributions obtained in the high resolution experiment of the 2179 keV state agree well with the known empirical $L=3$ angular distributions of (p,t) reactions in nearby nuclei. Evidence for a doublet at 2.2 MeV is found in single particle pickup studies as well.[7]

Above 2180 keV correspondences of states populated by the (p,t) reaction exist only for levels observed in pickup reactions.[7] The spin and parity assignments in these (d,t) and (p,α) reactions, although consistent with our results, do not further restrict the J possibilities.

DISCUSSION

Models of the even-even nuclei in this mass region have been proposed by several investigators.[4,9,12] While all of these were successful in describing the low excited states, difficulties arise at higher excitations. Our data may be useful in understanding the problems encountered in the description these models give for the higher excited states; however, the aim of the present study is to determine population strengths in the (p,t) reaction with the goal of comparing corresponding strengths in the silver isotopes in order to test this aspect of the core-coupling model.

TABLE III. Comparison of (p,t) strength in ^{106}Pd and ^{107}Ag.

	^{106}Pd			^{107}Ag			
L	E (keV)	$\sigma(20°)$ (μb/sr)		E (keV)	$\sigma(20°)$ (μb/sr)	$\Sigma\sigma(20°)$ (μb/sr)	^{107}Ag $\Sigma\sigma(20°)$ / ^{106}Pd $\sigma(20°)$
0	0	557		0	599	599	1.08
0	1134	27		1613	4.3		
0	1706	6.4	41.3	1651	15.0	29.2	0.71
0	2002	7.9		1851	9.9		
2	511	78		324	36	87	1.12
				422	51		
2	1128	7.2		784	5.2	14.2	1.97
				947	9.0		
4	1229	12.3		970	3.3	7.0	0.57
				1144	3.7		
$3^-(4^+)$	2085	83		2177	54.6	104.9	1.26
				2199	50.3		

The correspondence of doublets or singlets depending on the spin value of the core state at similar excitation has been shown before.[1] In Tables III and IV we compare the (p,t) strengths for the low excited multiplets in the odd-Ag isotopes to corresponding Pd core states. In terms of the core-coupling model the (p,t) cross sections summed over the members of the odd-A multiplets should be close to the cross sections of the corresponding core states since all reactions were done at the same bombarding energy and the Q values are similar. The cross sections at 20° summed over a given multiplet are indicated in Tables III and IV in the columns headed by the notation $\Sigma\sigma(20°)$. The ratios to the cross sections in the core states are also given. Because of the uncertainties in our absolute cross sections the ratios have errors of the order of 30% and are therefore not reliable indicators of the presence or absence of blocking of the (p,t) strength in the odd-A nuclei. Nevertheless one expects the ratios to be constant from multiplet to multiplet if the weak coupling predictions are valid. The experimental ratios for the higher excited states up to 1.5 MeV of nonzero L transfer values including the three-octupole vibrational states generally follow the ground state ratios; there may be significant deviations particularly for the 2^+ and 4^+ members of the two phonon multiplet.

In view of the strong (p,t) population of the two phonon 0^+ levels in ^{104,106}Pd the previous tentative assignment of $\frac{1}{2}^-$ to the weakly excited levels at 1096 and 1061 keV in ^{105,107}Ag, respectively, must now be regarded as erroneous.[1] Recent $(^3\mathrm{He},d)$ reaction studies[14] indicate these states in Ag are not $\frac{1}{2}^-$ but rather positive parity states. Hence, one must look at higher excitations for the $\frac{1}{2}^-$ core-coupled states associated with the 0^+ two phonon level. Unfortunately possible candidates for the $\frac{1}{2}^-$ states are considerably higher in excita-

TABLE IV. Comparison of (p,t) strength in ^{104}Pd and ^{105}Ag.

	^{104}Pd			^{105}Ag			
L	E (keV)	$\sigma(20°)$ (μb/sr)		E (keV)	$\sigma(20°)$ (μb/sr)	$\Sigma\sigma(20°)$ (μb/sr)	^{105}Ag $\Sigma\sigma(20°)$ / ^{104}Pd $\sigma(20°)$
0	0	645		0	561	561	0.87
0	1334	13.3		1959	9.0		
0	1789	Weak	21.6	2127	4.7	22.7	1.05
0	2137	8.3		2521	9.0		
2	557	72		346	30	73	1.01
				432	43		
2	1342	8.9		876	5.6	14.6	1.64
				1041	9.0		
4	1324	11.2		1022	6.9	16.9	1.50
				1166	10.0		
3	2179	62		2276	42	72	1.16
				2313	28		

tion than anticipated from the simplest core-coupling model. A recent theoretical calculation[10] which includes particle-vibration mixing places the first excited $\frac{1}{2}^-$ state in the odd-Ag isotopes above 2 MeV. Indeed, experimentally they are observed at about 2 MeV. The spacing between these $\frac{1}{2}^-$ states is comparable to the energy differences between the members of the doublet states. Therefore, phonon mixing is probably present in these $\frac{1}{2}^-$ states and a one to one correspondence between the even-Pd and the odd-Ag isotopes is not justified. For this reason we compare the summed (p,t) strength for all $L=0$ states except the ground state and find good agreement. Finally, whereas one to one correspondences cannot be made for excitations above 1.5 MeV, the weak coupling model still applies in a statistical sense; there are about twice as many states for a given L value in the odd isotopes as in the even cores in the energy range between 1.5 and 3 MeV and the (p,t) strength summed over all states at the same L for the odd nuclei agrees within a factor of 2 with a similar sum for the corresponding even-even nuclei.

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