Spectroscopy of Pd^{106} by Direct (d, p) and (p, α) Reaction Studies*

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Pd^{106} was investigated by the $Pd^{105}(d, p)Pd^{106}$ and $Ag^{109}(p, \alpha)Pd^{106}$ reactions at Van de Graaff bombarding energies of 17 and 12 MeV, respectively. Particle analysis for the stripping study employed nuclear emulsions in an Enge split-pole spectrograph and yielded 10–12-keV resolution for the detected protons of 21–24 MeV. Comparison of measured (d, p) angular distributions with nonlocal, finite-range distorted-wave Born-approximation (DWBA) calculations led to l-value assignments, J^π limits, and spectroscopic strengths for 34 transitions. The deduced values U_{lj}^2 were 0.42 for 2d states and 0.80 for the $3s_{1/2}$ neutron orbital and agree to within 10% with our (d, t)-derived occupancies for the same Pd^{105} target. The low $Ag^{109}(p, \alpha)$ yield at 12-MeV incident energy necessitated use of thick targets (130 $\mu g/cm^2$) and large solid angles, which led to resolutions of about 35–40 keV for Si counter data and 20 keV for spectrograph analysis. Angular distributions for ten (p, α) transitions were measured out to 150° and compared with local, zero-range DWBA predictions. Based on a macroscopic triton-transfer model, these calculations were particularly successful in duplicating the j dependence observed in the $p_{1/2}$ ground-state transition. A modified Pd^{106}-level scheme incorporating our results with the previous literature is presented and includes 20 new states from the present studies.

I. INTRODUCTION

IN the recent past, considerable emphasis has been directed toward the investigation of the spectroscopy of Pd^{106}, particularly by β-γ decay studies.[1–9] Such decays excite a limited number of levels that are singled out by β and γ-decay selection rules and do not yield a complete energy-level diagram, especially for the higher excitations. The present work examines the level structure of Pd^{106} with high-resolution stripping and pickup reactions and allows an independent verification of existing assignments as well as extension of the spectroscopy of this nucleus to ~3.2-MeV excitation.

Interest in the Pd isotopes centers around the fact that they are considered to possess collective characteristics that give rise to a vibrational energy-level spectrum. Our earlier study[10] of Pd^{104} furnished strong evidence for the existence of multiplets characteristic of vibrational excitation for this nucleus. The present work extends the investigation of collective structure to the isotope Pd^{106}.

II. EXPERIMENTAL METHOD

Deuterons of 17 MeV and protons of 12 MeV from the Pittsburgh Tandem Van de Graaff were employed to investigate the $Pd^{105}(d, p)Pd^{106}$ and the $Ag^{109}(p, \alpha)Pd^{106}$ reactions. In the stripping study, protons were observed over an angular range 10°–50°. Particle detection was accomplished with nuclear emulsions (Kodak NTB, 25 μ) at the focal plane of an Enge split-pole spectrograph. A 75-mil-thick Al foil, placed directly in front of the photographic plates, served both as an interceptor for the less penetrating reaction products (primarily deuterons) and as a means of degrading the energetic protons to the 3–7-MeV energy range required for optimum track delineation. Angular distributions for the (p, α) transitions to the same final nucleus were measured at 5° intervals between 10° and 150° and were obtained using an experimental procedure identical to that employed previously.[10]

Figure 1 shows the results of a $Pd^{105}(d, p)Pd^{106}$ plate scan at $\theta = 30°$. Since the resolution for a magnetic analysis system is a fixed percentage of the total detected particle energy, the (d, p) measurements were resolution limited by the 21–24-MeV analyzed protons. A 10–12-keV broadening was observed for single levels and was attributed primarily to the width of the beam spot at the target (source size) and to the horizontal divergence of the incident deuteron beam (see Table I). Stripping peaks from light impurities in the target as well as the $C^{13}(d, p)C^{14}$ ground-state reaction from the carbon foil backing were observed in the spectrum and identified by their kinematic shift and broadening. The 32-$\mu g/cm^2$-thick Pd^{105} target was the same as used in the $Pd^{105}(d, t)Pd^{104}$ studies.[10]

The low yield associated with the $Ag^{109}(p, \alpha)Pd^{106}$ reactions at 12 MeV necessitated the use of thick targets (130 $\mu g/cm^2$) and multiple-detector data accumulation. The bulk of the (p, α) information was obtained with a four-detector array of thin, fully depleted Si surface barrier detectors as described in our previous publication. A typical $Ag^{109}(p, \alpha)Pd^{106}$ counter spec-

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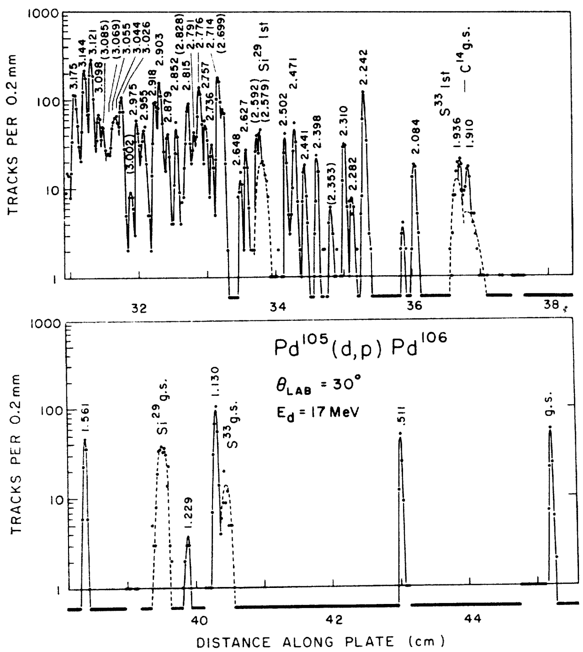

FIG. 1. Energy spectrum for levels excited in Pd^{106} by Pd^{105} (d, p) stripping at 17 MeV. Spectrograph resolution is 10–12 keV for the 21–24-MeV analyzed protons.

TABLE I. Calculated contributions to the experimental resolution for 24-MeV protons from the $Pd^{105}(d,p)Pd^{106}$ reaction at $\theta=30°$ (Fig. 1).

	ΔE (keV)
a. Source size.	6.3
b. Kinematic broadening due to horizontal divergence of the incident beam.	~6.1
c. Increase in source size due to divergence between slit and target.	~3.4
d. Target thickness, straggling and differential energy loss.	~0.3
e. Spectrograph aberrations (1.4-msr entrance aperture).	4.8
f. Incident-beam-energy spread.	~2.0
g. Plate-scanning resolution.	4.8
h. Miscellaneous factors, includes magnetic field fluctuations and incorrect focal-plane positioning.	~2.0
Total calculated resolution $(\Sigma_i \epsilon_i^2)^{1/2}$.	~11.9

trum, exhibiting 35–40-keV resolution, is shown in Fig. 2. While this setup was satisfactory over most of the angular range, proton pileup at small angles required magnetic analysis of the α groups using the spectrograph. Figure 3 displays an energy spectrum taken at $\theta=10°$ with nuclear emulsions and exhibits an improved resolution of about 20 keV for the ground-state transition. On the order of 85% of this width can be attributed to target-thickness contributions arising from differential energy loss and straggling.

Random experimental errors arising from statistics, background subtraction, particle group separation, and monitoring inconsistencies are indicated by the error bars displayed in the angular distributions. The major uncertainty in the absolute cross-section scale is due mainly to target-thickness measurements, systematic plate-scanning errors, and, for the (p,α) work, charge collection. It is estimated that the (d,p) experiment has a scale error of $\pm15\%$, while the earlier (p,α) study is believed to have a $\pm20\%$ absolute scale uncertainty.

Excitation-energy assignments for levels in Pd^{106} were obtained by calibration with unambiguous known levels from the literature. The (d,p) level assignments, averaged over all spectra, are uncertain by about ±3 keV,

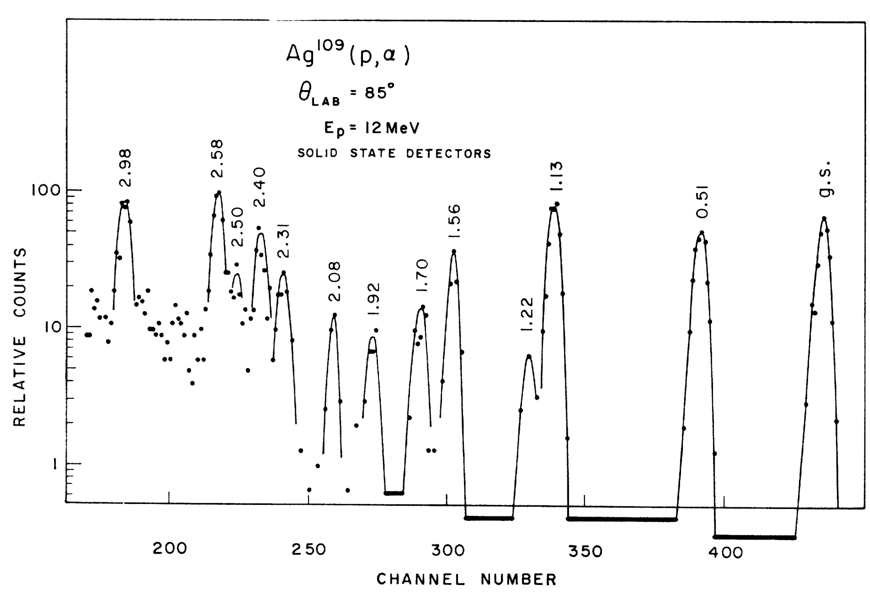

FIG. 2. $Ag^{109}(p,\alpha)$ Pd^{106} surface-barrier counter spectrum at $\theta=85°$ displaying 35–40-keV resolution for 130-μg/cm^2 targets. The Q value for the ground-state transition is 6.054 MeV.

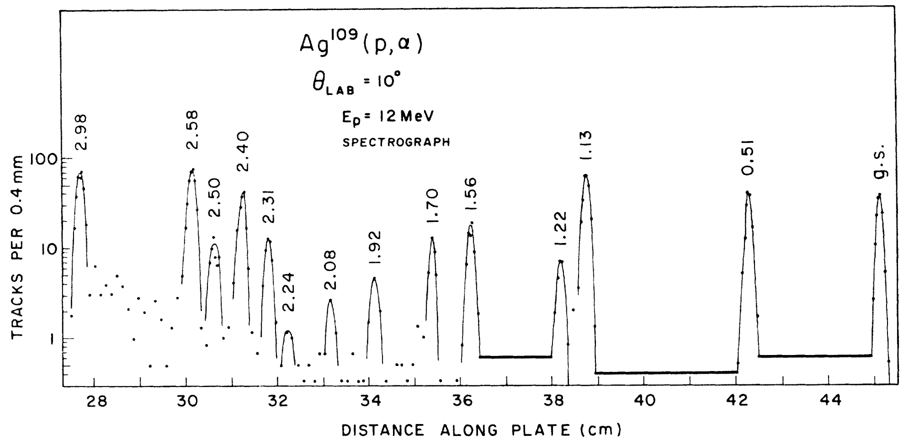

FIG. 3. $Ag^{109}(p, \alpha)$ plate scan showing an improved 20-keV α particle resolution. Proton pileup required magnetic analysis of small-angle data using an Enge spectrograph.

and within this error agree with previously documented states. New level-energy assignments determined by the (d, p) study are believed to be better than $\pm 0.15\%$ of excitation energy. The less precise (p, α) values are listed to tens of keV and are estimated to be uncertain to ± 15 keV.

III. DISTORTED-WAVE ANALYSIS

Local, zero-range DWBA theory has been applied to many reaction studies, and the mathematical simplicity of this approach has been the major impetus for its widespread application to direct-reaction calculations. However, failure of the simplified theory to correctly account for the suppression of contributions from the nuclear interior has often resulted in the use of unphysical sharp, lower, radial integration cutoffs. It has been shown by several authors[11–13] that the inclusion of nonlocality and finite-range effects in the DWBA calculations leads to an attenuation of contributions from the nuclear interior in a smooth fashion and results in predictions in better agreement with experiment.

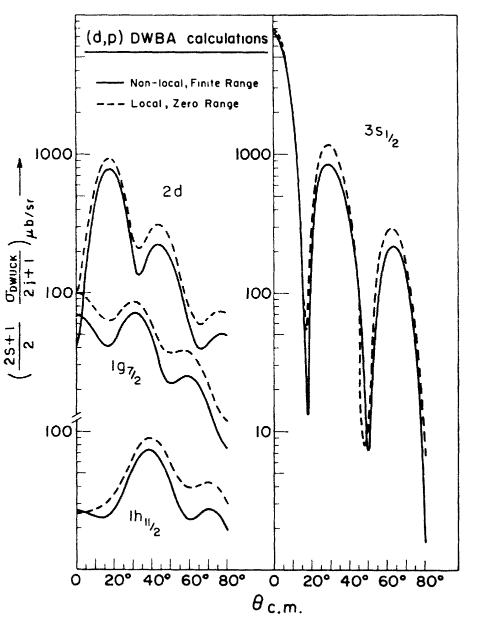

FIG. 4. Comparison of nonlocal finite-range DWBA calculations with local zero-range predictions for neutron stripping expected in $Pd^{105}(d, p)Pd^{106}$.

For the present (d, p) investigations, theoretical calculations were performed using the University of Colorado DWBA code DWUCK[14] both with and without nonlocal and finite-range corrections. The optical parameters[15,16] describing the elastic scattering channels and the bound-neutron well geometry employed in the form factor are listed in Table II. Spin-orbit coupling was included only for the bound state, since the j dependence of the shape of the angular distributions is not pronounced over the angular range of the experiment. Effects of nonlocal optical potentials and finite-range stripping were incorporated in the DWBA calculations by damping factors characterized by nonlocality ranges β and a finite-range parameter R. The values of $\beta_d = 0.54$ and $\beta_p = 0.85$ had been deduced from the energy dependence of local optical potentials,[11,17,18] and were also used here. The finite-range (d, p) stripping correction used $R = 0.621$, and was suggested by Goldfarb.[14]

Figure 4 shows the comparison between the two versions of the DWBA calculation for neutron transfers expected in $Pd^{105}(d, p)Pd^{106}$. Reduction of the differential cross section resulting from nonlocal and finite-range effects is on the order of 15%, except for the more deeply penetrating $l = 0(3s_{1/2})$ stripping where a 25–30% decrease is predicted for the observable second-stripping maximum.

DWBA calculations involving the $Ag^{109}(p, \alpha)Pd^{106}$

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TABLE II. Optical-model parameters used in thc $Pd^{105}(d, p)Pd^{106}$ and $Ag^{109}(p, \alpha)Pd^{106}$ DWBA calculations.

Channel	V (MeV)	$r_{0s}=r_{0c}$ (F)	a (F)	W (MeV)	$4W_D$ (MeV)	r_{0I} (F)	a_I (F)	V_{so} (MeV)	B (F)	R (F)
$Pd(d, d)$	103	1.09	0.85	...	49.6	1.41	0.90	...	0.54	...
$Pd(p, p)$	49.1	1.25	0.65	...	55.0	1.25	0.47	...	0.85	...
$Ag(p, p)$	51.56	1.25	0.65	...	65.08	1.25	0.47	7.5	...	...
$Pd(\alpha, \alpha)$	150	1.49	0.60	20	...	1.49	0.60	...	...	...
Neutron well	...	1.25	0.65	...	...	...	...	$\lambda=25$	...	0.621
Triton well	...	1.38	0.45	...	...	...	...	$\lambda=25$		0

study were based on a local, zero-range triton-cluster transfer mechanism, using Oak Ridge code JULIE,[19] as in our earlier $Ag^{107}(p, \alpha)Pd^{104}$ investigations.[10] As in the previous work, these predictions were most successful in duplicating the j dependence for the $p_{1/2}$ ground-state data. Predictions for other angular momentum transfers are indicated along with the experimental angular distributions in Figs. 5–7 in Sec. IV. The elastic-channel parameters and triton-well geometry used in the present calculations are given in Table II.

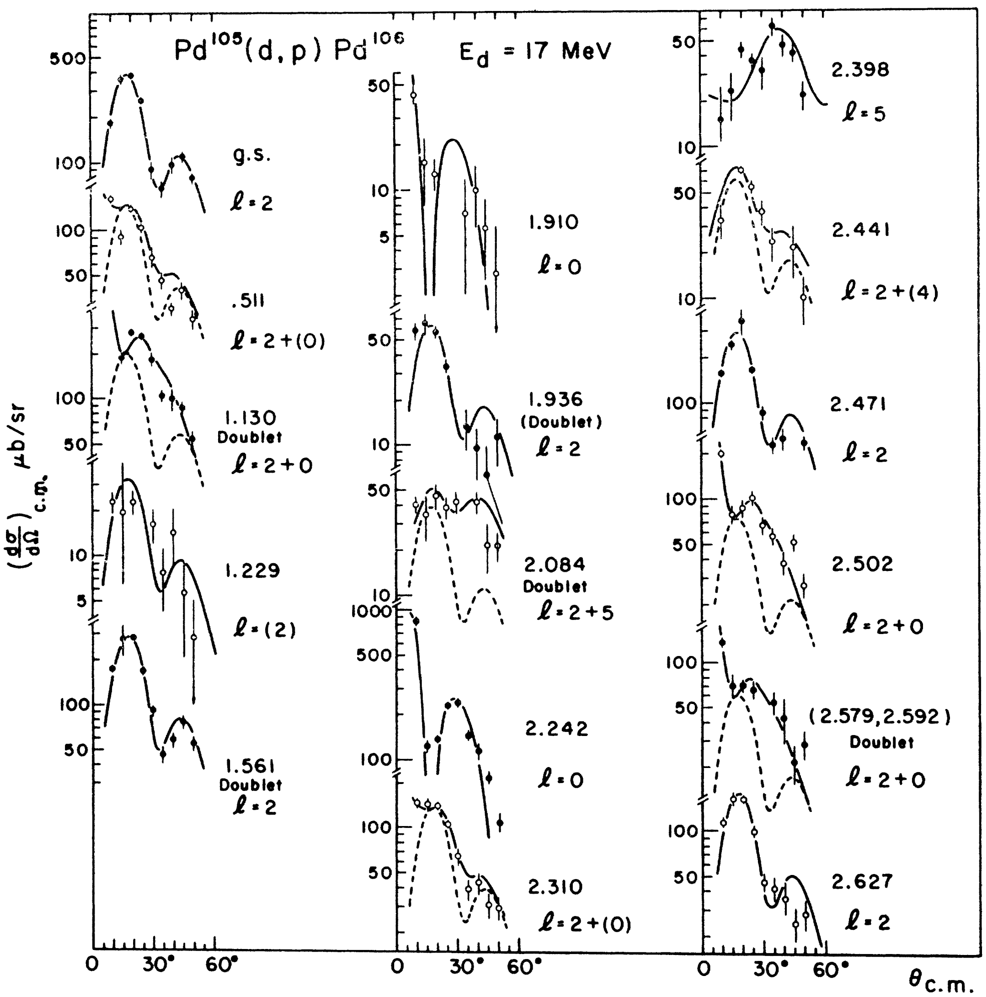

FIG. 5. Experimental angular distributions from the $Pd^{105}(d, p)Pd^{106}$ study. Data are grouped according to Pd^{106} excitation. Solid curves represent the distorted-wave predictions with nonlocality and finite-range corrections. Dashed curves exhibit the principal l contribution to transitions proceeding by more than one orbital-angular-momentum transfer.

[19] R. H. Bassel, R. M. Drisko, and G. R. Satchler, Oak Ridge National Laboratory Report No. ORNL-3240 (1962); Suppl., 1966 (unpublished).

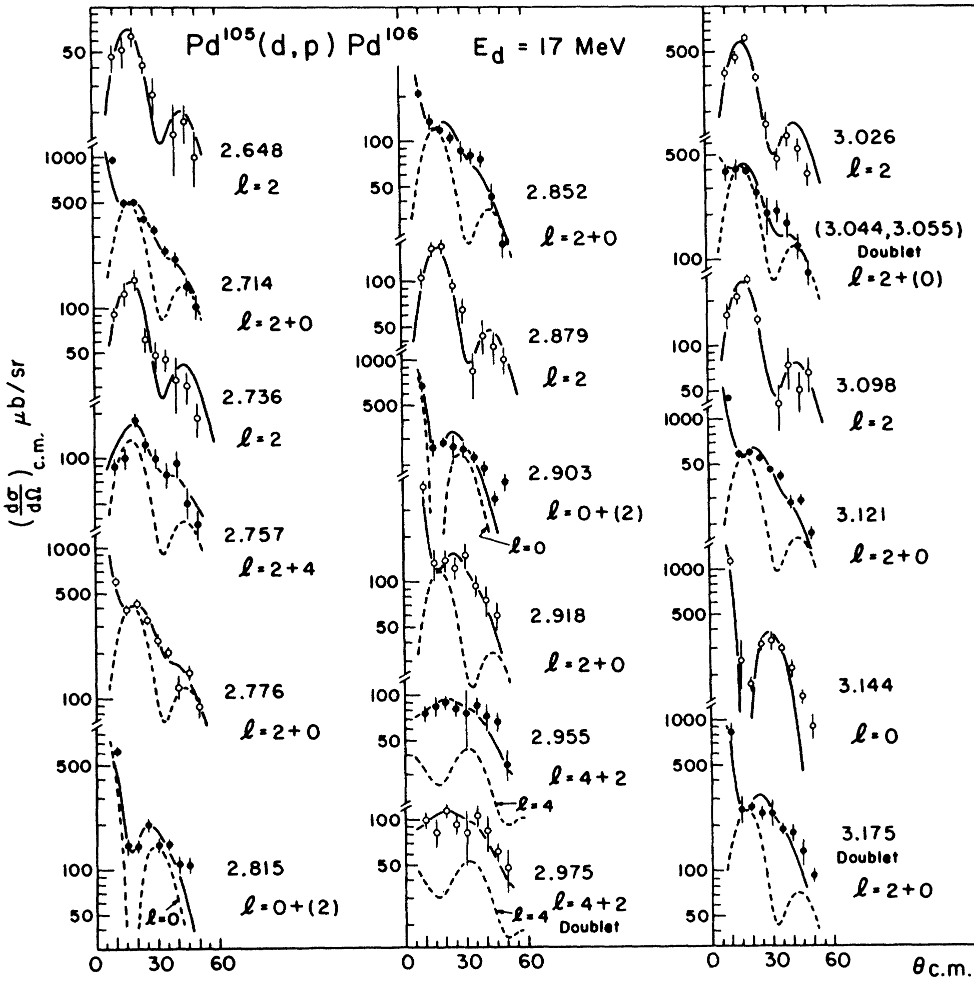

FIG. 6. $Pd^{105}(d, p)Pd^{106}$ angular distributions to higher excited states. Error bars drawn through the data points represent the estimated random error. The curves are DWBA calculations (see caption of Fig. 5).

IV. EXPERIMENTAL RESULTS AND SPECTROSCOPIC FACTORS

The experimental angular distributions in comparison with nonlocal, finite-range DWBA predictions are exhibited in Figs. 5 and 6 for levels populated by the $Pd^{105}(d, p)Pd^{106}$ study. $l=2$ transfer contributions, resulting from neutron stripping to the $2d_{3/2}$ and $2d_{5/2}$ orbitals in the target, were observed in nearly 90% of the displayed transitions. Inclusion of nonlocality and finite-range corrections in the calculations (see Fig. 4) led to a reduction of the $l=2$ secondary maximum relative to the primary-stripping peak and permitted duplication of the data for the required $d_{5/2}$ ground-state transition. DWBA s-wave calculations predict a sharper descent from the 30° maximum than the more asymmetric, less steep large-angle falloff seen in the experimental data (note, for example, the strong $l=0$ distribution at 3.144-MeV excitation). Nevertheless, the characteristic small-angle behavior of $l=0$ stripping supports assignment of three transitions as pure $3s_{1/2}$ transfer.

Although the $\frac{5}{2}^+$ Pd^{105} target spin usually leads to relatively wide final-state spin limits for pure l_j transfer, the identification of $s_{1/2}$ transfers or $s_{1/2}$ admixtures in the experimental angular distributions narrowly limits the final-state assignments. Ten angular distributions were best described by $l=2+0$ DWBA curves and were associated with final-state spin and parity of 2^+ and 3^+. Several less-oscillatory angular distributions were interpreted as $l=2+4$ superpositions, and led to $J^\pi = 1^+ \rightarrow 5^+$ limits for the Pd^{106} levels. Two negative-parity states were determined, at 2.084 and 2.398 MeV, on the basis of a broad peak at $\theta=40°$, indicative of $h_{11/2}$ stripping patterns.

In Table III we list the excitation energies, l transfers, J^π limits, experimental cross sections at the stripping peak, and spectroscopic factors for levels excited by (d, p) along with the experimental results from the (p, α) studies. Also included are reliable J^π assignments from previous investigations.[1–9] The final column indicates our suggested assignments based on all the information currently available.

Spectroscopic information can be obtained from the

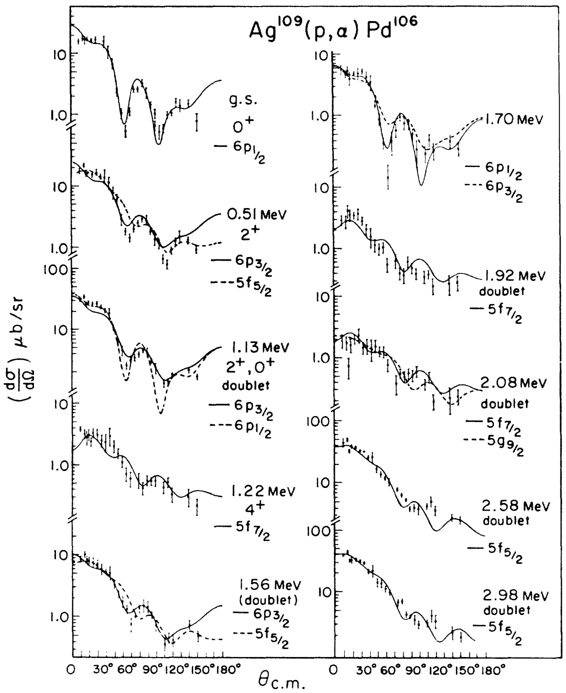

FIG. 7. α-particle angular distributions form the $Ag^{109}(p, \alpha)$ Pd^{106} reaction at $E_p=12$ MeV. Local zero-range DWBA calculations (curves) indicate primarily $l=1$ and 3 triton pickup. A strong E dependence is observed for $p_{3/2}$ and $p_{1/2}$ transfer.

$Pd^{105}(d, p)Pd^{106}$ experiment using the relation for the differential cross section,

$$\frac{d\sigma}{d\Omega}=1.5\,\frac{2I_f+1}{2I_i+1}\sum_{lj}S_{lj}\left(\frac{2s+1}{2}\,\frac{\sigma_{lj}(\theta)}{2j+1}\right), \qquad (1)$$

where $\sigma_{lj}(\theta)$ is the cross section calculated by code DWUCK,[14] S_{lj} is the spectroscopic factor for a given lj and s and j represent the intrinsic and total spin of the transferred neutron.

For a particular angular distribution, the experimental and calculated cross sections are divided to extract from (1) the unknown quantity $S_{lj}'\equiv(2I_f+1)S_{lj}$. Summed over all transitions of a given lj, this strength is directly related to the emptiness U_{lj}^2 of the corresponding neutron-shell model orbital by[20]

$$\sum_{I_f,k}(2I_f+1)S_{lj}^{kI_f}\simeq(2I_i+1)(2j+1)U_{lj}^2, \qquad (2)$$

where the summing index k represents states of a particular I_f.

Figure 8 illustrates the single-particle stripping strength for the neutron transfers in $Pd^{105}(d, p)Pd^{106}$ as a function of excitation energy in the residual nucleus. As mentioned in the Sec. III, j discrimination in (d, p) transitions and differentiation of $d_{3/2}$ from $d_{5/2}$ transfers was not possible in the angular range investigated. Although one would expect considerably more stripping to the former orbital than the latter,[21] the DWBA calculation used in extracting spectroscopic factors for d transfer did not employ spin-orbit coupling for the bound state. Calculations including bound-state j dependence show that the listed $l=2$ spectroscopic factors are on the order of 14% too small if $d_{3/2}$ stripping is assumed, and 4% too large for $d_{5/2}$ stripping.

For all identified d transfers, we have $\sum S'_{l=2}=24.96$, and, with the aid of Eq. (2), approximately 5.8 neutrons are predicted for the $l=2$ orbits of Pd^{105}. Similar j-independent calculations for our earlier $Pd^{105}(d, t)Pd^{104}$ pickup results[10] indicated 6.2 d-state neutrons for the Pd^{105} target, in good agreement with our present (d, p) determination. Previous 12-MeV stripping data[21] deduced 5.1 d-state neutrons for the neighboring isotope Pd^{106}.

Considerable $l=0$ strength was observed in the present experiment and is interpreted as stripping to the $3s_{1/2}$ orbital. DWBA calculations with finite-range and nonlocality corrections led to the extraction of $U_{s1/2}^2=0.80$ or a 20% filling of this shell-model state in the target. This is in substantial agreement with our $V_{s1/2}^2=0.27$ result obtained in the $Pd^{105}(d, t)$ studies[10] and suggests a larger s-neutron emptiness than that given by Cohen *et al.*[21] ($U_{s1/2}^2=0.57$) for $Pd^{106}(d, p)$. It is noted, however, that the U_{lj}^2 values determined in Ref. 21 were based on local, zero-range DWBA predictions. Under the assumption that the effect of nonlocal and finite-range corrections to the 12-MeV $l=0$ stripping calculations is similar to that effect experienced in the present work (i.e., a 25–30% decrease in the predicted cross section at the second stripping peak), one observes that the $U_{s1/2}^2$ obtained from the $Pd^{106}(d, p)$ data would come into close agreement ($U_{s1/2}^2\simeq0.78$) with our results.

Surprisingly little $g_{7/2}$ strength was identified ($U_{g7/2}^2=0.02$), in marked contrast to previous indica-

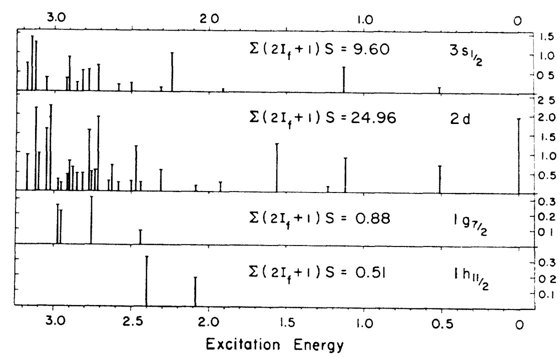

FIG. 8. Experimentally measured spectroscopic strengths for the observed single particle transfer as a function of excitation energy in Pd^{106}. Sum rules yield s and d state U_{lg}^2 values within 10% of our earlier (d, t) results for the same Pd^{105} nucleus.

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TABLE III. Experimental results for levels of Pd^{106} from the $Pd^{105}(d, p)Pd^{106}$ and $Ag^{109}(p, \alpha)Pd^{106}$ reactions and a comparison with previous assignments (Refs. 1–9).

$Pd^{105}(d,p)Pd^{106}$ Excit. energy (MeV)	l	l_j	J^π	$d\sigma^a/d\Omega$ (μb/sr)	$(2I_f+1)S_{lj}$	$Ag^{109}(p,\alpha)Pd^{106}$ Excit. energy (MeV)	l_j	J^π	$d\sigma_{max}/d\Omega$ (μb/sr)	Previous assign.[b] Excit. energy (MeV)	Previous assign.[b] J^π	Suggested J^π assign.
0	2	$d_{5/2}$	0^+-5^+	365	1.95	0	$p_{1/2}$	$0^+, 1^+$	20	0	0^+	0^+
	2	$(d_{5/2})$		140	0.70							
0.511			$(2^+, 3^+)$			0.51	$p_{3/2}$	$1^+, 2^+$	19	0.512	2^+	2^+
	(0)	$(s_{1/2})$		33	0.15							
	0	$s_{1/2}$	$2^+, 3^+$	31	0.15					1.128	2^+	2^+
1.130[c]						1.13[c]	$p_{3/2}, p_{1/2}$	$1^+, 2^+, 0^+$	31			
	2	d	0^+-5^+	190	0.90					1.133	0^+	0^+
1.229	(2)	(d)	$(0^+$-$5^+)$	31	0.15	1.22	$(f_{7/2})$	$(3^+, 4^+)$	3.0	1.229	4^+	4^+
						...	...			1.557	$(4^+, 3^+)$	$(4^+, 3^+)$
1.561[c]	2	d	0^+-5^+	275	1.26							
						1.56	$p_{3/2}$	$1^+, 2^+$	8.5	1.562	2^+	2^+
						1.70	$p_{1/2}$	$0^+, 1^+$	5.5	1.704	(1^+)	$0^+, 1^+$
1.910	(0)	$(s_{1/2})$	$(2^+, 3^+)$	21	0.08					(1.91)	?	$(2^+, 3^+)$
						1.92[c]	$(f_{7/2})$	$(3^+, 4^+)$	3.5			
1.936[c]	2	d	0^+-5^+	60	0.27					1.932	$4^+, (3^+)$	$3^+, 4^+$
...						...				2.002	0^+	0^+
...						...				(2.040)	$(2^+, 3^+, 4^+)$	?
	2	d	0^+-5^+	37	0.16					2.076	$(3^+, 4^+, 5^+)$	3^+-5^+
2.084[c]						2.08	$(f_{7/2})$	$(3^+, 4^+)$	2.0			
	5	$h_{11/2}$	3^--8^-	35	0.19					2.084	$3^-, (3^+, 4^+, 5^+)$	3^-
										(2.189)	$(1^+, 2^+)$	$(1^+, 2^+)$
2.242	0	$s_{1/2}$	$2^+, 3^+$	255	1.01	2.24				2.241	(2^+)	2^+
2.282	...		weak							(2.282)	$(3^+, 4^+)$	$(3^+, 4^+)$
...										2.306	4^-	4^-
	2	d		133	0.57							
2.310			$(2^+, 3^+)$			2.31				2.308	$1^+, 2^+, 3^+, 4^+$	$(2^+, 3^+)$
	(0)	$(s_{1/2})$		31	0.12							
2.353			weak							2.350	$3^+, 4^+$	$3^+, 4^+$
...										2.365	$3^+4^+(5^+)$	$3^+, 4^+$
2.398	5	$h_{11/2}$	3^--8^-	60	0.32	2.40				(2.41)	$(?)^-$	3^--8^-
	2	d		58	0.25							
2.441			$(1^+$-$5^+)$							2.437	$(1^+, 2^+)$	$(1^+, 2^+)$
	(4)	$(g_{7/2})$		18	0.10							
2.471	2	d	0^+-5^+	280	1.18							0^+-5^+

TABLE III (*Continued*)

Excit. energy (MeV)	$Pd^{105}(d, p)Pd^{106}$ l	l_j	J^{π}	$d\sigma^a/d\Omega$ (μb/sr)	$(2I_f+1)S_{lj}$	$Ag^{109}(p, \alpha)Pd^{106}$ Excit. energy (MeV)	l_j	J^{π}	$d\sigma_{max}/d\Omega$ (μb/sr)	Previous assign.[b] Excit. energy (MeV)	J^{π}	Suggested J^{π} assign.
2.502	{0	$s_{1/2}$	$2^+, 3^+$	59	0.23}	2.50[c]						$2^+, 3^+$
	2	d		70	0.29							
										(2.529)	$(1^+, 2^+)$	$(1^+, 2^+)$
2.579}	{2	d	0^+-5^+	57	0.24}	2.58	$(f_{5/2})$	$(2^+, 3^+)$	40			?
2.592	0	$s_{1/2}$	$2^+, 3^+$	49	0.19							$2^+, 3^+$
2.627	2	d	0^+-5^+	170	0.70					2.623	$1^+, 2^+$	$1^+, 2^+$
2.648	2	d	0^+-5^+	68	0.28							0^+-5^+
(2.699)	...	poorly resolved										?
2.714	{2	d	$2^+, 3^+$	475	1.95}					(2.709)	$(1^+, 2^+)$	2^+
	0	$s_{1/2}$		180	0.70							
2.736[c]	2	d	0^+-5^+	140	0.57					(2.738)	$(5^{\pm}, 6^+)$	?
2.757	{2	d	1^+-5^+	128	0.52}					2.756	5^+	5^+
	4	$g_{7/2}$		61	0.31							
2.776	{2	d	$2^+, 3^+$	395	1.61}					(2.778)		$2^+, 3^+$
	0	$s_{1/2}$		149	0.58							
2.791	...		weak									?
2.815	{0	$s_{1/2}$	$2^+, 3^+$	142	0.55}							$2^+, (3^+)$
	(2)	(d)		120	0.49							
(2.828)	...	poorly resolved								2.827	$(1^+, 2^+)$	$(1^+, {}^+2)$
2.852	{2	d	$2^+, 3^+$	115	0.47}							$2^+, 3^+$
	0	$s_{1/2}$		66	0.25							
2.879	2	d	0^+-5^+	158	0.64							0^+-5^+
2.903	{0	$s_{1/2}$	$2^+, 3^+$	235	0.90}							$2^+, 3^+$
	(2)	(d)		200	0.81							

TABLE III (*Continued*)

Pd$^{105}(d,p)$Pd^{106} Excit. energy (MeV)	l	l_j	J^π	$d\sigma^a/d\Omega$ (μb/sr)	$(2I_f+1)S_{lj}$	Ag$^{109}(p,\alpha)$Pd^{106} Excit. energy (MeV)	l_j	J^π	$d\sigma_{max}/d\Omega$ (μb/sr)	Previous assign.[b] Excit. energy (MeV)	J^π	Suggested J^π assign.
2.918	{2	d	$2^+, 3^+$	112	0.45}					2.918	$(1^+, 2^+)$	2^+
	{0	$s_{1/2}$		95	0.36}							
2.955	{4	$g_{7/2}$	1^+-5^+	44	0.22}					2.951	$5^+, 6^+$	5^+
	{2	d		58	0.23}							
2.975[c]	{4	$g_{7/2}$	1^+-6^+	53	0.26}	2.98	$(f_{5/2})$	$(2^+, 3^+)$	40			{?}
	{2	d	0^+-5^+	81	0.32}							{$(2^+, 3^+)$}
(3.002)	...		weak									?
3.026	2	d	0^+-5^+	560	2.23							0^+-5^+
{3.044}	{2	d	0^+-5^+	415	1.64}					3.042	$(1^+, 2^+)$	{$(1^+, 2^+)$}
{3.055}	{(0)	$(s_{1/2})$	$(2^+, 3^+)$	95	0.36}					3.057	$(1^+, 2^+)$	{(2^+)}
(3.069)	...		poorly resolved									?
(3.085)	...		poorly resolved									?
3.098	2	d	0^+-5^+	255	1.00							0^+-5^+
3.121	{2	d	$2^+, 3^+$	550	2.17}							$2^+, 3^+$
	{0	$s_{1/2}$		340	1.28}							
3.144	0	$s_{1/2}$	$2^+, 3^+$	380	1.43							$2^+, 3^+$
3.175[c]	{2	d	0^+-5^+	245	0.96}							?
	{0	$s_{1/2}$	$2^+, 3^+$	197	0.74}							$2^+, 3^+$

[a] Experimental differential cross section near the maximum ($\theta=20°$ for $l=2$, $\theta=30°$ for $l=0$ and 4, and $\theta=40°$ for $l=5$).

[b] Consensus of assignments from the literature.

[c] Doublet structure.

TABLE IV. Comparison of U_{lj}^2 determinations for neutron single-particle states in the $N=50$–82 shell.

Single-particle state	Pd^{105} (d, p)	Pd^{105} (d, t)	Pd^{106} 12 MeV(d, p)
$2d_{5/2}$	0.42	0.38	0.49 {0.27
$2d_{3/2}$			0.82
$3s_{1/2}$	0.80	0.73	0.57

tions[21,22] of a relatively vacant single-particle state. It is likely that the inherently smaller $l=4$ stripping cross sections (see Fig. 4) are often masked by strong $l=0$ and $l=2$ patterns, and therefore are missed in the analysis. In addition, sizable g strength may exist for excitations higher than those considered in this experiment.

The observed $l=5$ stripping strength was also considerably reduced from that expected from shell-model considerations. It is believed that sizable strength arising from excitations above 3.175 MeV and fragmentation of the $h_{11/2}$ component may be responsible for this discrepancy. A comparison of U_{lj}^2's deduced from the $Pd^{105}(d, p)$ studies with our earlier $Pd^{105}(d, t)$ results and with the 12-MeV $Pd^{106}(d, p)$ deductions of Cohen *et al.* is presented in Table IV.

Angular distributions for the ten transitions observed in $Ag^{109}(p, \alpha)Pd^{106}$ are shown in Fig. 7. The comparison of data and theoretical predictions, based on local, zero-range DWBA calculations,[19] primarily indicates triton orbital-angular-momentum transfers of $l=1$ and 3. The weakly excited doublet at 2.08 MeV contains the known 3^- octupole vibrational level and would require some $g_{9/2}$ strength if this state is appreciably excited by (p, α).

As discussed in the Pd^{104} paper,[10] the inclusion of $\mathbf{l}\cdot\boldsymbol{\sigma}$ potential terms in the proton channel and form factor reproduces the deep 65° minimum in the $l=1$ ground-state data and predicts a distinctive j dependence for $p_{3/2}$ and $p_{1/2}$ transitions. The nonzero spin of the Ag^{107} target allows lj mixing for transitions to other than 0^+ final states. The (p, α) analysis is further complicated by the fact that over half of the analyzed angular distributions represent transitions to doublets.

The curves in Fig. 7 indicate that in most cases the observed transitions can be well explained by a single dominant l_j transfer, although the agreement for the pure $p_{1/2}$ transitions to the ground state and the 1.70 level is by far the best. It is clear that no other l_j value would fit these levels. For the 0.51-MeV (2^+) state and the 1.13-MeV $(0^+, 2^+)$ doublet, $p_{3/2}$ seems to dominate. The higher l transfers are seen and predicted with less distinct structure. But in some cases good statistics seem to permit a choice between $f_{7/2}$ and $f_{5/2}$.

[22] B. L. Cohen, R. A. Moyer, J. B. Moorhead, L. H. Goldman, and R. C. Diehl, Phys. Rev. **176**, 1401 (1968).

V. DISCUSSION OF Pd^{106} LEVEL STRUCTURE

Coulomb excitation[23–26] and inelastic scattering[27] have been instrumental in establishing collective features of the lowest levels in the Pd^{106} nucleus. As in the other even-even Pd isotopes,[10,26] one observes a two-phonon quadrupole triplet at roughly twice the excitation energy of the single-phonon first-excited state. High-resolution conversion-electron measurements[1] and recent γ-decay studies employing Ge(Li) detectors[4,6,8,26] have resolved the highly degenerate 1.128 and 1.133 MeV 2^+ and 0^+ members of this triplet. While differentiation of levels 5 keV apart is beyond our experimental resolution, the (d, p) data to this unresolved doublet (see Fig. 5) are best fitted by an $l=2+0$ composite curve, consistent with previous assignments. The (p, α) angular distribution (see Fig. 7) to the 1.13 MeV doublet is best reproduced by a mixture of $p_{3/2}$ and $p_{1/2}$ pickup, and more closely verifies the 2^+ and 0^+ designations.

Assignment of the isolated 1.229-MeV level as the 4^+ component of the vibrational triplet has been generally accepted, although its spin has not been unambiguously measured. The level is surprisingly weakly excited in (d, p) and (p, α), but our best l assignments also allow $J^\pi=4^+$. In (d, p) stripping the 4^+ level is excited about an order of magnitude less than the 1.130-MeV doublet, whereas the (d, t) strength to the corresponding 4^+ state in Pd^{104} was larger than the pickup strength to either of the other two members. The nondegeneracy (~100 keV) noted for this multiplet is of the order of the spread observed for the two-phonon states[26] in Pd^{108} and Pd^{110}, but in significant contrast to the 18-keV triplet recently measured[10] in Pd^{104}. It appears that the vibrational interpretation for Pd^{106} cannot easily be carried beyond the two-phonon triplet, and that even here modifications of the simple collective model are required.

The 1.557-MeV level $(4^+, 3^+)$ in Pd^{106} has been placed in all level schemes resulting from the decay of the 6^+ isomers Ag^{106m} [1,4–9] and Rh^{106m}.[3] $Ag^{106}(1^+)$ and $Rh^{106}(1^+)$ decay studies[4,6] also indicate a nearby 2^+ state at 1.562 MeV on the basis of inferred β-decay of these low-spin isomers to this level and observation of γ lines to the ground and first excited states. Confirming the doublet structure, we note a slight broadening in the (d, p) data for this level. The observed $l=2$ (d, p) pattern agrees with the previous spin assignments. Further evidence for the existence of the less well-established higher excitation is furnished by the $Ag^{109}(p, \alpha)$ study. Here, the 1.56 MeV transfer is

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[25] P. H. Stelson and F. K. McGowan, Phys. Rev. **121**, 209 (1961).
[26] R. L. Robinson, F. K. McGowan, P. H. Stelson, W. T. Milner, and R. O. Sayer, Nucl. Phys. **A124**, 553 (1969).
[27] R. L. Robinson, J. L. C. Ford, Jr., P. H. Stelson, and G. R. Satchler, Phys. Rev. **146**, 816 (1966).

reasonably well duplicated by a $p_{3/2}$ DWBA calculation, with possibly some $f_{5/2}$ admixture, indicating that the 1.562-MeV member is more strongly excited in (p, α) than the lower level.

A state at 1.70 MeV, apparently of proton-hole character, is excited by (p, α), but is not seen in the (d, p) spectrum. Two of the schemes[1,4] resulting from Ag^{106m} decay place a level at 1.703 MeV, although Rao and Fink[6] present evidence that such a level is not fed in the Ag^{106m} decay. However, they do establish a 1^+ state at 1.704 MeV by γ-γ coincidences following the decay of the low-spin Ag^{106g} isomer. Strutz[4] furnishes the only other report of an investigation of Ag^{106g} decay, but does not postulate a 1.704-MeV level in his scheme. We note that one of the coincidence lines found by Rao and Fink is placed elsewhere by Strutz and represents the sole basis for his assignment of a level at 2.324 MeV. This latter state is not seen in any of the other studies, including the present work, and we prefer Rao and Fink's interpretation.[6] The (p, α) angular distribution for the 1.70-MeV transition is well fitted by $p_{1/2}$, which indicates 0^+ or 1^+ for the final state.

In a recent $Pd^{108}(p, t)Pd^{106}$ investigation[28] all low-lying states including the 1.229-MeV (4^+) level and at least one level of the 1.557–1.562-MeV doublet (probably the latter) were noticeably excited. Since direct (p, t) reactions excite natural parity states (here J^+_{even}, J^-_{odd}), this observation further corroborates the existing J^π assignments for these levels. The 1.704-MeV level is not or at least not strongly excited in (p, t), consistent with the 1^+ assignment of Ref. 6. However, the existence of such a low-lying 1^+ level would be in disagreement with the vibrational character of the lower Pd^{106} states. It must also be emphasized that a 1.704-MeV γ decay to the 0^+ ground state has not been seen[6]; hence, a 0^+ assignment for the 1.704-MeV level is not ruled out.

Up to 2.4 MeV excitation, the remaining levels populated by $Pd^{105}(d, p)$ have all been previously identified. The states at 1.932, 2.076, and 2.350 MeV as well as the 2.084-MeV octupole vibration are well established by many earlier measurements. The 1.910-MeV excitation had previously only been observed in (p, p')[27] while the 2.241-MeV state received tentative prior identification through the only reported Rh^{106g} decay.[6] Both (d, p) transitions to these levels proceed by pure $l=0$, yielding a 2^+, 3^+ assignment for the former and strengthening the 2^+ designation of the latter state.

Two reports[8,9] include a level at 2.282 MeV, although none of the other Ag^{106m} decay studies have indicated such a state. Our stripping spectra show a weak level at 2.282 MeV and confirm its existence.

Supported by coincidence spectra,[6] the literature postulates a 2.306- (4^-) and 2.308-MeV (+) doublet. Stripping restricts the positive-parity component to 2^+, 3^+. The weak odd-l contribution is masked in the (d, p) angular distribution for this multiplet. The $h_{11/2}$ stripping to the 2.398-MeV excitation confirms a negative-parity state, which was postulated in a low-resolution (d, d') experiment[29] at 2.41 MeV.

No appreciable evidence is found in the (d, p) and (p, α) spectra for the four states below 2.4 MeV that have been included in some earlier level schemes of Pd^{106}. A 0^+ state at 2.002 MeV is directly populated by β decay[4,6] from Ag^{106g} and Rh^{106g} and is well established.

A 2.040-MeV state has been postulated in some investigations[3,4,6] of the 6^+ isomers. However, Taylor *et al.*[8] reject this energy level on the basis of improper γ-ray intensity balance and account for the four singles lines involved in its prior institution. Based only on a single transition, one investigator[6] has reported an excitation at 2.189 MeV. Several studies[3,4,6,8,27] have disclosed an excitation at 2.365 MeV, and although there is no unanimous agreement,[1,5] this level is incorporated in our Pd^{106} diagram.

Other than classification of the two high-spin levels (2.756 and 2.951 MeV) that account for over 99% of the branching of Ag^{106m}, little definite information for Pd^{106} levels above 2.4 MeV has been obtained previously. The 2.437-, 2.623-, 2.709-, 2.827-, 2.918-, 3.042-, and 3.057-MeV states seen in Rh^{109g} decay, with the exception of the 2.623-MeV excitation, are identified only by singles transitions. Within the combined experimental error in absolute energy, all seven levels seem to be populated by (d, p) stripping. DWBA calculations were particularly useful in establishing the spin and parity of the 2.918-MeV level and one of the components of the 3.042–3.057-MeV doublet as 2^+.

Our high-resolution (d, p) spectra permitted the location of 20 additional, previously unknown, levels for excitations of 2–3 MeV. (See Table III). Good DWBA fits resulted in assignments of parities and reliable J^π limits for these as well as previously known levels. Relatively strong excitation by (p, t)[28] of the levels at 2.502, 2.738, 2.815, and 2.918 MeV indicates that these states have natural parity. This condition leads to fairly reliable 2^+ assignments for the 2.502-, 2.815-, and 2.918-MeV levels. The 2.738-MeV level presents a problem. The γ-ray data[1,5] require spin $5^\pm$ or 6^+, whereas the highest spin that can be reached by $l=2$ in $Pd^{105}(d, p)Pd^{106}$ is 5^+. This would seem to lead to a definite 5^+ assignment; however, 5^+ cannot be excited by (p, t). The most likely explanation is that there exists a doublet at this energy, possibly a 5^- state as suggested in Ref. 1, as well as the positive-parity state seen in (d, p).

Above 3 MeV, the Pd^{106}-level density is so high that the correlation of different experiments becomes difficult. We arbitrarily terminated our (d, p) analysis at 3.2 MeV, but even for lower excitation energies we

[28] J. H. Orloff and W. W. Daehnick (unpublished).

[29] R. K. Jolly, E. K. Lin, and B. L. Cohen, Phys. Rev. **128**, 2292 (1962).

must expect to have missed, or not resolved, a fair percentage of weaker levels, as there are at least 30 levels between 2- and 3-MeV excitation. This expectation is borne out by very recent results from average-resonance-capture studies of $Pd^{105}(n, \gamma)Pd^{106}$, for which Thomas and Bollinger[30] report the excitation of 40 Pd^{106} levels below 3 MeV. Twenty-eight of these states, including all levels below 2 MeV are identical with levels discussed above, and their parities and spin limits are consistent with those listed in Table III. The remaining 12 seem to be previously unknown levels. In particular, no previous evidence had been available for states with energies (parities) of $2.055^{(+)}$, $2.485^{(-)}$, $2.662^{(+)}$, $2.705^{(+)}$ (or 2.714^{+}), $2.784^{(+)}$, $2.861^{(-)}2.886^{(-)}2.908^{(-)}$, and $2.936^{(-)}$, MeV.

It is perhaps surprising that the 2.055-MeV level has not been seen in this or previous studies.[1–9] The other levels, if only weakly excited in (d, p) could easily be hidden in the tails of stronger peaks (see Fig. 1). This explanation is very likely for negative-parity states, which in $Pd^{105}(d, p)Pd^{106}$ would have to be populated by dynamically disfavored $l=5$ transitions. Reference 30 also assigns previously unknown negative-parity levels at 2.500, 2.579, 2.899, and 2.973 MeV, i.e., at energies very close to states that in Table III have been assigned positive parity. There is good evidence in our data for a 2.579-MeV level, which is often unresolved from the 2.592-MeV level. One member of the doublet, presumably the 2.592 level, is excited by $l=0$; hence we have $J^{\pi}=2^{+}$, 3^{+} (see Fig. 5). However, only the $l=0$ component is certain in the decomposition of the angular distribution. An admixture of $l=5$ in addition to the proposed $l=2$ component is possible, and the $2.579^{(-)}$ assignment is not inconsistent with our (d, p) data. Similarly, we see an unresolved doublet at 2.975 MeV, which might include the $2.973^{(-)}$ level of Ref. 30.

There is no similarly persuasive (d, p) evidence for negative-positive–parity doublets at 2.500 (2.502) and 2.899 (2.903) MeV. However, in these cases, too, the (d, p) transitions are not pure $l=0$, and odd l's may be part of the admixtures. Since negative-parity states are more strongly excited in the $Pd^{105}(n, \gamma)Pd^{106}$ experiment,[30] the converse of that observed for $Pd^{105}(d, p)Pd^{106}$ (see Fig. 4), it seems reasonable to conclude that the two experiments detect different members of some very close doublets. This argument is strengthened by the observation that apart from the four states discussed, there are at least six other established positive-parity states below 3 MeV which are not reported in Ref. 30.

[30] G. E. Thomas and L. M. Bollinger, Bull. Am. Phys. Soc. 14, 515 (1969).

VI. SUMMARY

Previously, much of the level structure of Pd^{106} has been deduced by studies of β-decay of Ag^{106} and Rh^{106}. The collective nature of its low-lying states was established by Coulomb excitation and inelastic scattering. The present high-resolution (d, p) and (p, α) investigations independently verify many previous level energy and spin assignments and clarify some discrepancies in the literature. In addition, 20 new levels are documented in the 2.4–3.2-MeV region of excitation.

Stripping calculations were performed using the University of Colorado DWBA code DWUCK and employed both local zero-range and nonlocal finite-range options. Better reproduction of (d, p) transitions was achieved by inclusion of the latter corrections. In addition to the deduction of l transfer and J^{π} limits, quantitative application of DWBA calculations yielded spectroscopic factors for 34 measured (d, p) transitions. The observed strength was composed predominantly of $l=2$ and 0 transfer and led to U_{lj}^2 estimates for the $2d$ and $3s_{1/2}$ neutron levels in Pd^{105}. Both were within 10% of the previous $Pd^{105}(d, t)$ results for this nucleus. Failure to detect sizable $l=4$ and 5 strengths is ascribed to maskings of the weak cross sections predicted for large l transfers by $l=0$ and 2 patterns, and little quantitative significance is attached to the extracted fullness of the g and h states.

The low cross sections and limited ($\sim$20 keV) resolution experienced in the 12-MeV $Ag^{109}(p, \alpha)Pd^{106}$ experiment rendered this work less successful than the (d, p) study in establishing spectroscopic details of the higher excitations in Pd^{106}. Nevertheless, angular distributions to ten levels or groups of levels were measured and compared with ORNL code JULIE local zero-range calculations. The theoretical predictions assumed a triton-cluster transfer and led to excellent agreement, particularly with the observed j-dependent $p_{3/2}$ and $p_{1/2}$ transitions.

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