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Levels in ^{144}Nd from the ^{143}Nd(d, p) and the ^{146}Nd(p, t) reactions*

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The energy levels in ^{144}Nd have been studied by means of the ^{143}Nd(d,p) reaction at $E_d = 25$ MeV and the ^{146}Nd(p,t) reaction at $E_p = 31$ MeV. Angular distributions, values for the transferred angular momenta, and spectroscopic and enhancement factors based on distorted-wave Born approximation calculations have been obtained for ≈ 30 states. The (d,p) spectroscopic strengths have been compared with the results of a calculation based on a two-particle core coupling model.

[NUCLEAR REACTIONS ^{143}Nd(d,p), $E=25$ MeV; measured $\sigma(\theta)$. ^{146}Nd(p,t), $E=31$ MeV; measured $\sigma(\theta)$. ^{144}Nd deduced levels, L, S. DWBA analysis.]

I. INTRODUCTION

The existing information on ^{144}Nd energy levels arises mainly from ^{144}Pr and ^{144}Pm decays,[1-5] the ^{143}Nd(n,γ) reaction,[6] and the ^{142}Nd(t,p) reaction.[7] The (n,γ) measurements show that above 3 MeV, the average level spacing is less than 20 keV, rendering charged-particle spectroscopy quite difficult. These measurements also suggest that below 3 MeV, it should be possible to characterize the energy levels in ^{144}Nd via the ^{143}Nd(d,p) and the ^{146}Nd(p,t) reactions. The present paper is concerned with these reactions. The (d,p) spectroscopic strengths determined in this study have already been utilized to test the predictions of the core coupling model as described in a later section.

II. THE ^{143}Nd(d,p) REACTION

A. Experimental details

The (d,p) measurements were carried out with a 25 MeV deuteron beam from the Oak Ridge Isochronous Cyclotron. The self-supporting targets were made by rolling metal enriched to 91.6% in ^{143}Nd. The main impurities were 2.6% ^{142}Nd and 3.9% ^{144}Nd. Target thicknesses ($\approx$500 μg/cm^2) were determined by direct weighing. The uncertainty in the thickness contributed 10% to the uncertainty in the absolute cross sections. The protons were analyzed by a broad range magnetic spectrograph and detected with photographic emulsions at the focal plane of the spectrograph.

Data were obtained at eleven laboratory angles between 4° and 48°. The spectra obtained at two angles are shown in Fig. 1. The resolution, limited by the energy spread in the rolled-metal target, was always better than 30 keV (full width at half maximum). Eighteen distinct proton groups were observed below 3.2 MeV excitation. The peak at $\approx$1.69 MeV was ascribed to the ^{142}Nd(d,p) reaction leading to the known 7/2$^-$ ground state of ^{143}Nd. The ^{144}Nd(d,p) reaction leading to the 7/2$^-$ ground state of ^{145}Nd contributed to an unresolved doublet at 2070 keV. The 2185 keV peak corresponded to a known 2178 (2$^+$) keV - 2186 (1$^-$) keV doublet.[6]

B. Distorted-wave analysis

The experimental angular distributions shown in Fig. 2 and 3 were analyzed by comparing them with DWBA (distorted-wave Born approximation) predictions calculated in zero-range approximation with the computer code JULIE.[8] The parameters used in the calculations are given in Table I. The ^{144}Nd ground state (J^π = 0$^+$) and the ^{143}Nd ground state (J^π = 7/2$^-$) can be reached only via pure ℓ = 3 transfers. Fig. 2 shows that the DWBA calculations are capable of correctly reproducing the measured angular distributions for these states.

Most of the observed levels in ^{144}Nd can be reached by more than one ℓ-transfer. The best combination of ℓ-values and strengths for each level was found through a least squares fit procedure. Stripping was restricted to the $2f_{7/2}$, $3p_{3/2}$ and $1h_{9/2}$ shell model states in the case of positive parity final states and to the $1i_{13/2}$, $2d_{3/2}$ and $3s_{1/2}$ states in the case of negative parity final states in ^{144}Nd. The excitation energies, J^π assignments and spectrographic strengths are given in

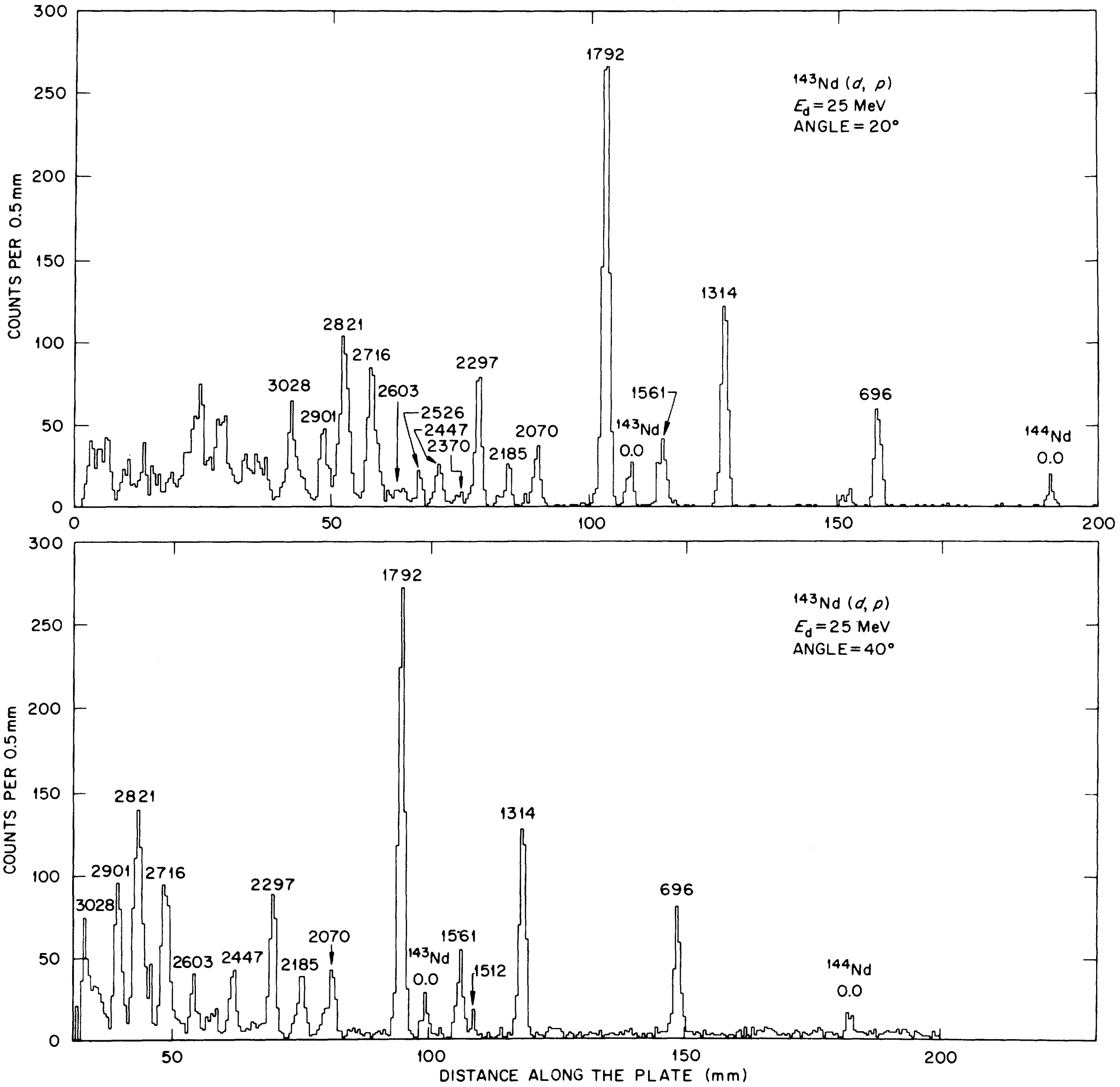

FIG. 1. The proton spectrum from the ^{143}Nd(d,p) reaction. Peaks are labeled by the excitation energy (in keV) measured in this reaction.

Table II. The J^π assignments are from previous studies.[4-6] The combinations of ℓ-values listed in Table II are those yielding the minimum chi-square value. Uncertainties listed for the individual ℓ-values are those derived from the error matrix associated with the chi-square minimization procedure. These uncertainties were obtained according to the expressions derived by Cziffra and Moravscik.[9] They correspond approximately to one standard deviation and are included to provide an indication of the accuracy with which one can determine the individual ℓ-transfer components in the case of mixed-ℓ transitions. In all cases it is seen that those ℓ-transfers which contribute a significant portion of the cross section are rather well determined. Weak transitions and high-ℓ transfers are noticeably less well established. It should also be noted that the uncertainties quoted in Table II are relative uncertainties associated with reducing each curve into its components and do not include the overall uncertainty of 20% generally associated with absolute spectroscopic amplitudes derived from comparisons of experimental results with DWBA predictions. For most levels, while the

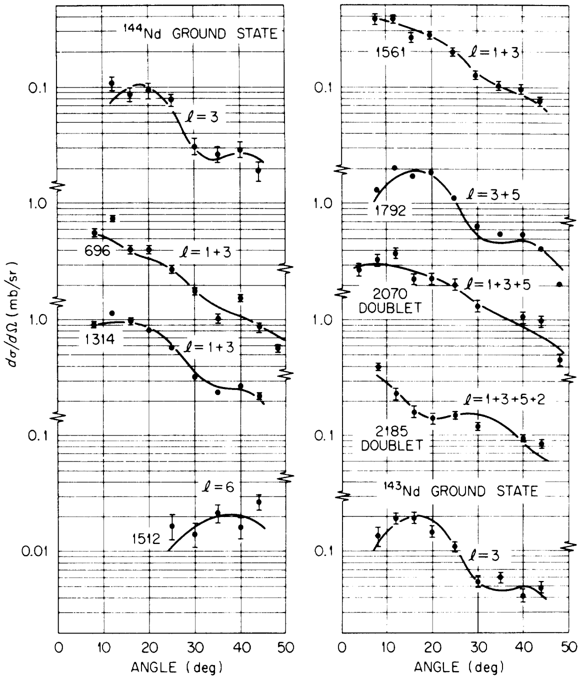

FIG. 2. Experimental angular distributions for states in ^{144}Nd below 2.2 MeV excited in the ^{143}Nd(d,p) reaction.

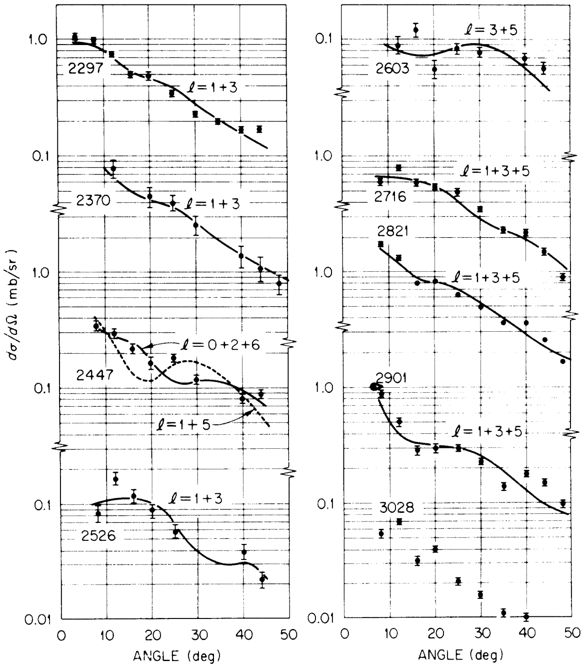

FIG. 3. Experimental angular distributions for states in ^{144}Nd in the 2.2 - 3.1 MeV range excited in the ^{143}Nd(d,p) reactions.

fits (see Figs. 2 and 3) were better for odd-ℓ stripping, the presence of even-ℓ values cannot be completely ruled out by these data. The known 3$^-$ state at 1512 keV was observed only at angles 25° or greater, consistent with an ℓ = 6 assignment. The only other state with a preference for even-ℓ stripping was the state at 2447 keV.

III. THE ^{146}Nd(p,t) REACTION

A. Experimental details

The (p,t) measurements were carried out with a 31 MeV proton beam from the Oak Ridge Isochronous Cyclotron. The targets were made by evaporating 90% enriched ^{146}Nd$_2$O$_3$ on a carbon foil. Target thicknesses were typically 250 μg/cm^2. The tritons were analyzed by a broad range magnetic spectrograph and detected with photographic emulsions.

Data were obtained over an angular range 9°-32°. A typical spectrum is shown in Fig. 4. Even with the ≈20 keV resolution (full width at half maximum) attained in these measurements, it was apparent that many of the peaks above 2 MeV excitation were due to unresolved multiplets.

B. Distorted-wave analysis

The experimental angular distributions shown in Figs. 5 and 6 were analyzed by comparing them with

TABLE I. Optical potential and bound-state parameters used in the distorted-wave calculations

		Deuteron[a]	Proton[b]	Bound state
V	(MeV)	101.4	52.7	
r_o	(fm)	1.085	1.16	1.20
a	(fm)	0.857	0.75	0.65
W	(MeV)	0	4.5	
W_D	(MeV)	15.25	4.5	
r'_o	(fm)	1.293	1.37	
a'	(fm)	0.788	0.63	
r_c	(fm)	1.3	1.25	1.25
V_s	(MeV)	7.2	6.04	
r_s	(fm)	1.085	1.064	
a_s	(fm)	0.857	0.738	
λ_s				25

[a] Average values from analyses by C. M. Perey and F. G. Perey, Phys. Rev. 152, 923 (1966).

[b] Average values from analyses by M. P. Fricke, E. E. Gross, B. J. Morton, and A. Zucker, Phys. Rev. 156, 1207 (1967).

DWBA predictions calculated with the code JULIE.[8] The optical model parameters for the proton channel were taken from the work of Becchetti and Greenlees[10] while the triton parameters were those used in previous studies of Zr isotopes.[11] The single-neutron binding energies employed to compute the transfer form-factor were taken as one half of the two-neutron separation energy required to reach the

TABLE II. Summary of ^{143}Nd(d,p) results

Experiment				Calculation[15]		
E(level) ± 7 keV	J^π	ℓ_n	$G_{\ell J}$ [a]	E(level)	ℓ_n	$G_{\ell J}$
0	0^+	3	0.09 ± 0.01	0	3	0.12
696	2^+	1	0.09 ± 0.03	696	1	0.06
		3	0.23 ± 0.04		3	0.26
1314	4^+	1	0.11 ± 0.02	1378	1	0.17
		3	0.67 ± 0.05		3	0.66
1512	3^-	6	0.22 ± 0.03	(1510)	6	0.07
1561	2^+	1	0.06 ± 0.02	1547	1	0.09
		3	0.18 ± 0.04		3	0.25
1792	6^+	3	1.37 ± 0.19	1812	3	1.93
		5	0.25 ± 0.10		5	0.03
2070[b]	2^+	1	0.04 ± 0.01			
		3[c]	0.14[c] ± 0.03			
		5	0.39 ± 0.20			
2185[b]		1	0.04 ± 0.04			
		3	0.02 ± 0.02			
		5	0.81 ± 0.30			
		2	0.04 ± 0.04			
2297		1	0.16 ± 0.02			
		3	0.28 ± 0.04			
2370	$(2)^+$	1	0.014 ± 0.003			
		3	0.026 ± 0.004			
2447[d]		0	0.07 ± 0.07			
		2	0.16 ± 0.07			
		6	0.41 ± 0.20			
2526	$(2)^+$	1	0.01 ± 0.01			
		3	0.07 ± 0.02			
2603		3	0.01 ± 0.01			
		5	0.74 ± 0.18			
2713		1	0.07 ± 0.03			
		3	0.33 ± 0.05			
		5	0.65 ± 0.22			
2821[b]		1	0.29 ± 0.06			
		3	0.37 ± 0.09			
		5	0.50 ± 0.50			
2901		1	0.14 ± 0.06			
		3	0.10 ± 0.05			
		5	0.44 ± 0.44			
3028						

[a] Deduced from $\sigma_{\text{exp}} = \Sigma\, 1.5\, G_{\ell J}\sigma_{\text{JULIE}}$, where $G_{\ell J} = [(2J_f + 1)/(2J_i + 1)]\, C^2S$, assuming $3s_{1/2}$ $(\ell = 0)$, $3p_{3/2}(\ell = 1)$, $2d_{3/2}(\ell = 2)$, $2f_{7/2}(\ell = 3)$, $1g_{7/2}(\ell = 4)$, $1h_{9/2}(\ell = 5)$ and $1i_{13/2}(\ell = 6)$ stripping. The summed spectroscopic strengths were as follows:

$\sum_{\ell=0} G_{\ell J} = 0.07 \pm 0.07$; $\sum_{\ell=1} G_{\ell J} = 1.02 \pm 0.11$; $\sum_{\ell=2} G_{\ell J} = 0.20 \pm 0.08$; $\sum_{\ell=3} G_{\ell J} = 3.89 \pm 0.24$;
$\sum_{\ell=5} G_{\ell J} = 3.78 \pm 0.62$; and $\sum_{\ell=6} G_{\ell J} = 0.63 \pm 0.20$.

[b] Complex peak

[c] An undetermined portion of the $\ell_n = 3$ strength is due to the excitation of the ground state of ^{145}Nd.

[d] Negligible interference from the excitation of the 742-keV, $3/2^-$ state in ^{143}Nd.

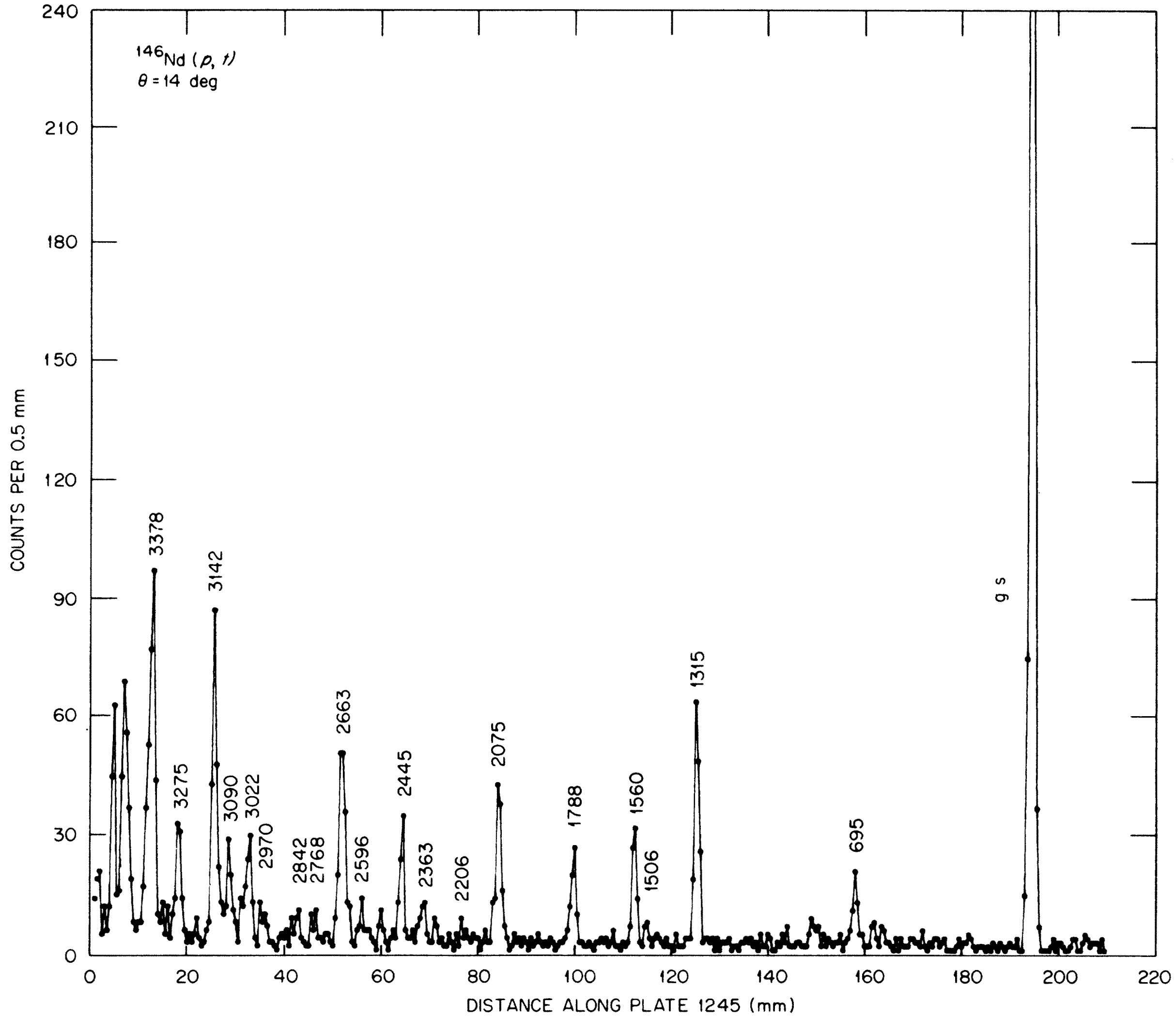

FIG. 4. The triton spectrum from the ^{146}Nd(p,t) reaction. Peaks are labeled by the excitation energy (in keV) measured in this reaction.

final state involved. The main results are given in Table III. Preliminary results restricted to L = 0 states have been previously reported.[12] The ^{146}Nd(p,t) reaction has also been studied by Yagi *et al.*[13] but only possible pairing states in the 3500 keV region were reported by these authors.

The ^{142}Nd(t,p) reaction was employed by Chapman *et al.*[7] to study ^{144}Nd levels. These authors reported, in addition to others, two levels near 2960 and 3020 keV which did not have L = 0. There was an apparent contradiction since the present (p,t) measurements suggested L = 0 assignments for levels at 2970 and 3022 keV. However, in view of the high level density and the fact that the two reactions are likely to excite different types of states, we suggest that these are probably not the same levels.

The angular distributions for most of the observed states are reproduced reasonably well by DWBA predictions for L = 0, 2 or 4 transfers as shown in Figs. 5 and 6. However, the 1506 and 1788 keV levels present some difficulties. The angular distributions for these states (see Fig. 5) would suggest L = 6 and L = 5, respectively, whereas they should be L = 3 and L = 6, respectively, from the known 3^- assignment for the level at 1510.2 keV and 6^+ assignment for the level at 1791.2 keV.[4,5] The lack of agreement for the 6^+ level may reflect a general insensitivity for high angular momentum transfers at this relatively low proton energy. However, the complete failure to fit the angular

TABLE III. Levels in ^{144}Nd from the ^{146}Nd(p,t) reaction

E(level)[a]	L[b]	ξ[c]
0	0	5.5
695	2	≈1.1
1315	4	1.5
1506	(6)	
1560	2	1.5
1788	(5,6)	≈1.3 if L = 6
2075[d]	0 (+?)	0.4
2206?		
2363	(2)	(0.7)
2445	2	1.1
2596	(4,5)	
2663[d]	0	0.5
2768	(4,5)	
2842[d]	0	0.1
2970	(0)	(0.06)
3022[d]	0 (+?)	0.3
3090	(2)	(1.1)
3142	0	0.6
3275	(2)	(1.4)
3378	(2)	(3.8)

a) Uncertainty estimated to be ±0.5%.

b) A parenthesis denotes an uncertain value for the angular momentum transfer.

c) Enhancement factor (see Ref. 11) assuming $(2f_{7/2})^4_0 \rightarrow (2f_{7/2})^2_J$ transition.

d) Probable multiplet indicated by peak shape.

distribution for the 3⁻ level may indicate a pathological case at this energy for this combination of target mass and angular momentum transfer. Since the causes for these discrepancies are not understood, only the L = 0 and L = 2 assignments should be considered reliable for J^π assignments.

IV. DISCUSSION AND COMPARISON WITH THEORY

The ^{144}Nd nucleus and the other even-even N = 84 nuclei offer a method of evaluating the predictions of both the unified and core-coupled models. The presence of the N = 82 shell closure allows calculations to be made under the assumption of two particles outside an inert core.

In the unified model calculations of Heyde and Brussaard,[14] the two extra-core neutrons were assumed to be in the $2f_{7/2}$ orbit and were coupled to a vibrational core. These calculations reproduced the observed energy levels below 2 MeV. However, restricting the neutrons to the $2f_{7/2}$ orbit severely limits the number of states which can be predicted.

Vanden Berghe[15] has recently carried out core-coupling model calculations for N = 84 nuclei with two neutrons coupled to the N = 82 core. These calculations assume the core to be a harmonic quadrupole vibrator. Preliminary (d,p) spectroscopic factors from the present study was employed by Vanden Berghe in comparing the experimental values with the theoretical ones. Such a comparison is also shown in Table II. It is seen that the correspondence is quite good with the possible exception of the ℓ = 5 component of the 1792 keV level. In his paper, Vanden Berghe also points out that the observed ℓ = 6 strength of the 1512 keV, 3⁻

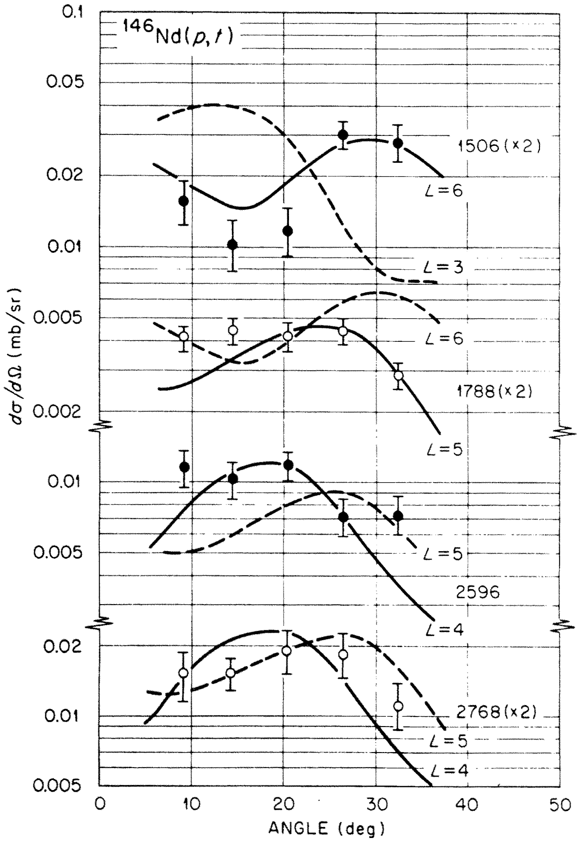

FIG. 5. Experimental angular distributions suggestive of high-L transfers in the ^{146}Nd(p,t) reaction. See text for discussion concerning the 1506 and 1788 keV levels.

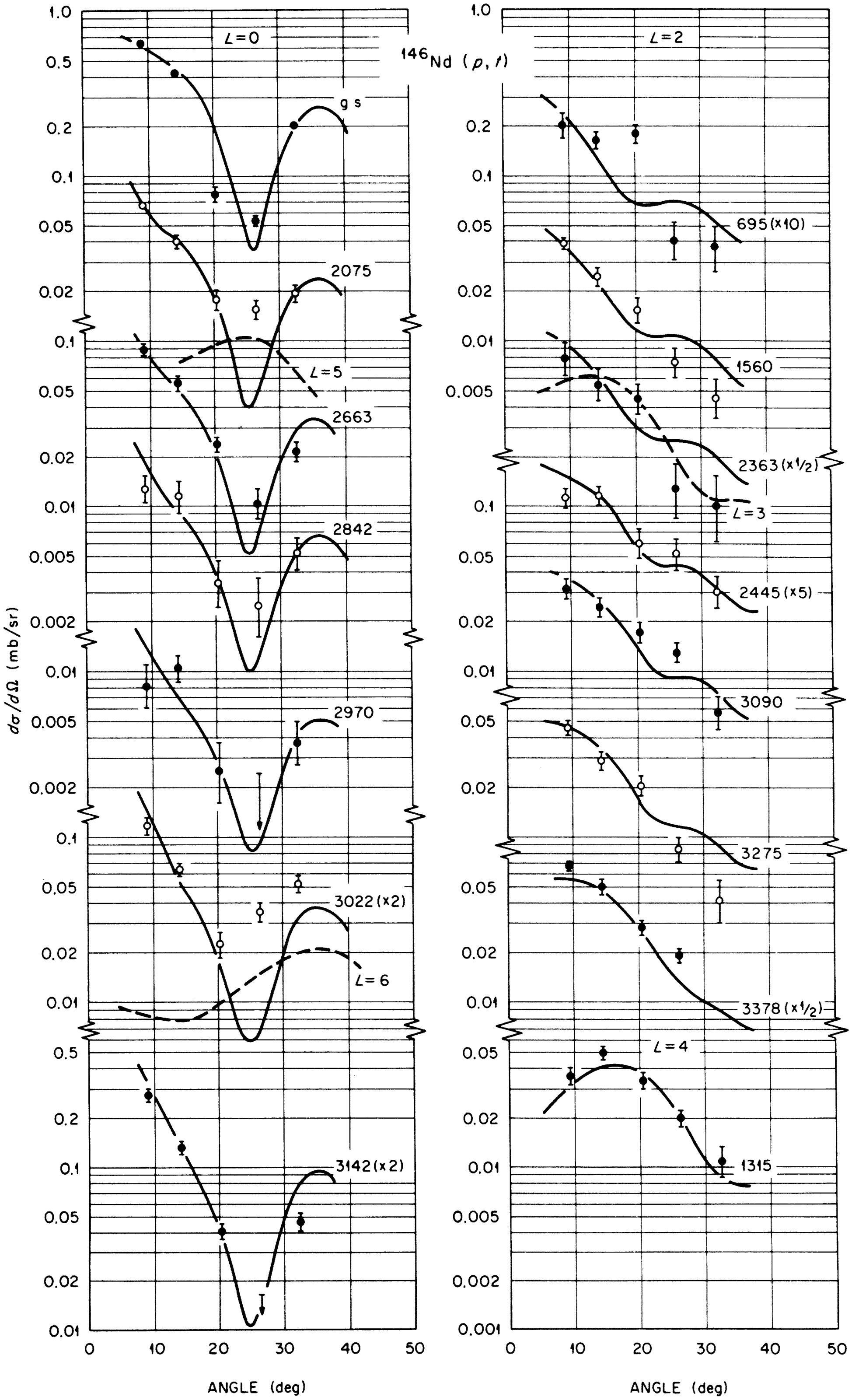

FIG. 6. Experimental angular distributions suggestive of low-L transfers in the ^{146}Nd(p,t) reaction.

state is approximately three times the calculated value but that a lowering of the $1i_{13/2}$ single-particle energy would result in an increase in the calculated strength. Such a lowering is supported by recent (d,p) studies in this mass region in which strong $\ell = 6$ transitions have been observed in the 1.0 - 1.6 MeV excitation energy region. These studies include (d,p) reactions on ^{138}Ba, ^{140}Ce, ^{142}Nd, and ^{144}Sm targets carried out by Booth, Wilson and Ipson[16] and on a ^{144}Nd target by Hillis, *et al.*[17]

The results of the calculations made by Vanden Berghe[15] indicate that the wavefunctions of the states below 2 MeV in ^{144}Nd are fairly well understood. The present data for the higher-lying levels, when compared with future calculations, may help to establish the wavefunctions for these levels also.

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