A STUDY OF THE ^{144}Nd(d, p)^{145}Nd AND ^{146}Nd(d, t)^{145}Nd REACTIONS

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Energy levels of the ^{145}Nd nucleus were studied using the ^{144}Nd (d, p) ^{145}Nd and ^{146}Nd (d, t) ^{145}Nd reactions at a bombarding energy of 12.1 MeV. The reaction products were observed using a magnetic spectrograph and photographic plate recording. The spectroscopic factors for the levels observed were obtained from DWBA calculations.

1. Introduction

Nuclei with $N = 85$ neutrons were usually considered to be "spherical" and are expected to have a closed neutron shell structure. The single particle shell-model states in the $83 \leqslant N \leqslant 125$ shell are: $3p_{1/2}$, $3p_{3/2}$, $2f_{5/2}$, $2f_{7/2}$, $1h_{9/2}$ and $1i_{13/2}$. A neutron transfer reaction, such as (d, p) or (d, t), is well suited for exciting these one-particle states. In a pick-up (d, t) reaction we expect to pick-up neutrons from orbitals outside the closed shell and from the closed shell core $N = 82$ itself ($2d_{3/2}$, $3s_{1/2}$, $1h_{11/2}$, $2d_{5/2}$ and $1\,g_{7/2}$).

The levels observed using pick-up reactions provide information complementary to the stripping reactions on the location of the neutron hole strength.

Coupling of the neutrons from the open shell to the $N = 82$ core results in a mixing of the single-particle states. Because of this mixing the single-particle strength is distributed over several states. The sum of the spectroscopic factors, S_J, for these states should equal unity.

The existing data on the properties of low-lying levels in the ^{145}Nd nucleus are limited and come mainly from analyses of the (d, p), (p, d), (α, ^{3}He) and (n, γ) reactions and from the decay of ^{145}Pr, [1–5]. Studies of the (d, p) reaction by Wiedner et al. [1] yielded energies and spins of only a few states. The (d, p) measurement of Gales et al. [2] supplied much information concerning many of the states up to 3.8 MeV. The studies of Hillis et al. [3] gave more complete information concerning the neutron shell structure of ^{145}Nd. Hillis et al. obtained information concerning the ^{145}Nd levels by means of γ-ray spectroscopy

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TABLE I

Levels populated in the ^{144}Nd(d, p) ^{145}Nd and ^{146}Nd(d, t) ^{145}Nd reactions

Energy average (keV)		Assignment		$d\sigma/d\Omega$(d,p) (μb/sr)			$d\sigma/d\Omega$(d,t) (μb/sr)			(d, p)	(d, t)
(d, p)	(d, t)	previous l, J^π	present l	60°	90°	125°	60°	90°	125°	$(2J+1)S^{(+)}_{lj}$	$S^{(-)}_{lj}$
1	2	3	4	5	6	7	8	9	10	11	12
0	0	3,7/2$^-$	3	1407	780	363	1100	646	323	4,08	1.81
68	67	1+3 3/2$^-$, 5/2$^-$	1	262	88	35	338	152	53	0.21	0.15
656	652	5 9/2$^-$	5	12	6	10	9	20	15	0.25	0.35
749	742	5 9/2$^-$	5	133	80	58	11	6	4	2.17	0.16
780	775	1 3/2$^-$	1	1763	885	343	288	155	63	1.41	0.20
919	912	1 1/2$^-$	1	794	358	152	102	56	19	0.58	0.08
937	929	3 5/2$^-$	3	511	313	123	57	30	12	1.13	0.13
	1077	2 3/2$^+$	2				57	37	26		0.14
1110	1100	6 13/2$^+$	6	112	—	87	1		2	3.70	0.07
1150		3 5/2$^-$	3	30	8	9				0.05	
1213	1205				1	1	2	1	1		
1250	1242	3 5/2$^+$	3	66	82	39	3	6	2	0.24	0.02
1284		3 5/2$^-$	3	3	5	3				0.01	
	1306	2 3/2$^+$, 5/2$^+$	2				36	24	10		0.09
	1325	0 1/2$^+$	0				267	171	102		0.43
1331		3 5/2$^-$	3	254	185	101				0.62	
	1522	2 3/2$^+$	2				614	497	297		2.32
1575	1575	3 5/2$^-$	3	56	42	16	5	4	2	0.12	0.02
1528		3,5 9/2$^-$	5	31	23	12				0.44	
1592		1,3 5/2$^-$	1	307	143	67				0.18	
1653		3(5/2)$^-$	3	8	6	3				0.02	
1684		3,(5/2$^-$)	3	16	5	5				0.03	
1700	1706	0, 1/2$^+$	0				408	276	181		0.90
1713			3	15		4				0.03	
1744		1	1	145	79	35				0.09	
1762		3	3	206	115	60				0.36	

	1793	5(11/2$^-$)	5				26	67	41		2.09
	1813		2				29	25	8		0.12
1822			5	6	5					0.10	
1846		6(13/2$^+$)	8	57	53	51				2.10	
1885		1(3/2$^-$)	1	178	85	37				0.09	
1913		1	3	11	11	4				0.02	
	1940							4	2		
	1953	5(11/2$^-$)	5				4	16	4		0.37
1969		(3,3+6)	3	92	83	27				0.18	
2004		1	1	54	5	5				0.02	
2018		5(9/2$^-$)	5		3	4				0.08	
	2047	2(3/2$^+$)	2				36	42	33		0.29
2090		1,5(9/2$^-$)	5	50	28	21				0.65	
	2117	3/2$^+$	2				5		8		0.05
2117		1	(5)		3	11				0.14	
2133			(5)		3	5				0.08	
2176	2175	1(3/2$^-$)	1		235	132		6		0.27	
	2198	(3/2$^+$, 5/2$^+$)	2				13	18			0.13
2223			3		65	44				0.20	
2246			1		22	10				0.02	
2270		1	1		90	44				0.09	
2291		(1,3)	3	138	70	38				0.20	
2331		1(3/2$^-$)	1	218	85	40				0.09	
2355		1	3	159	73	43				0.21	
2374		3(5/2$^-$)	3	370	214	111				0.46	
2423		1	1	169	84	33				0.08	
2449			3	42	21	17				0.07	
2471			1	34	18	5				0.02	
2481		(3,1+5)	(6)	33	47	34				1.27	
2510		30	3	229	184	68				0.37	
2533		1	3	36	24	15				0.06	
2566		1	(3)	161	91	47				0.22	
2606		1	(3)		138	73				0.33	
2627		3	(3)		87	43				0.20	
2643			(1)		20	5				0.02	
2670			(6)		38	54				1.58	

TABLE I (continued)

1	2	3	4	5	6	7	8	9	10	11	12
2713		3	(3)	364	179	89				0.45	
2748		3	1	331	111	51				0.11	
2781		3	1	214	78	40				0.08	
2810		1	1	283	122	61				0.11	
2839			1	57	30	10				0.02	
2858			1	54	22	8				0.02	
2882		1	(3)	89	57	29				0.12	
2907			(1)								
2938			1	84	57	15				0.03	
2977		3	1	201	76	35				0.06	
3001			1		38	13				0.03	
3027		1	1	131	75	38				0.06	
3051			1	107	83	29				0.05	
3086			1	48	15	5				0.01	
3117			1	104	46					0.04	
3140			3	74	61					0.11	
3159			3	75	56					0.10	
3181			3	67	47					0.09	
3214		1	1	234	107					0.09	

from the decay of ^{145}Pr and from the ^{144}Nd(n, γ) reaction with thermal neutrons and by charged-particle spectroscopy from the complement (d, p) and (α, ^{3}He) stripping reaction and from the pick-up (p, d) reaction.

It appears that independent investigations of the structure of the ^{145}Nd nucleus in a wide variety of reactions are generally consistent, but the level density above 1 MeV is quite high and different reactions populate different sets of levels.

In the present experiment the ^{144}Nd(d, p)^{145}Nd and ^{146}Nd(d, t)^{145}Nd reactions were used to study the structure of ^{145}Nd. The energy spectra of protons and tritons were measured for transitions to a number of final states, from the (d, p) and (d, t) reactions up to the 3.2 MeV and 2.2 MeV excitation energies, respectively. The data were analysed by the DWBA method.

2. *Experimental procedure and results*

The experimental method is very similar to that used in [6, 7]. The beam of 12.1 MeV deuterons was obtained from the Niels Bohr Institute EN tandem accelerator and the reaction charged products were analysed in a high-resolution magnetic spectrograph [8] with photographic plate recording.

The targets were prepared by vacuum evaporation onto a thin carbon backing using isotopically enriched materials in an oxide form. The neodymium targets were enriched to about 96% in ^{144}Nd and ^{146}Nd. The target thicknesses were approximately 50 μg/cm^2 and the carbon backing films about 40 μg/cm^2. The spectra were recorded at angles of 60°, 90° and 125°. The energy resolution was approximately 12–15 keV. The photographic plates were reviewed on 0.25 mm strips. The absolute cross sections were determined by normalization to the cross section for elastic deuteron scattering [9]. The uncertainties in the absolute cross section are about 20%, while for the smaller cross sections or poorly resolved levels they are approximately 60%. Relative cross sections of well resolved peaks are more accurately determined about 10%. The major contributions to the experimental uncertainties arise from the normalization procedure, from track-counting reproducibility and from the statistics. The level energies obtained by averaging determinations at three different angles are listed in Table I. The uncertainties of the energy level determination are about ± 3 keV and ± 6 keV for strong and weak levels.

The protons and triton spectra obtained from the ^{144}Nd(d, p)^{145}Nd and ^{146}Nd(d, t) ^{145}Nd reactions at an angle of 90° are shown in Fig. 1. The vertical lines represent the energies at which proton and triton groups were found and the heights of the lines indicate the absolute cross sections for the states. The level energies obtained from average level positions at three different angles are listed in Table I, which also summarizes the differential cross sections measured and the suggested assignments for most of the levels investigated. The assignment was taken from Refs. [1–3] and was also determined in the present measurements from the ratios

$$R = (d\sigma/d\Omega)_{60°}/(d\sigma/d\Omega)_{90°} \text{ and } R = (d\sigma/d\Omega)_{60°}/(d\sigma/d\Omega)_{125°}.$$

To extract spectroscopic information from the experimental data a series of DWBA calculations were done using the computer code DWUCK. The deuteron, proton and triton optical model parameters were taken from papers [10, 11] because those parameters have been applied successfully for the analyses of the (d, t) and (d, p) reactions on rare-earth targets [10, 12].

The calculations were performed for neutrons transferred to the $3p_{1/2,\,3/2}$; $2f_{5/2,\,7/2}$; $1h_{9/2}$; $1i_{13/2}$; $2d_{3/2,\,5/2}$; $3s_{1/2}$ and $1h_{11/2}$ shell model states. The DWBA calculations

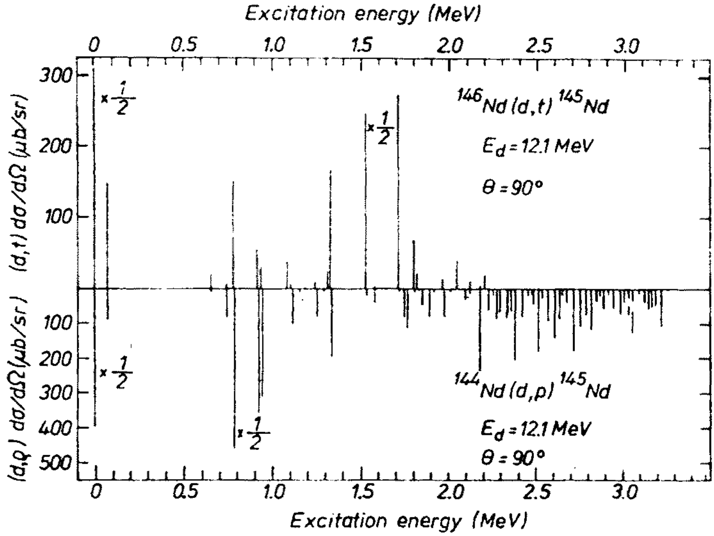

Fig. 1. Triton and proton spectra for the ^{146}Nd(d, t) ^{145}Nd and ^{144}Nd(d, p)^{145}Nd reactions

were used to extract the spectroscopic factors $S_{lj}^{(+)}$ and $S_{lj}^{(-)}$ by fitting the experimental cross sections obtained at 60°, 90° and 125° to the DWBA cross sections:

$$\frac{d\sigma}{d\Omega} = N^{(+)}S_{lj}^{(+)}(2J+1)\sigma_l^{(+)}(\theta) \quad \text{for the (d, p) reaction,}$$

$$\frac{d\sigma}{d\Omega} = N^{(-)}S_{lj}^{(-)}\sigma_l^{(-)}(\theta) \quad \text{for the (d, t) reaction,}$$

where $\sigma_l^{(+)}(\theta)$ and $\sigma_l^{(-)}$ are the single particle transfer cross sections obtained from DWBA calculations for the (d, p) and (d, t) reactions, respectively, and $N^{\pm}$ is the normalization factor assumed to be 1.5 and 3.0 for the (d, p) and (d, t) reactions, respectively.

The spectroscopic factors $S_{lj}^{(+)}(2J+1)$ and $S_{lj}^{(-)}$ extracted from the (d, p) and (d, t) reactions studied are listed in Table I.

The earlier and present high-resolution studies of the ^{145}Nd nucleus using the (d, p), (p, d) and (d, t) reactions are summarized in Fig. 2 together with the l-transfer values and spectroscopic factors. From Fig. 2 one can see that, in general, there is a reasonably good agreement between the energies and the spectroscopic factors obtained from the different (d, p) reactions studied.

The present (d, p) results and previous results [2, 3] are in satisfactory agreement. However, in a few cases the assignment is not consistent with that of Refs. [2] and [3]. This occurs mostly in the higher excitation energy region (above 1 MeV).

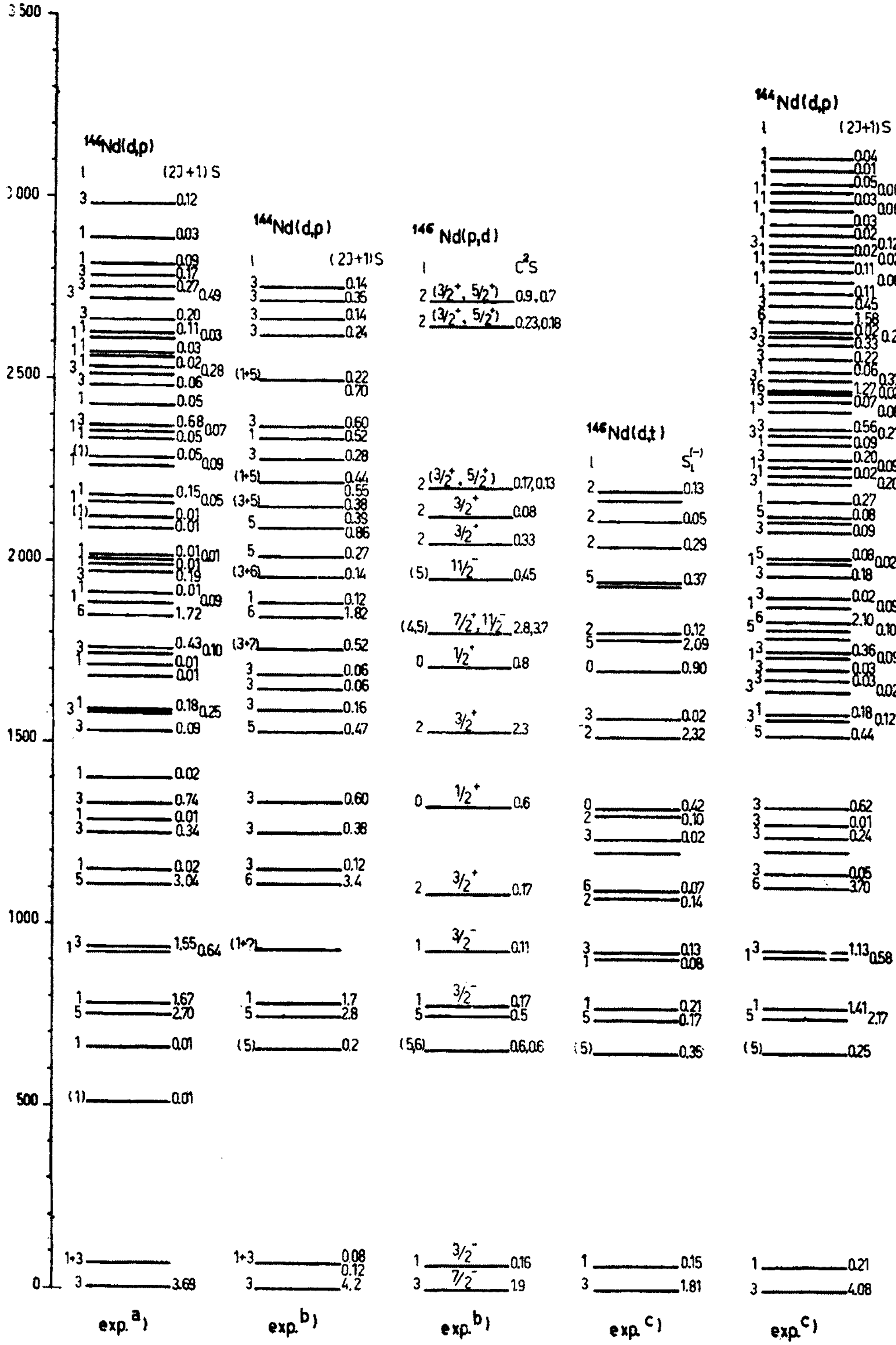

Fig. 2. Comparison of previous experimental data with the present results: (a) Ref. [2], (b) Ref. [3], (c) present experiment

The levels in ^{145}Nd populated by the neutron pick-up (d, t) reaction are also in satisfactory agreement with the results obtained by Hillis et al. [3] in the (p, d) reaction. The present (d, t) results in the region below and slightly above 1 MeV excitation energy correlate well with those observed for the neutron stripping reaction. Above the 1.3 MeV excitation energy there appears to be no correlation between the levels observed in the pick--up and stripping reactions.

The ^{146}Nd target nucleus can be considered as a core of $N = 82$ neutrons building a closed shell with four valence neutrons in the $N = 82$ to 126 shell. These four valence particles are distributed among the $2f_{7/2},\ _{5/2}$; $3p_{3/2},\ _{1/2}$; $1h_{9/2}$ and $1i_{13/2}$ orbits which form the $N = 82$ to 126 shell and most of them should correspond to low lying particle states in the ^{145}Nd nucleus. By summing the (d, t) spectroscopic factors, $\sum S_{lj}^{(-)}$, obtained for all the states originating in the $N = 82$ to 126 shell one should get the average number of particles in the target outside the $N = 82$ core. Theoretically, this number should be four for the ^{146}Nd nucleus. In Table I the spectroscopic strength, $S_{jl}^{(-)}$, are listed for the states where the assignments are fairly certain. The spectroscopic strength, $\sum S_{jl}^{(-)}$, summed over all states orginating in the $N = 82$ to 126 shell is 3.2 which is near the expected value when a fairly large uncertainty in the spectroscopic strength is taken into account.

TABLE II

Comparison of the sum rules and neutron single-hole states energies obtained by previous experiments and in the present experiments

Single particle state	^{141}Nd[a]		^{143}Nd[b]		^{145}Nd		^{147}Nd[c]	
	$\sum_m S_J^m$	ε_J^m (keV)	$\sum_m S_J^m$	ε_J^m (keV)	$\sum_m S_J^m$	ε_J^m (keV)	$\sum_m S_J^m$	ε_J^m (keV)
$3s_{1/2}$	1.47 $m = 1$	193	1.38 $m = 2$	1669	1.33 $m = 2$	1583	1.23 $m = 3$	1459
$2d_{3/2}$	3.43 $m = 1$	0	2.00 $m = 2$	1577	3.14 $m = 2$	1593	2.07 $m = 3$	1272
$1h_{11/2}$	6.72	753	2.55 $m = 1$	2213	2.09 $m = 1$	1793	2.02 $m = 1$	1464
$2d_{5/2}$								

m — number of observed states; a — [15], b — [14], c — [16]

The levels observed in the (d, t) reaction at a higher excitation energy correspond to the removal of neutrons from the closed $N = 82$ core, mostly from the neutron orbitals $3s_{1/2}$, $3d_{3/2}$, $1h_{11/2}$ and $1g_{7/2}$. Since these neutron orbitals are essentially completely filled, they should yield large spectroscopic factors in the pick-up reaction and they are not expected to appear in the stripping reaction. Table II gives a comparison of the sum rule for the neutron hole states obtained in the present experiment. For the (d, t) reaction in the ^{145}Nd nucleus the results for ^{141}Nd, ^{143}Nd and ^{147}Nd nuclei obtained from the (d, t) reaction [14–16] are also shown. The spectroscopic factors for $s_{1/2}$ and $d_{3/2}$ are approximately constant for these nuclei, but for $1h_{11/2}$ the spectroscopic factors systematically decrease, this means that not all strengths are observed and that these strengths cover a larger number of states when the neutron number of the target nucleus increases.

3. *General description of the excited levels*

3.1. Levels populated by the $l = 3$ transitions

The ^{145}Nd ground state is known to have a spin of 7/2⁻ and large $S_{lj}^{(+)}$ spectroscopic factors as does the ground state of ^{143}Nd [14]. On the assumption that the ground state contains most of the 7/2⁻ strength, $J^{\pi} = 5/2^-$ can be assigned to the other $l = 3$ states. The level at 937 keV is the most strongly excited level among these $l = 3$ levels and can be considered to be the principal component of the $2f_{5/2}$ neutron single-particle state. With these assignments the sum rule gives $\sum S_{7/2}^{(+)} = 0.51$ and $\sum S_{5/2}^{(+)} = 1.02$. The summed spectroscopic factors from the (d, p) and (d, t) reactions data for the ground state 7/2⁻ $[(2J+1)S_{lj}^{(+)}+S_{lj}^{(-)}] = 5.9$ are slightly smaller than the expected maximum value for the $2f_{5/2}$ neutron single-particle state. This indicates that the ground state carries nearly all the $2f_{7/2}$ available strength (73 %) which is, however, smaller than the sum rule limit for the $f_{7/2}$ levels. This may also indicate that some of the $L_n = 3$ states tentatively assigned as 5/2⁻ may be 7/2⁻.

The summed spectroscopic factors, $\sum S_{lj}^{(+)}$, for the other $l = 3$ states have a value of 1.02 which is slightly greater than the expected maximum value for the $2f_{5/2}$ state.

TABLE III

Comparison of ^{145}Nd sum rules and neutron single-particle energies obtained by previous experiments and in the present experiment

Single particle state	Gales et al. [2] $\sum(2J+1)S^{(+)}$	Hillis et al. [3]		Present experiment				
		$\sum(2J+1)S^{(+)}$	$\sum S$	$\sum(2J+1)S^{(+)}$	$S^{(+)}$	ε_J (keV)	$\sum S^{(-)}$	$\sum S^{(-)}/(2J+1)$
$2f_{7/2}$		4.24	0.53	4.08	0.51	0	1.81	0.23
	9.55		0.72	10.19				
$2f_{5/2}$		5.88	0.98	6.11	1.02	1972	0.17	0.03
$3p_{3/2}$		3.56	0.89					
$3p_{1/2}$	4.00			3.91	0.65	1485	0.43	
$1h_{9/2}$	5.74	7.30	0.73	3.77	0.38	1150	0.51	0.05

The single-particle energies ε_J are calculated as centres of gravity of the observed members of the same spin and parity of a single-particle transition multiplet, i.e. $\varepsilon_J = \sum_m E_J^m S_{lj}^m / \sum_m S_{lj}^m$, where E_J^m are the excitation energies of the various states of the same spin and parity.

The summed (d, p) and (d, t) spectroscopic factors for all the $l = 3$ states $(2f_{7/2}+2f_{5/2})$ have a value of 12.17 (about 90%) of the expected value. This indicates that most of the strength for the $l = 3$ states in ^{145}Nd were observed.

The neutron single particle energies, $\varepsilon_{7/2}$, and, $\varepsilon_{5/2}$, are listed in Table III.

3.2. Levels populated by $l = 1$ transitions

Apart from the ground state, the 780 and 919 keV levels showing angular momentum transfers of $l = 1$ are the two most strongly excited levels in the (d, p) reaction. The spins of these levels have been determined as $3/2^-$ and $1/2^-$ and they may be considered as the principal components of the $3p_{3/2}$ and $3p_{1/2}$ neutron single particle states.

The spins for the other $l = 1$ states are unknown. The summed spectroscopic factors, $\sum(2J+1)S^{(+)}_{3/2,\,1/2}+\sum S^{(-)}_{3/2,\,1/2}$, for the $3p_{3/2}$ and $3p_{1/2}$ neutron single particle states have the value $3.91+0.43 = 4.34$ (about 72% of the maximum strength). This indicates that some strength for the $l = 1$ states is not observed. The calculated single particle energies, $\varepsilon_{3/2,\,1/2}$, listed in Table III give only the lower limit for the position of the $3p_{3/2}+3p_{1/2}$ neutron single particle state.

3.3. Levels populated by $l = 5$ transitions

The levels at 657, 749, 1528, 1827, 2018, 2090 and 2133 keV show $l = 5$ transitions. The level at 749 keV is the most strongly excited $l = 5$ level in the (d, p) reaction and it may be considered to be the principle component of the $1h_{9/2}$ neutron single particle state. The summed (d, p) and (d, t) spectroscopic factors give the value: $3.77+0.51 = 4.28$ (43% of the maximum strength). This indicates that most of the strength is not observed and the strength of the $1h_{9/2}$ neutron-single-particle state is distributed over more states than observed in the present experiment. The calculated single-particle energy, $h_{9/2}$, also gives only the lower limit of the position of the $1h_{9/2}$ neutron single particle state (Table III).

In the (d, t) reaction a high spin transition is found at 1793 keV. This level is not excited by the (d, p) reaction and this indicates that it is a hole state. On this basis we assigned this level as $h_{11/2}$.

3.4. Levels populated by $l = 6$ transitions

The levels at 1110, 1846, 2481 and 2670 keV appear to show the angular momentum transfers with $l = 6$. Assuming for these states a spin $13/2^+$, we obtained a summed (d, p) spectroscopic factor $\sum S^{(+)}(2J+1) = 8.65$ (62% of the maximum strength). The (d, t) reaction gives a very small contribution to this strength of about one per cent. The levels at 1110 and 1846 keV are the most strongly excited $l = 6$ levels and they may be considered as the principal components of the $1i_{13/2}$ neutron single particle state.

The calculated single particle energy, $\varepsilon_{13/2}$, also gives only a lower limit of the position of the $1i_{13/2}$ neutron single particle state.

3.5. Levels populated by $l = 0$ and $l = 2$ transitions

The levels with $l = 0$ and $l = 2$ transitions are considered to be excited only by the pick-up reaction. The (d, t) angular dependence suggests that the two levels at 1325 and 1706 keV are populated by $l = 0$ transitions and the seven levels at 1077, 1306, 1528, 1813, 2047, 2117 and 2198 keV are populated by $l = 2$ transitions. The summed spectroscopic factors for the $l = 0$ and $l = 2$ transitions are equal to 1.33 (~70% of the maximum value) and 3.14 (~80% of the maximum value), respectively, and these values are slightly less than the expected maximum theoretical values for the $s_{1/2}$ and $d_{3/2}$ neutron hole states. These results indicate that most of the strength for the $s_{1/2}$ and $d_{3/2}$ orbital in ^{145}Nd have been observed.

4. Conclusions

The charged particle spectroscopy involving the (d, p) and (d, t) reactions supplies new nuclear structure information concerning the ^{145}Nd nucleus. For the levels below 1 MeV the characteristics obtained in the present and previous experiments agree quite well and for the levels above 1 MeV there is also agreement between various experiments, but there exist some discrepancies.

The spectroscopic factor for the $7/2^-$ ground state is smaller than the sum rule limit for the $2f_{7/2}$ levels. The spectroscopic factors for the other $l = 3$ states, tentatively assigned as $5/2^-$, are slightly higher than the sum rule limit for $2f_{5/2}$. This may indicate that some of the states assigned as $5/2^-$ may be $7/2^-$.

The summed (d, p) and (d, t) spectroscopic factors for all $l = 3$ states ($2f_{7/2}$ and $2f_{5/2}$) show about 90% of the theoretical strengths. This indicates that most of the $l = 3$ states in ^{145}Nd have been observed.

The strength for $1h_{9/2}$, $1h_{11/2}$ and $1i_{13/2}$ are significantly lower than expected. This means that not all levels with $l = 5$ and 6 were observed.

Assuming (according to [3]) that no transitions are assigned to the $3p_{2/2}$ orbital (except at 919 keV), we obtained more than 90% of the theoretical strength for the $3p_{3/2}$ orbital the states from the $3p_{1/2}$ orbital lie according to the shell model at higher excitation energies.

The summed $S_{lj}^{(-)}$ spectroscopic factors for the orbitals $2f_{7/2,\,5/2}$, $3p_{3/2,\,1/2}$, $1h_{9/2}$ and $1i_{13/2}$ above the closed shell of $N = 82$ neutrons give for levels excited by the ^{146}Nd (d, t) reactions about 80% of the sum rule strength of 4 which represents the excess neutrons.

The calculated U^2 and V^2 values for the ground state of the ^{145}Nd nucleus are 0.69 and 0.31, respectively.

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