A STUDY OF THE ^{146}Nd (d, p) ^{147}Nd AND ^{148}Nd (d, t) ^{147}Nd REACTIONS

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Energy levels of the ^{147}Nd nucleus have been studied by means of the ^{146}Nd (d, p) ^{147}Nd and ^{148}Nd (d, t) ^{147}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 observed levels were obtained from DWBA calculations.

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1. *Introduction*

Recently considerable experimental and theoretical work has been devoted to the study of transitional nuclei around $N = 89$ where the transition between a spherical and a permanently deformed nuclear shape takes place. The level structure of the transitional nuclei can possibly be described in terms of either vibrational or rotational models.

Also great interest has been shown in the determination of the neutron single particle states for the $83 \leqslant N \leqslant 126$ shell ($3p_{1/2,3/2}$, $2f_{5/2,7/2}$, $1h_{9/2}$ and $1i_{13/2}$) from the (d, p) reaction and in the determination of the neutron hole states from the closed shell core $N = 82$ ($2d_{3/2,5/2}$, $3s_{1/2}$, $1h_{11/2}$ and $1g_{7/2}$) from pick-up (d, t) and (^{3}He, α) reactions. Because of the mixing of single-particle or hole states with spin and parity J and the single-particle states coupled to the collective states of the core, forming the same spin and parity, it is expected that the single-particle or hole strength will be distributed over several states.

The existing experimental data on the properties of low-lying levels in the ^{147}Nd nucleus are limited and come mainly from analyses of the (d, p) [1], (d, t) ($\vec{d}$, t), (^{3}He, α) [2, 3, 4] and (n, γ), (n, e$^-$) [5, 6] reactions and from the decay ^{147}Pr $\rightarrow$ ^{147}Nd [7]. The studies of the (d, p) reaction of Wiedner et al. [1] yielded energies and spins of only a few states. The nucleus ^{147}Nd was studied by Straume et al. [2, 3] who used the 12 MeV (d, t) and 17 MeV (d, t) reactions and by Løvhøiden et al. [4] who applied the (^{3}He, α) and 17 MeV (d, t) reactions. These investigations supplied a wealth of information about many of the states up to 3 MeV excitation. Roussille et al. [5, 6, 7] obtained information on the ^{147}Nd

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levels by means of γ-ray spectroscopy from the decay of ^{147}Pr and from the ^{146}Nd (n, γ) reaction with thermal neutrons.

It appears that independent investigations of the structure of the ^{147}Nd nucleus in a wide range 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 ^{146}Nd (d, p) ^{147}Nd and ^{148}Nd (d, t) ^{147}Nd reactions were used to study the structure of ^{147}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 2.9 MeV and 2.20 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 Refs. [8, 9]. The beam of 12.1 MeV deuterons was obtained from the Niels Bohr Institute EN tandem Van de Graaff accelerator, and the reaction charged products were analysed in a high-resolution magnetic spectrograph [10] 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 ^{146}Nd and ^{148}Nd. The target thicknesses were approximately 50 μg/cm^2

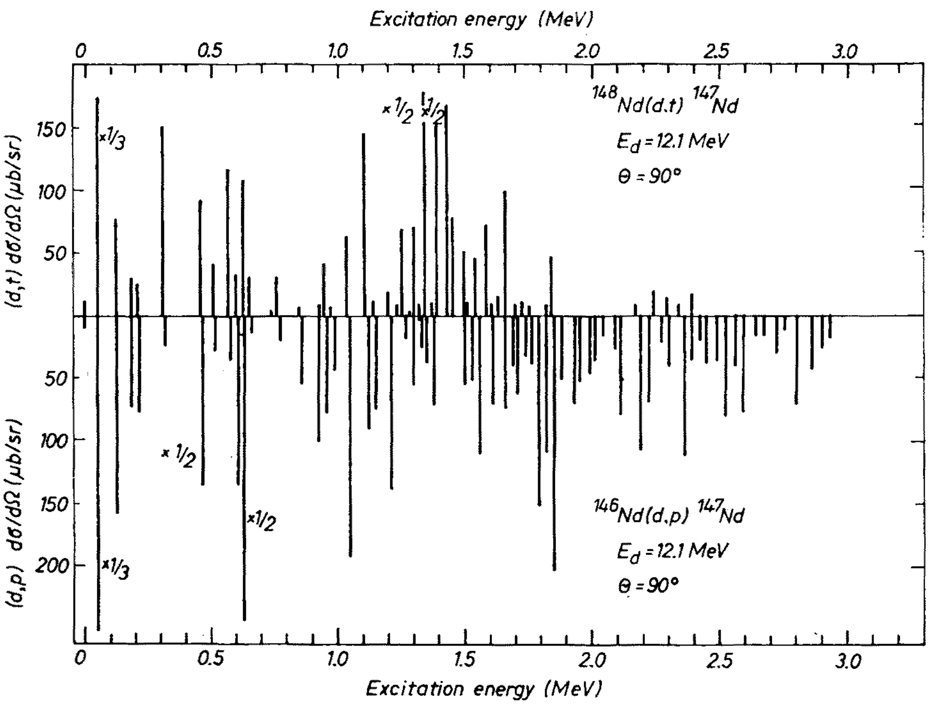

Fig. 1. Triton and proton spectra for the ^{148}Nd (d, t) ^{147}Nd and ^{146}Nd (d, p) ^{147}Nd reactions

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 in 0.25 mm strips. The absolute cross sections were determined by normalization to the cross section for elastic deuteron scattering [11]. The uncertainties of the absolute cross sections are of the order of 20%, while for the smaller cross sections or poorly resolved levels they are of the order of 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, the track-counting reproducibility and statistics. The uncertainties of energy level determination are of the order ± 3 keV and ± 6 keV for strong and weak levels, respectively.

The proton and triton spectra obtained from the ^{146}Nd (d, p) ^{147}Nd and ^{148}Nd (d, t) ^{147}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 summarized the measured differential cross sections, the suggested assignments for most of the investigated levels and the extracted spectroscopic factors. The level assignment was taken from Refs. [2–7] and was also determined in the present measurements from the ratios

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

To allow extracting spectroscopic information from the experimental data a series of DWBA calculations were carried out using the computer code DWUCK. The deuteron, proton and triton optical model parameters were taken from papers [12] and [13], since those parameters have been successfully applied for analysis of the (d, t) and (d, p) reactions on rare-earth targets [12], [14].

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 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 $\sigma_l^{(-)}(\theta)$ 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 investigated (d, p) and (d, t) reactions are listed in Table I.

The earlier and present high-resolution studies of the ^{147}Nd nucleus by means of the (d, p), (^{3}He, α) and (d, t) reactions are summarized in Fig. 2 together with the l-transfer values and spectroscopic factors.

TABLE I

Levels populated in the ^{146}Nd (d, p) ^{147}Nd and ^{148}Nd (d, t) ^{147}Nd reactions

Energy average (keV)		Assignment		$d\sigma/d\Omega$(d, p) (μb/sr)			$d\sigma/d\Omega$(d, t) (μb/sr)			(d, p) $(2J+1)S_{lj}^{(+)}$	(d, t) $S_{lj}^{(-)}$
(d, p)	(d, t)	previous l, J^{π}	present l	60°	90°	125°	60°	90°	125°		
1	2	3	4	5	6	7	8	9	10	11	12
0	0	3,5/2⁻	3	16	12	6	27	11	6	0.06	0.04
52	49	3,7/2⁻	3	828	697	346	994	531	239	3.01	1.61
130	126	3,5/2⁻	3	241	158	76	150	78	34	0.66	0.24
192	187	5,9/2⁻	5	101	79	12	43	30	21	1.46	0.52
218	212	1,1/2⁻	1	204	77	15	69	25	11	0.14	0.04
319	312	1,3/2⁻	1	91	25	4	357	152	67	0.04	0.18
469	459	1,3/2⁻	1	683	374	138	199	92	33	0.60	0.12
520	512	3,5/2⁻	3	40	26	19	57	42	16	0.12	0.13
580	571	3,7/2⁻	3	51	35	19	206	117	59	0.13	0.40
610	600	1,1/2⁻	1	305	134	64	72	32	17	0.22	0.05
637	627	1,3/2⁻	1	950	484	163	253	108	43	0.74	0.16
665	650	5(9/2⁻)	5	—	—	14	19	30	24	0.50	0.50
778	763	2,3/2⁺	2	36	23	9	52	31	17	0.06	0.07
862	851		1	104	55	15		6	2	0.07	0.01
938	928	6,13/2⁺	6	96	100	113	16	8	7	4.44	0.54
963	950	1,3/2⁻	1	183	78	41	94	41	19	0.12	0.07
993	976	(3)	3	88	44	37	11	6	6	0.20	0.03
1048	1035	1,1/2⁻	1	399	192	83	117	65	23	0.26	0.10
1125	1106	2,3/2⁺	2	121	90	40	187	144	81	0.18	0.42
1156	1141		3	123	73	36	7	9	4	0.24	0.03
1212	1200		3	229	137	56	24	19	8	0.40	0.08
	1235		(5)					6	6		0.17
1269	1254	2,3/2⁺	2	29	19	12	88	67	35	0.04	0.19
1298			3	78	56	25				0.16	

	1302	2,3/2+	2				75	69	37		0.21
	1322		(5)				3	10	5		0.17
1334			1	41	25	6				0.02	
	1344	0,1/2+	0				443	352	182		0.65
1355			3	69	38	24				0.16	
1386			1	151	73	27				0.08	
	1390	2,3/2+	2				385	302	173		1.06
	1437	0,1/2+	0				236	166	94		0.35
	1454	5,11/2−	5				24	78	65		2.17
	1498	5,11/2−	5				30	52	10		1.30
1503			3	66	55	20				0.12	
1531			1	130	52	25				0.06	
	1540	1,3/2−	1				26	46	10		0.05
1558			1	228	110	49				0.12	
	1586	2,5/2+	(2)				61	72	31		0.28
	1605	2,3/2+							8		0.05
1610			3	96	70	31				0.14	
1660			1		74	30				0.08	
	1661	0,1/2+	0				125	98	56		0.28
1694			3		40	23				0.12	
	1698		(5)				6	9	8		0.12
1711			3		63	31				0.16	
	1724	3,7/2−	(3)				7	11	8		0.06
1739			3		33	24				0.10	
1758			(1)		38	18				0.04	
1791			3		151	88				0.42	
1817			3		109	55				0.26	
	1818		(5)				6	8	9		0.10
	1841	(2)	(2)				44	45	35		0.23
1851			1		202	91				0.20	
1881			3		51	34				0.16	
1936			1	269	69	61				0.10	
1953					52						
1987			(1)	100	46	23				0.04	
2010			1	62	37	12				0.03	

TABLE I (continued)

1	2	3	4	5	6	7	8	9	10	11	12
2042			(3)	51	16	24				0.08	
2087			1	46	27	10				0.02	
2110			(3)	122	79	40				0.18	
2189			(1)		106	47				0.10	
2226			(3)		68	35				0.16	
2276			(5)		22	20				0.40	
	2292							6	13		
2301			1	131	40	13				0.04	
2366			(3)	175	112	55				0.24	
2392			1	134	36	22				0.04	
2425			(1)	66	19	13				0.02	
2447			3	57	37	11				0.06	
2486			3	55	36	18				0.07	
2524			(1)	197	80	41				0.08	
2562					40						
2591			1	322	75	49				0.09	
2641			(1)	94		18				0.04	
2676			1	110		16				0.05	
2724			(1)	140		31				0.06	
2754			1	122		11				0.04	
2805			1	262		69				0.10	
2865			3	126		43				0.16	
2900			3	60		26				0.08	
2928			(1)	73		19				0.02	

From Fig. 2 one sees that in general there is reasonably good agreement between the energies and the spectroscopic factors obtained from the different (d, t) reactions studied.

The present (d, t) results are in satisfactory agreement with the results of Ref. [2] and in only a few cases are the extracted spectroscopic factors not consistent. The spectroscopic factors published in Ref. [4] are systematically higher in comparison with the present data and with data in Ref. [2].

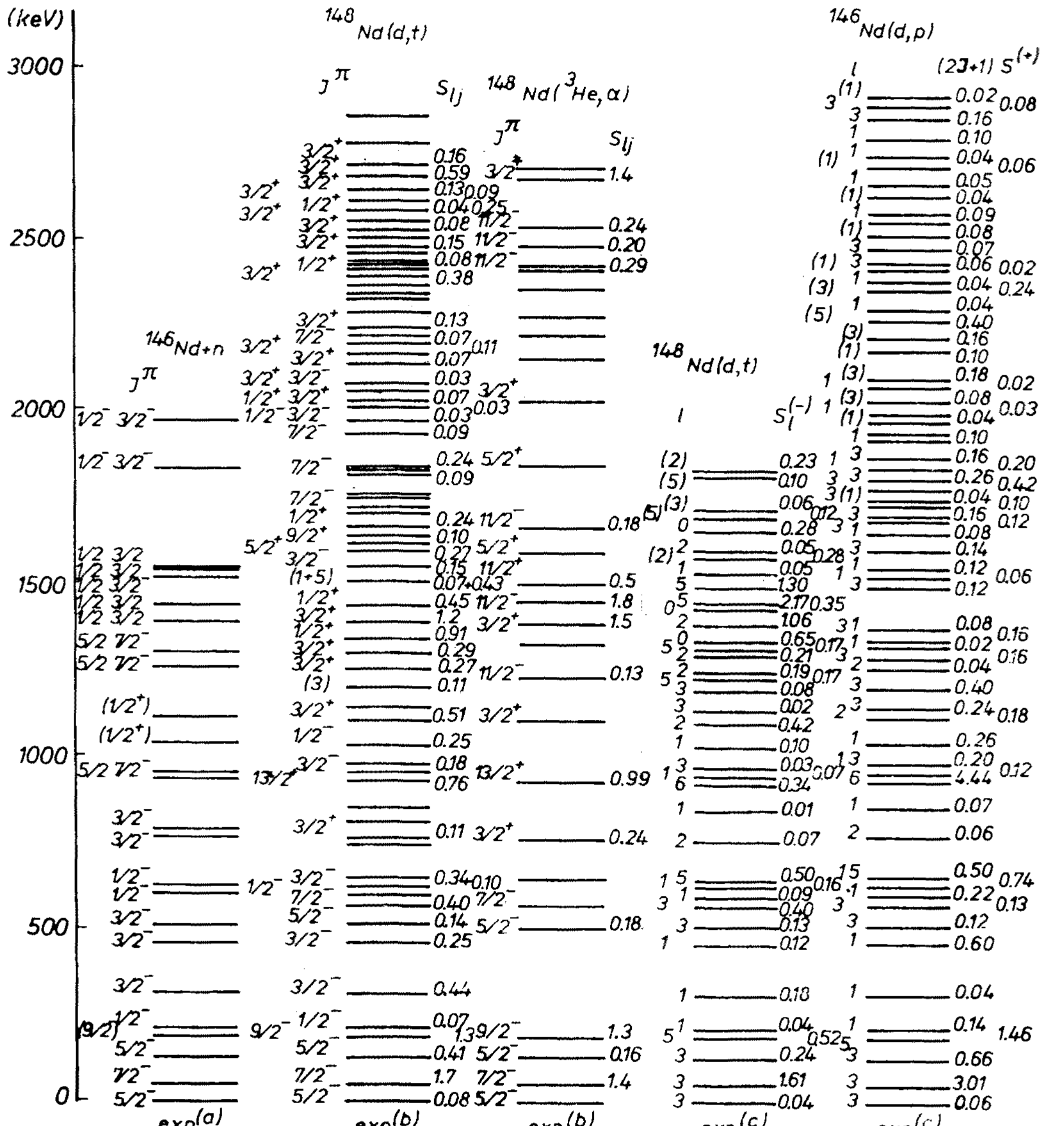

Fig. 2. Comparison of earlier experimental data with the present results: (a) Ref. [5], (b) Ref. [4], (c) present experiment

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 [c]		^{147}Nd [d]		^{147}Nd [e]		^{147}Nd (present experiment)	
	S_J	ε_J (keV)	S_J	ε_J (keV)	S_J	ε_J (keV)	S_J	ε_J (keV)	S_J	ε_J (keV)	S_J	ε_J (keV)
$3s_{1/2}$	1.47	193	1.38	1669	1.33	1583	1.23	1459	1.75	1508	1.28	1439
	$m = 1$		$m = 2$		$m = 2$		$m = 3$		$m = 6$		$m = 3$	
$2d_{3/2}$	3.43	0	2.00	1577	3.14	1593	2.07	1272	4.69	1870	2.01	1294
	$m = 1$		$m = 2$		$m = 7$		$m = 5$		$m = 18$		$m = 6$	
$1h_{11/2}$	6.72	753	2.55	2213	2.09	1793	2.02	1464	3.16	1692	3.92	1468
			$m = 1$		$m = 1$		$m = 1$		$m = 6$		$m = 2$	
$2d_{5/2}$												

m — number of observed states; [a] [15], [b] [16], [c] [17], [d] [2], [e] [4].

The present (d, t) results in the region below and slightly above the 1 MeV excitation energy correlate well with those observed for the neutron stripping (d, p) reaction. Above the 1.3 MeV excitation energy no correlation appears between the levels observed in the pick-up and stripping reactions.

The ^{148}Nd target nucleus can be regarded as a core of $N = 82$ neutrons building a closed shell with six valence neutrons in the range $N = 82$ to 126. These six 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 ^{147}Nd nucleus. By summing the (d, t) spectroscopic factors, $\Sigma S_{lj}^{(-)}$, 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 six for the ^{148}Nd nucleus. In Table I the spectroscopic strengths $S_{lj}^{(-)}$ are listed for the states where the assignments are fairly certain. The spectroscopic strength $\Sigma S_{lj}^{(-)}$ summed over all states originating in the $N = 82$ to 126 shell is 4.93 which is reasonably close to the expected value if we take into account the fairly large uncertainty in the spectroscopic strength.

The levels observed in the (d, t) reaction at 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 in principle 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 previous and in the present experiments for the (d, t) reaction in ^{147}Nd nucleus; the results for ^{141}Nd, ^{143}Nd and ^{145}Nd nuclei obtained from the (d, t) reaction [15, 16, 17] are also shown. The spectroscopic factors for $s_{1/2}$ are approximately constant for these nuclei but for $1h_{11/2}$ the spectroscopic factors are too small which means that not all strength are observed and that these strengths are smeared over a larger number of states when the neutron number of the target nucleus increases.

3. Conclusions

Charged particle spectroscopy involving the (d, p) and (d, t) reactions has supplied new nuclear structure information on the ^{147}Nd nucleus. For the levels below 1.5 MeV the characteristics obtained in the present and previous experiments are in quite good agreement, while for the levels above 1.5 MeV there is also agreement between different experiments though some discrepancies also occur.

The summed (d, p) and (d, t) spectroscopic factors for all $l = 3$ states, $2f_{7/2}$ and $2f_{5/2}$ give the value 10.43 (about 75%) of the theoretical strengths and this indicates that most of the $l = 3$ states in ^{147}Nd have been observed. The neutron single particle energies $\varepsilon_{7/2,5/2}$ are listed in Table III and give only the lower limit for the position of the $2f_{7/2}+2f_{5/2}$ neutron single particle state.

The summed (d, p) and (d, t) spectroscopic factors $\Sigma(2J+1)S_{3/2,1/2}^{(+)}+\Sigma S_{3/2,1/2}^{(-)}$ for the $3p_{3/2}$ and $3p_{1/2}$ neutron single particle states give the value $3.64+0.78 = 4.42$ (about 74% of the maximum strength). This indicates that most of the strength for the $l = 1$

TABLE III

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

Single particle state	^{143}Nd			^{145}Nd [c]			^{147}Nd [d]			^{147}Nd	
	$\sum_m (2J+1)S^{(+)}$ [a]	ε_J(keV)	$S^{(-)}$ [b]	$\sum_m (2J+1)S^{(+)}$	ε_J(keV)	$\sum_m S^{(-)}$	$\sum_m (2J+1)S_l^{(+)}$	ε_J(keV)	$\sum_m S_l^{(-)}$	$\sum_m (2J+1)S_l^{(+)}$ [e]	$\sum_m S_l^{(-)}$ [f]
$2f_{7/2}$	5.28 $m = 1$	0	1.21 $m = 1$	4.08 $m = 1$	0	1.81 $m = 1$					2.02 $m = 2$
$2f_{5/2}$	4.68 $m = 5$	1830	0.01 $m = 1$	6.11 $m = 27$	1972	0.17 $m = 3$	7.64 $m = 25$	883	2.59 $m = 8$	4.04 $m = 1$	0.61 $m = 3$
$3p_{3/2}$	2.32	1210	0.17	3.91 $m = 29$	1485	0.43 $m = 3$	3.6 $m = 31$	1337	0.78 $m = 2$	1.9 $m = 2$	0.81 $m = 5$
$3p_{1/2}$	0.74		0.04 $m = 1$								0.24 $m = 3$
$1h_{9/2}$			0.07 $m = 1$	3.77 $m = 7$	1150	0.51 $m = 2$	1.96 $m = 2$				0.8 $m = 1$

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. $\varepsilon_J = \frac{\sum_m E_J^m S_{lJ}^m}{\sum_m S_{lJ}^m}$, where E_J are the excitation energies of the various states of the same spin and parity. [a] [18], [b] [16], [c] [17], [d] present experiment, [e] [1], [f] [2].

states are observed. The calculated single particle energies, $\varepsilon_{3/2,1/2}$, listed in Table III give also the lower limit for the position of the $3p_{3/2}+3p_{1/2}$ neutron single particle states.

The strengths for the $1h_{9/2}$, $1h_{11/2}$ and $1i_{13/2}$ are significantly smaller than expected.

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 three levels are populated by $l = 0$ transitions and seven levels by $l = 2$ transitions.

The summed spectroscopic factors for the $l = 0$ and $l = 2$ transitions are equal to 1.28 (about 65% of the maximum value) and 2.01 (about 50% of the maximum value), respectively, and these values are significantly smaller than thee xpected maximum theoretical value.

The summed (d, t) $S_{lj}^{(-)}$ 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 ^{148}Nd (d, t) reactions about 82% of the sum rule strength.

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