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STUDY OF THE ^{61,62}Ni(p,α) REACTIONS

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The ^{61,62}Ni(p,d) reactions were studied at 40 MeV. A very pronounced j-dependence effect was observed for the $\ell = 3$ transitions. Spins and parities are assigned to levels of ^{61}Ni which include two $1/2^+$ states. Spectroscopic factors extracted from DWBA analysis are compared to shell model predictions.

[NUCLEAR REACTIONS ^{61,62}Ni(p,d), E = 40 MeV ; measured $\sigma(E_d,\theta)$; enriched targets. Extracted spectroscopic factors. ^{61}Ni deduced levels, L, J, Π.]

A typical spectrum, as recorded with nuclear emulsion, is shown in fig. 1. The angular distributions, measured from 4° to 54° are shown in figs 2 and 3a-b. The uncertainty in the absolute cross section obtained in measuring the target thickness, the spectrograph solid angle, and the collected charge is estimated to be about 15 %.

III. ANALYSIS OF EXPERIMENTAL ANGULAR DISTRIBUTIONS

For the ^{62}Ni(p,d) reaction, the value of the orbital angular momentum ℓ for each transition is unique, and thus can be determined directly from comparison with the angular distribution of low-lying states with known spin and parity. The distorted wave Born approximation (DWBA) calculations, made with the DWUCK /2 Code[11], provide the spectroscopic factors $S_{\ell j}$ according to the formula,

$$\frac{\sigma(\theta)_{\mathrm{exp}}}{\sigma_{\ell j}(\theta)_{\mathrm{DWUCK}}} = \frac{2.29}{2j+1}\, C^2 S_{\ell j} ,$$

where C^2 is an isospin coupling coefficient and is equal to unity for all cases considered here. For the ^{61}Ni(p,d) reaction, the spin and parity selection rules are less restrictive, and in most cases two values of ℓ can contribute to the same transition (table I). A least-square fitting procedure was thus necessary to determine the relative reduced strength of each ℓ-value involved. This method was also applied for non-resolved transitions in the ^{62}Ni(p,d) reaction. Since the DWBA calculations do not reproduce exactly the experimental angular distributions for pure transitions, the values of the spectroscopic factors obtained with the latter procedure were thus less certain.

Finite-range and non-local corrections were included using the standard non-locality parameters (0.85 fm for the proton, 0.54 fm for the deuteron) and a finite range parameter of 0.69 fm. The neutron compared with previous data in table III. Spins and parities were assigned to several levels in ^{61}Ni, which include two yet unreported $1/2^+$ states located at 5.589 and 5.697 MeV excitation energy. A pronounced j-dependence in the shape of the angular distribution for $\ell = 3$ transfers was observed in both ^{61,62}Ni(p,d) reactions and is discussed in detail elsewhere[18]. The $7/2^-$ assignment was based on this j-dependence effect.

1. $\ell = 0$ transitions

Three $\ell = 0$ transfers leading to levels at 3.068, 5.589 and 5.697 MeV in ^{61}Ni were identified. The experimental angular distributions were consistent with the DWBA analysis although they do not show such deep minima as predicted by the calculation. The last two transitions have not been reported previously. The relatively strong excitation and the energy positions of the two relevant final states suggest a simple $2s_{1/2}$ neutron pickup. A $\ell = 0$ transfer leading to the state at 3.07 MeV of ^{61}Ni has already been reported in ^{60}Ni(d,p)^{61}Ni experiment[1,3] with a spectroscopic factor of 0.07. Since the $2s_{1/2}$ orbit is very likely full in the ground state of ^{60}Ni, the excitation of this state in both (p,d) and (d,p) reactions reveals a more complex nuclear structure, e.g. its wave-function may contain a small $3s_{1/2}$ component.

2. $\ell = 1$ transitions

The experimental angular distributions were quite well reproduced by the DWBA calculation. Since no evidence of j-dependence effects have been observed for $\ell = 1$ transfers, the spin values of the final states were taken from the literature. There is some controversy concerning the states at 1.10 and 1.73 MeV for which the assignments $1/2^-$ and $3/2^-$ have been proposed[1;2].

3. $\ell = 3$ transitions

Figure 4 shows ten $\ell = 3$ transitions observed in the ^{61,62}Ni(p,d) reactions. The solid and dashed lines represent, respectively, smooth curves drawn through the data of the $5/2^-$, 0.067 MeV state and the $7/2^-$, 3.30 MeV state of ^{61}Ni. The difference in shape between the angular distributions of the $f_{5/2}$ and $f_{7/2}$ transitions is clearly exhibited. The experimental data for $f_{7/2}$ transfer are nicely reproduced by the conventional DWBA calculations but there is an angular shift of about 4° between the experimental angular distribution for $f_{5/2}$ transfer and the DWBA predictions. (Fig. 2). The spin and parity $7/2^-$ can be attributed to the levels at 2.01, 3.31, 3.94 and 4.59 MeV and also to the level at 2.47 MeV for which the $5/2^-$ assignment has been suggested previously. The present data also confirm the $5/2^-$ assignment for the level at 1.61 MeV and $7/2^-$ for the level at 4.95 MeV.

B. ^{61}Ni(p,d)^{60}Ni

The experimental angular distributions are presented in figs. 3a-b, and the extracted spectroscopic factors are compared with previous data in table IV. Besides two $\ell = 4$ transitions, all the other measured experimental angular distributions were essentially consistent with an orbital angular momentum $\ell = 1$ or $\ell = 3$ or a mixture of the two. In contrast with the ^{62}Ni(p,d)^{61}Ni reaction, no $\ell = 0$ transfer has been identified. This reaction provides mainly the parity of the final states but gives relatively little information on the spin values of the relevent energy levels. Thus, the spins from 1 to 4 are all possible for the levels at 4.112, 4.355, 4.539, 4.607, 5.307, 5.381, 6.194, 6.545, 6.605 and 6.824 MeV since they are excited by either a transfer $\ell = 3$ or a mixture of $\ell = 1$ and 3.

However, since the spin and parity values for the low-lying levels of ^{60}Ni are well known from other experiments[4-9], it is of interest to point out the following salient features of the experimental data.

1. Although several orbits can contribute to the excitation of the same final state, we find that some transitions involve only one value of ℓ. It can be noticed that the two neighbouring 2^+_1 (1.332 MeV) and 2^+_2 (2.159 MeV) states were excited the former by an $\ell = 1$ transfer and the latter by an $\ell = 3$ transfer. This selection is not a consequence of the angular momentum coupling rules but is very likely due to the nuclear structure of these levels.

2. The nuclear structure effect is even more remarkable for the transition leading to the 2^+_1 (2.159 MeV), 4^+_1 (2.506 MeV) and 3^+_1 (2.626 MeV),

References

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[1] J. Vervier, Nucl. Data, 2, B2-5-81 (1968).

[2] B. Stecher-Rasmussen et al., Nucl. Phys. A18[illegible], [illegible] (19[illegible]2).

[3] E.R. Cosman et al., Phys. Rev. 163, 1134 (1967).

[4] R.H. Fulmer, W.W. Daehnick, Phys. Rev. B139, 579 (1965).

[5] R. Sherr, B.F. Bayman, E. Rost, M.E. Rickey, and C.G. Hoot, Phys. Rev. 139 B1272 (1965).

[6] D.E. Rundquist, Thesis Univ. Illinois (1966).

[7] H. Ronsin et al., Nucl. Phys. A207, 577 (1973).

[8] D.H. Kong-A-Siou, A.J. Cole, A. Giorni and J.P. Longequeue, Nucl. Phys. A221, 45 (1974).

[9] W. Darcey et al., Nucl. Phys. A170, 253 (1971).

[10] H.G. Blosser et al., Nucl. Instr. Meth., 91, 6[illegible] (1971).

[11] P.D. Kunz, Univ. Colorado, unpublished.

[12] F.D. Becchetti, Jr. and G.W. Greenlees, Phys. Rev. 182, 1190 (1969).

[13] R.C. Johnson et P.J. Soper, Phys. Rev. C1, 976 (1970).

[14] G.R. Satchler, Phys. Rev. C4, 1485 (1971).

[15] E. Newman et al., Nucl. Phys. A100, 225 (1967).

[16] F. Hinterberger et al., Nucl. Phys. A111, 265 (1968).

[17] Except in table IV and fig 3a-b, all energies are labelled in MeV.

[18] D.H. Kong-A-Siou and W.S. Chien, Phys. Lett. 52B, 175 (1974). The energy calibration given in this letter is not correct for levels above 4 MeV.

[19] P.W.M. Glaudemans, M.J.A. De Voigt and E.F.M. Steffens, Nucl. Phys. A198, 609 (1972).

[20] J.B. French, E.C. Halbert, J.B. McGrory and S.S.M. Wong, Adv. in Nucl. Phys. 3, 193 (1969).

[21] D.H. Koang and B.H. Wildenthal (to be published).

[22] D.H. Kong-A-Siou and H. Nann, Phys. Rev. C11, 1681 (1975).

[23] S. Raman, Nucl. Data 2, B2-5-41 (1968).

Table I

J_I	J_F	L	orbit
$3/2^-$	0^+	1	$p_{3/2}$
	1^+	1	$p_{1/2}$, $p_{3/2}$
		3	$f_{5/2}$
	2^+	1	$p_{1/2}$, $p_{3/2}$
		3	$f_{5/2}$, $f_{7/2}$
	3^+	1	$p_{3/2}$
		3	$f_{5/2}$, $f_{7/2}$
	4^+	3	$f_{5/2}$, $f_{7/2}$
	1^-	0	$s_{1/2}$
		2	$d_{3/2}$
	3^-	2	$d_{3/2}$
		4	$g_{9/2}$

Table IV

E_x (keV)		ℓ_n^a	$J^{\pi\,a-b}$	C^2S		
[a])	[b])			(p,d)[a]	(d,t)[c]	(τ,α)[d]
0	0	1	0^+	.32	.46	.35
1332	1332	1	2^+	.43	.62	.40
2159	2159	3	2^+	.17	.22	
2284	2284	1	0^+	.08	.11	
2506	2506	3	4^+	.39	.44	
2626	2626	3	3^+	.60	.86	.43
	3119		4^+			
3123	3124	1	2^+	.37	.58	
		+3		.30		
3189	3187	1	3^+	.04		
	3194	+3	1^+	.19		.91
3270	3269	1	2^+	.29	.34	
		+3		.32		
	3318		(0^+)			
3394	3394	1	2^+	.30	.49	
		+3		.08		
	3530		0^+			
3618	3619	1	(3)	.005		
		+3		.04		
3670	3671	3	(4^+)	.07		
	3736		1^+			
3734	3738	1	(0^+)	.02		
	3741	+3		.06		
3871	3871	1	2^+	.05		
	3875	+3		.04		
	3926		3^+			
4005	4008	1	2^+	.04		
		+3		.01		
4022	4020	1	$(0\text{-}3)^+$	.12		
	4035		1^+			
4045	4045	4	3^-	.13		

Table V

^{61}Ni

Ex (MeV)				Pick-up 100 x S			
J	Exp.	D4	D3	Exp.		a)	b)
				(p,d)	(d,t)		
$1/2^-_1$	0.283	.24	0.08	50	88	46.	51.
$1/2^-_2$	(1.10)	1.19	0.81	11	26	5.7	16.
$1/2^-_3$	2.12	2.32	1.93	2	8	0.	0.
$1/2^-_4$		2.64	2.54			0.	0.
$3/2^-_1$	50.68	50.90	50.74	180	277	262.	256.
$3/2^-_2$	0.656	1.25	0.78	9	18	4.1	10.5
$3/2^-_3$	1.19	1.77	1.34	25	34	1.7	4.6
$3/2^-_4$	1.73	2.33	1.83	6	8	0.03	0.7
$5/2^-_1$	0.067	0.09	0.04	250	259	217.	251.
$5/2^-_2$	0.909	1.42	1.01	8		3.5	7.
$5/2^-_3$	1.13	1.75	1.42	18		0.4	1.6
$5/2^-_4$	1.611	1.98	1.50	13		0.9	1.2
$9/2^+_1$	2.114	2.24		25	72	48.	
$9/2^+_2$		3.43				0.5	

a) ref. 21

b) ref. 19

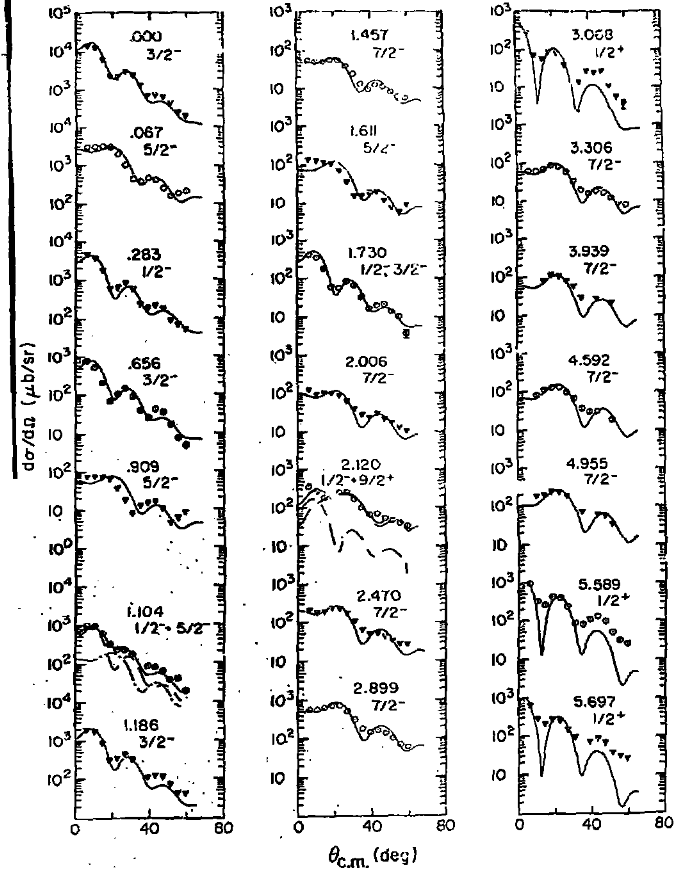
Figure Captions

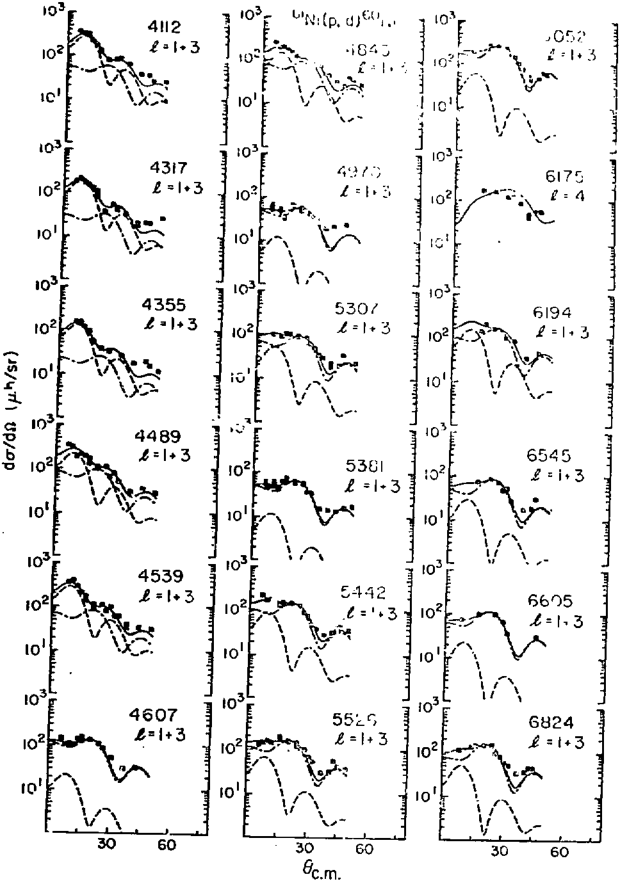
Fig. 1 Deuteron spectrum from the ^{61}Ni(p,d)^{60}Ni reaction.

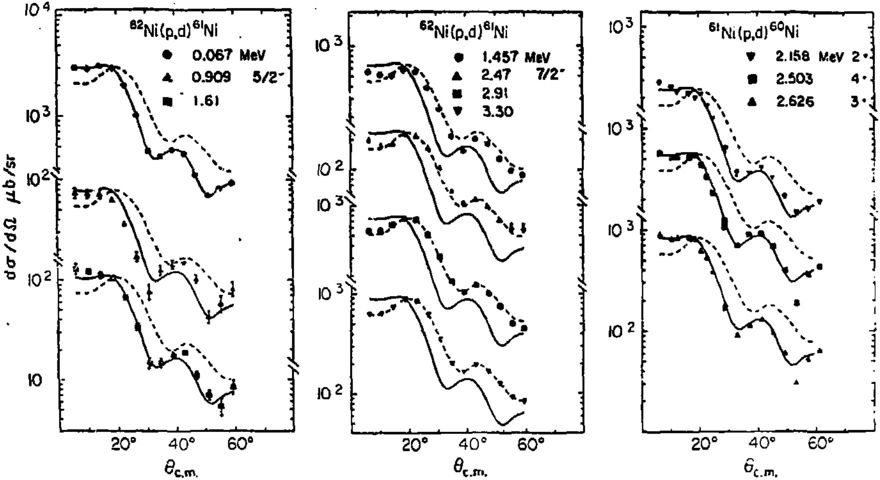
Fig. 2 Angular distributions measured from the ^{62}Ni(p,d)^{61}Ni reaction compared with DWBA predictions. The excitation energy is in MeV.

Fig. 3a-b Angular distributions measured from the ^{61}Ni(p,d)^{60}Ni reaction. The solid lines are the DWBA predictions. The dashed and the the dashed-dotted lines represent, respectively, pure $\ell = 1$ and $\ell = 3$ transitions. The excitation energy is in keV.

Fig. 4 Experimental $\ell = 3$ angular distribution observed in ^{61,62}Ni(p,d) reactions. The solid and dashed lines are, respectively, smooth curves drawn through the experimental data points of the known f 5/2 and f 7/2 transfer to the levels at 0.07 and 3.30 MeV of ^{61}Ni.


dσ/dΩ (μb/sr)
θc.m. (deg)
.000 3/2⁻
.067 5/2⁻
.283 1/2⁻
.656 3/2⁻
.909 5/2⁻
1.104 1/2⁻+5/2⁻
1.186 3/2⁻
1.457 7/2⁻
1.611 5/2⁻
1.730 1/2⁻, 3/2⁻
2.006 7/2⁻
2.120 1/2⁻+9/2⁺
2.470 7/2⁻
2.899 7/2⁻
3.068 1/2⁺
3.306 7/2⁻
3.939 7/2⁻
4.592 7/2⁻
4.955 7/2⁻
5.589 1/2⁺
5.697 1/2⁺
10⁵
10⁴
10³
10²
10
10⁰
0
40
80


^{61}Ni(p, d)^{60}Ni
dσ/dΩ (μb/sr)
$\theta_{c.m.}$
10^3
10^2
10^1
30
60
4112 ℓ = 1+3
4317 ℓ = 1+3
4355 ℓ = 1+3
4489 ℓ = 1+3
4539 ℓ = 1+3
4607 ℓ = 1+3
4845 ℓ = 1+3
4970 ℓ = 1+3
5307 ℓ = 1+3
5381 ℓ = 1+3
5442 ℓ = 1+3
5529 ℓ = 1+3
6052 ℓ = 1+3
6175 ℓ = 4
6194 ℓ = 1+3
6545 ℓ = 1+3
6605 ℓ = 1+3
6824 ℓ = 1+3



$d\sigma/d\Omega$ μb/sr
^{62}Ni(p,d)^{61}Ni
● 0.067 MeV
▲ 0.909 5/2⁻
■ 1.61
10^4
10^3
10^2
10^2
10
^{62}Ni(p,d)^{61}Ni
● 1.457 MeV
▲ 2.47 7/2⁻
■ 2.91
▼ 3.30
10^3
10^2
10^3
10^3
10^2
^{61}Ni(p,d)^{60}Ni
▼ 2.158 MeV 2⁺
■ 2.503 4⁺
▲ 2.626 3⁺
10^3
10^3
10^3
10^2
20°
40°
60°
$\theta_{c.m.}$

(a)

(b)

(c)