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INTERACTION OF DEUTERONS WITH O^{16} AND Ni^{58}

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Abstract: Absolute cross-sections for the reactions $O^{16}(d, d)O^{16}$ ground state, $O^{16}(d, p)O^{17}$ ground and 0.872 MeV states at 26.3 MeV deuteron energy and for the reactions $Ni^{58}(d, d)Ni^{58}$ ground state, $Ni^{58}(d, d')Ni^{58}$ 1.45 MeV state and $Ni^{58}(d, p)Ni^{59}$ ground state at 27.5 MeV bombarding energy were measured by using the scintillation technique with a resolution in energy of 2.5 to 3 %. A simple analysis of the elastic interactions was performed in terms of a Fraunhofer-type diffraction model resulting in an interaction radius of 4.9 ± 0.6 fm and 5.9 ± 0.6 fm for O^{16} and Ni^{58}, respectively. The inelastic interaction measured was analysed in terms of the Huby and Newns model; the best fit was obtained by the addition of two l-value contributions since with a unique l-value was not possible to fit the experimental points. The stripping reactions measured were analysed in terms of the Butler theory; it was found that the best fit was obtained by the addition of two l_n-value contributions since a unique l_n-value did not describe the experimental points.

1. Introduction

The interactions of deuterons in the medium energy region with nuclei have not been as extensively studied as those of nucleons or alpha-particles.

Deuteron elastic scattering analysis in terms of optical nuclear model were performed at low and medium energies describing fairly well the experimental data [1]).

Inelastic deuteron scattering did not receive as much attention as elastic scattering; in principle simple models were able to describe this reaction mechanism to a good degree of agreement with experiments [2,3]).

On the other hand, deuteron stripping and pickup reactions were widely studied both experimentally and theoretically in the low and medium energy regions, due to their ability to provide information on nuclear properties of the involved states and on the reaction mechanism [3–5]).

Plane wave stripping cross-section calculations do fit the experimental data to a reasonable extent, but the best agreement occurs when the energy of the projectile in the centre-of-mass system has a simple relation with the reaction Q-value, i.e., $E_d \approx -2Q$ for endothermic reactions and $E_d \approx Q$ for exothermic reactions [6]).

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For the case $E_d \approx -2Q$ there are some experimental results confirming the above statement [7]) while the case $E_d \approx Q$ is a theoretical prediction. It should be observed that distorted wave Born approximation (DWBA) calculations might in general describe the stripping cross-section provided that a correct choice of the various involved parameters is made.

When the deuteron stripping cross-section is expressed in terms of the dispersion relation theory, it turns out that there is a second order pole when $q^2 = -\kappa^2$, where q is the momentum with which the captured nucleon approaches the nuclear surface and κ is the wave number of the captured nucleon in its final state; the Butler cross-section formula is valid for reaction conditions near the stripping pole [8]) so a distance D (in MeV) could be defined [9]) below which experiments could be well fitted by Butler theory.

In the present work a study was performed with deuterons of energies around 27 MeV on 2 different nucleides by measuring absolute differential cross-sections for the elastic, inelastic and stripping (d, p) reactions and a simple analysis was performed in terms of the above mentioned ideas by using only the plane-wave approximation theory.

2. Experimental

2.1. GASEOUS TARGET PROCEDURE

The 27.5 ± 0.1 MeV magnetically collimated deuteron beam from the Buenos Aires synchrocyclotron has been used to bombard an oxygen gaseous target on which elastic and stripping cross-sections were measured.

The beam is magnetically extracted by Le Couteur's method [10]) and focussed by two pair of quadrupole lenses to a circular spot of 5 to 6 mm in diameter about 7 m from the cyclotron vacuum tank. The direction of the beam is determined by 2 graphite blocks 15 mm thick and spaced 50 cm apart with 15 mm circular apertures through which the collimated beam is passing to a scattering chamber described previously [11]).

The gas target chamber consisted of a thin polyethylene bag filled up to a pressure of 4 mm of mercury over the atmospheric pressure with commercially pure oxygen.

The atmospheric pressure was measured with a Fortin barometer and the room temperature was used to calculate the target density. The difference between the pressure inside the bag and the atmosphere was measured with a U-shaped mercury manometer.

The external beam vacuum system was sealed with an aluminium window 12 mg/cm^2 thick through which passed the deuteron beam to the atmospheric air.

The filled bag was set at the centre of the scattering chamber and irradiated by the deuteron beam. The polyethylene wall tolerated the incident beam quite well during almost 6 to 8 h of continuous irradiation with a current of 0.01 μA before showing any leakage.

The undeflected beam was collected through a pipe 5 cm in diameter by a Faraday cup provided with a permanent ring magnet to prevent secondary electron losses, and then electronically integrated up to a prefixed amount of charge after which the counting run is automatically stopped; under such conditions the beam collection error was about 1.5 %.

The beam shape was checked by irradiating a common glass in which a dark brownish spot appears when a few tenths of a μC of deuterons are collected; the diameter was found to be 11 to 12 mm in the gaseous target region and about 14 mm at the entrance to the Faraday cup.

The scattering chamber used has a set of detecting windows every 5° from 10° up to 100° on one half of the side wall and from 80° to 170° on the other half of the side wall.

The 0° in the laboratory system was checked by measuring the symmetry of the elastic group from carbon using a polyethylene target taking points on both sides of the scattering chamber.

The detecting system consisted of a telescope formed by a vertical slit 4 mm wide and a circular back aperture 4 mm in diameter spaced 150 mm apart from the slit together with a 5 mm thick CsI(Tl) scintillation crystal mounted on a 6097B-EMI photomultiplier tube.

The angular aperture of the detecting system was 1.5°, introducing only small geometrical corrections to the measured cross-sections.

Measurements were taken every 5° in the region from 10° to 105° and every 10° in the region up to 130° for the reactions $O^{16}(d, d)O^{16}$ ground state and $O^{16}(d, p)O^{17}$ ground and 0.872 MeV states. Pulse-height analysis was done with a single-channel analyser; enough activity was accumulated in each measured group to keep the statistical error below 10 %; energy resolution was 2.5 to 3 %.

In computing cross-sections, corrections were made for the geometry factor up to the second derivative of the cross section in laboratory system σ'', including the finite beam correction considering the beam as non-divergent [12]). These corrections were small, usually less than 10 %.

Errors were computed in every case including background subtractions. They are represented on the measured experimental points in the graphs; they range from 5 to 50 %.

2.2. SOLID TARGET PROCEDURE

The interaction of deuterons with a 99.98 % enriched Ni^{58} foil was studied by measuring the cross-sections in the reactions $Ni^{58}(d, d)Ni^{58}$ ground and 1.45 MeV states together with $Ni^{58}(d, p)Ni^{59}$ ground state.

The scattering chamber was evacuated and the detector system replaced by an anthracene scintillation crystal thick enough to stop the proton group mounted on a 6097B-EMI photomultiplier tube; the solid angle of detection was 1.92×10^{-4} sr.

A non-linear response of anthracene for protons and deuterons was observed in the energy region of 27 MeV; the pulse-height for protons of a given energy is higher than that due to deuterons of the same energy. However, this does not make any difficulty in this particular case because the groups to be measured are well identified.

The advantage in using this detector is its low efficiency to detect the gamma background present around the scattering chamber and its short decay constant which reduces pile-up effects for a given beam current.

Total errors including those arising from background subtractions ranged from 4 to 35 % as indicated on every measured point in the graphs.

The beam energy was measured by its range in aluminium using the Faraday cup as a detector of beam current. The mean range obtained was 592 ± 4 mg/cm^2 corresponding to 27.5 ± 0.1 MeV according to range-energy curves [13]). This value was checked during the whole set of runs and was found to be constant within the indicated error.

The beam energy at the scattering region was then calculated for each case due to the presence of entrance windows and target thickness.

3. Results and Discussion

3.1. ELASTIC SCATTERING

Table 1 gives the experimental data obtained for elastic scattering of deuterons on natural oxygen and on nickel-58. The ratio to Rutherford cross-section for every case is represented in fig. 1 in which typical diffraction structures are observed similar to those obtained at lower energies [14]).

In the case of oxygen, a ratio higher than unity at almost all scattering angles was observed. Pronounced maxima and minima are produced by interference effects between the nuclear and Coulomb elastic scattering contributions. For the case of nickel-58 this ratio is smaller than unity and interference effects are also quite noticeable with sharp maxima and minima.

These elastic scattering patterns show that a diffraction-like process is dominating the interaction; due to the small binding energy of the deuteron the interaction with the target nucleus should be localized on its surface because a deep penetration into the nuclear body will very probably break off the deuteron thus preventing an elastic process.

A simple and crude interpretation of the above results could be made by considering the deuteron elastic scattering as plane waves scattered by a completely black spherical nucleus.

The incident beam could be described in terms of partial waves being completely absorbed by the target if the corresponding impact parameter is smaller than the interaction radius. Those partial waves with impact parameter greater than the radius pass away without interaction [15]).

In consequence, only the partial waves of the incident beam with angular momentum $l \approx kR$ are diffracted by the "border" of the black nucleus producing an interference pattern; here k is the wave number of the beam and R is the elastic scattering interaction radius.

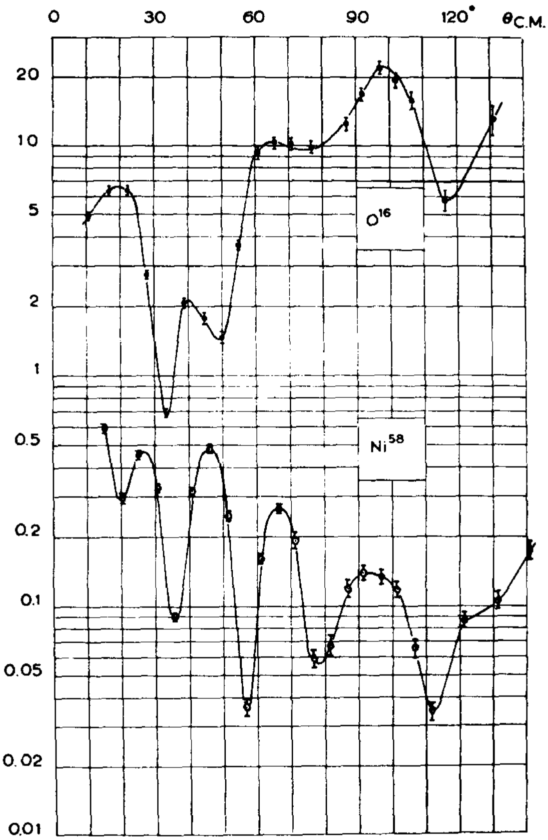

Fig. 1. Ratio of cross sections $(d\sigma/d\Omega)_{exp}/(d\sigma/d\Omega)_{Ruth.}$ in the reactions $O^{16}(d, d)O^{16}$ and $Ni^{58}(d, d)Ni^{58}$ at $E_d = 26.3$ and 27.5 MeV, respectively.

This problem is similar to that of diffraction of light by a circular hole in an opaque screen or diffraction by an opaque disk, where the distribution of diffracted light is described by the first order cylindrical Bessel function $J_1(x)$.

It has been shown [16, 17]) that the present analogy leads to a differential cross-section for elastic scattering expressed by a Fraunhofer-type formula

$$d\sigma/d\Omega = k^2R^4 \cos^2 \tfrac{1}{2}\theta (J_1(x)/x)^2,$$

where k and θ are wave number and scattering angle, respectively, in the centre-of-mass system; R, as above, is the interaction radius and $x = 2kR \sin \frac{1}{2}\theta$ is the variable which best describes the interaction.

TABLE 1

Elastic differential cross-section in the reactions O^{16}(d, d)O^{16} and Ni^{58}(d, d)Ni^{58}

O^{16}(d, d)O^{16} $E_d = 26.3$ MeV		Ni^{58}(d, d)Ni^{58} $E_d = 27.5$ MeV	
θ_{cm} (degrees)	$d\sigma/d\Omega$ (mb/sr)	θ_{cm} (degrees)	$d\sigma/d\Omega$ (mb/sr)
11.24	5142	10.30	14223
16.85	1954	15.50	2616
22.45	674	20.67	422
28.03	121	25.83	268
33.58	15.1	30.97	99.6
39.11	25.2	36.09	14.2
44.61	13.3	41.25	29.9
50.07	6.8	46.38	29.1
55.49	11.8	51.50	10.1
60.88	20.8	56.59	1.1
66.21	17.8	61.69	3.4
71.50	13.4	66.77	4.3
76.75	10.2	71.83	2.4
81.93	7.5	76.88	0.6
87.07	8.4	81.92	0.5
92.15	9.3	86.94	0.7
97.18	10.6	91.95	0.8
102.15	8.0	96.94	0.6
107.07	5.8	101.92	0.5
116.75	1.7	106.88	0.2
130.88	2.9	111.83	0.1
		121.69	0.2
		131.50	0.2
		141.25	0.3

The interaction radius R could be obtained by fitting the experimental data with the above formula or more quickly by considering that the maxima and minima of the angular distribution should correspond mainly to the maxima and zeros of the Bessel function or:

$$x_{i+1} - x_i \approx \pi \approx 2kR(\sin \tfrac{1}{2}\theta_{i+1} - \sin \tfrac{1}{2}\theta_i),$$

where θ_{i+1} and θ_i correspond to succesive maxima or minima.

The values of R extracted in this way from the angular distributions are listed in table 2. In general the values are greater than the target radius by about 1.5 fm when the value $R_0 = 1.33$ fm is chosen [18]) in the expression for nuclear radius.

TABLE 2

Radius of interaction for elastic scattering

Reaction	$(E_d)_{lab}$ (MeV)	Maxima (degrees)	Minima (degrees)	R (fm)	Mean R (fm)
$O^{16}(d, d)O^{16}$	26.3	39.0		5.5	
		63.5		4.7	
		97.0			4.9±0.6
			49.5	4.3	
			82.5	5.2	
			119.0		
$Ni^{58}(d, d)Ni^{58}$	27.5	24.0			
				6.2	
		43.5			
				5.9	
		65.5			
				5.7	
		91.5			5.9±0.6
			36.0		
				6.2	
			56.0		
				5.6	
			81.0		
				5.6	
			112.0		

The difference should correspond to the effective radius of the deuteron during the elastic scattering process which is considerably smaller than the so-called "radius of the deuteron" defined by [19]) $\rho = \hbar/(2\mu\varepsilon_d)^{\frac{1}{2}} = 4.31$ fm. This effective radius is the result of both the intrinsic finite size and the de Broglie wave-length.

The results obtained here are in agreement with those obtained at similar deuteron energies on different targets and could be crudely interpreted by considering that deuterons with an effective radius greater than about 1.5 fm break off during the elastic scattering process and consequently do not contribute to the cross-section [17, 20]).

3.2. INELASTIC SCATTERING

Fig. 2 shows the angular distribution measured for the reaction $Ni^{58}(d, d')Ni^{58}$ 1.45 MeV where a prominent forward peak indicates that a direct interaction inelastic scattering is the main reaction mechanism.

However, in addition to the forward peak, a "bump" in the cross-section corresponding to the angular region between 30° and 40° can be observed. It is not expected in terms of a plane wave direct interaction process.

A DWBA calculation would probably explain the experimental points to a certain extent; we have made a simpler approach by comparing the data with the Huby and Newns [2]) theory. It turned out that for this approach is required an $l = 4$ contribution in addition to an $l = 2$ contribution for best fitting the data.

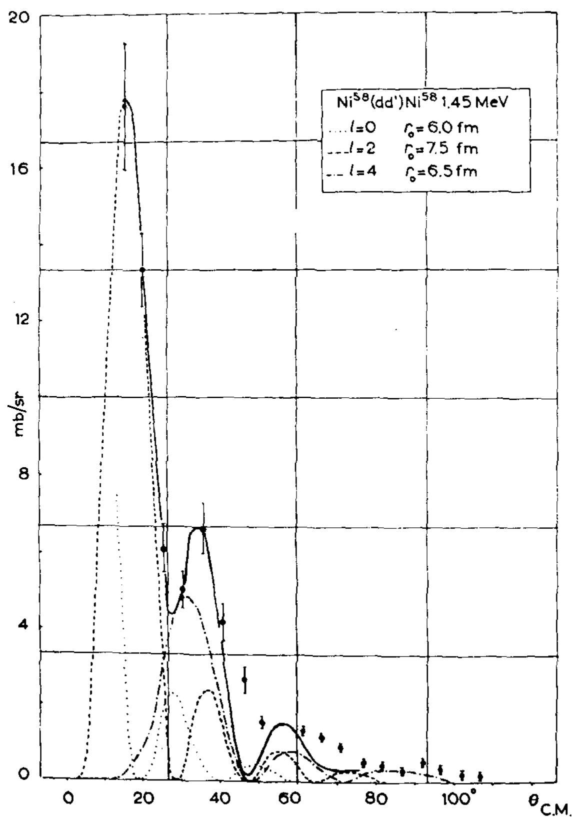

Fig. 2. Angular distribution in the reaction Ni^{58}(d, d')Ni^{58} 1.45 MeV at $E_d = 27.5$ MeV. Vertical bars indicate relative errors. Solid line results in Huby and Newns theory from the addition of $l = 2$ and $l = 4$ contributions. The $l = 0$ is shown but not added in the fit of experimental points. Interaction radii are indicated for different contributions.

As is well-known, the spin and parities of the Ni^{58} ground and first excited states are 0^+ and 2^+, respectively [21]). Therefore the $l = 2$ contribution can be explained in terms of the simple selection rules for deuteron inelastic scattering

$$|\mathbf{J}_f + \mathbf{J}_0|_{\min} \leqq l \leqq J_f + J_0$$

and total parity conservation.

The $l = 4$ contribution cannot be explained as above, and we have to consider the possibility of a deuteron spin-flip as a whole in the vicinity of the target nucleus; then the angular momentum selection rule is

$$|\mathbf{J}_f+\mathbf{J}_0+2\mathbf{s}_d|_{\min} \leqq l \leqq J_f+J_0+2s_d,$$

which will give $l = 0$, 2 and 4 as possible contributions in the present case.

The inelastic scattering is then understood as a direct interaction process as is assumed in the Huby and Newns model but the deuteron has an extra interaction with the target nucleus. Contributions with different l-values should add incoherently. This seems to be a good way to describe the observed angular distribution.

The $l = 0$ contribution was not observed with the present resolution; in general it is hard to detect an inelastic group in the forward direction due to the presence of the abundant elastic group.

In fig. 2 this contribution was represented only to show its behaviour but it was not added to the $l = 2$ and 4 contributions.

A comparison of the data was also made with Blair's expression [22]) for inelastic scattering

$$d\sigma/d\Omega \approx (qR_0^2)^2\{\tfrac{1}{4}J_0^2(qR_0)+\tfrac{3}{4}J_2^2(qR_0)\},$$

where as above q is the momentum transferred during the collision. The constant R_0 is related to nuclear radius by the expression

$$R(\theta, \phi) = R_0(1+\sum_{lm} \alpha_{lm} Y_{lm}(\theta\phi)),$$

where α_{ln} are nuclear deformation parameters, $Y_{lm}(\theta\phi)$ are spherical harmonic functions and $J_0(qR_0)$; $J_2(qR_0)$ are cylindrical Bessel functions. No satisfactory fit to the data could be obtained for reasonable values of R_0.

3.3. STRIPPING REACTIONS

Figs. 3 to 5 show the experimental stripping cross-section angular distributions taken for the reactions O^{16}(d, p)O^{17} ground state, O^{16}(d, p)O^{17} 0.872 MeV state and Ni^{58}(d, p)Ni^{59} ground state.

The stripping cross-section was not studied in detail above 90°; a brief survey indicated a monotonic decrease in this angular region.

A simple plane wave Butler [3]) analysis was made using Lubitz's tables [23]). The best fits obtained in this way are shown together with the corresponding experimental data.

It turned out, strikingly in ground state cases, that a good fit is only reached by adding incoherently [24]) more than one l_n-value contribution (l_n is the orbital angular momentum of the captured nucleon).

On the other hand, a successful fit could be expected in a DWBA approach. In fact, recently reported computations [28, 29]) suggest that departures from Butler's patterns as shown in the present work may be fitted by using DWBA methods. The agreement may, however, not always be significant due to the use of a large number of parameters [25]) which frequently assume unrealistic values [29]).

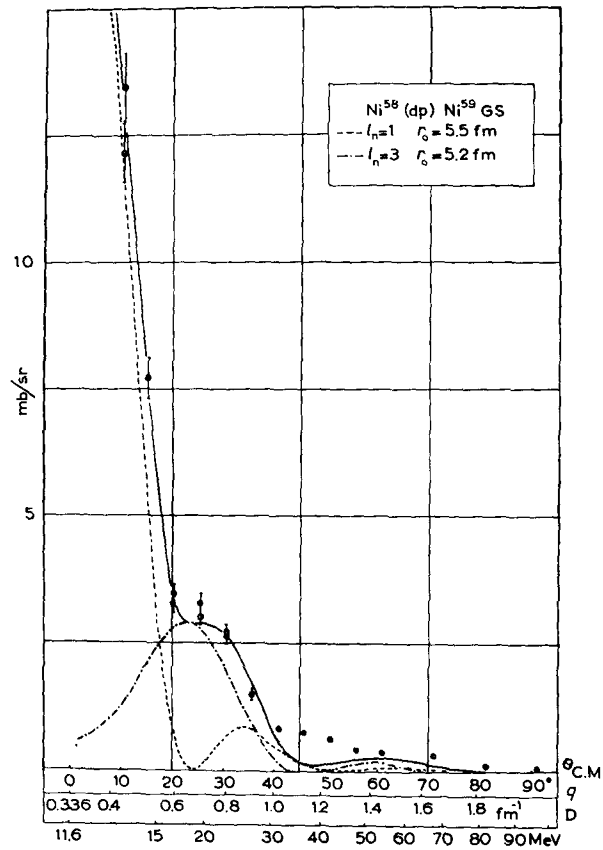

Fig. 3. Angular distribution in the reaction Ni^{58}(d, p)Ni^{59} ground state at $E_d = 27.5$ MeV. Vertical bars indicate relative errors. Solid line results in Butler theory from the addition of $l_n = 1$ and $l_n = 3$ contributions. Interaction radii are indicated for different contributions. Horizontal scales are centre-of-mass scattering angle, transferred momentum and "distance" to stripping pole of the reaction, respectively.

Let us, now, tentatively examine the features of the present plane wave analysis.

In the reaction Ni^{58}(d, p)Ni^{59} ground state an $l_n = 3$ in addition to an $l_n = 1$ are required to obtain a satisfactory fit (fig. 3). Since the initial and final states are 0^+ and $\frac{3}{2}^-$, respectively [21]), only the main $l_n = 1$ contribution can be justified in terms of the simple (d, p) selection rule

$$|\mathbf{J}_f+\mathbf{J}_0+\mathbf{s}_n|_{min} \leqq l_n \leqq J_f+J_0+s_n.$$

This is derived under the assumption of non-interaction between the free outgoing proton and the remainder of the reaction. Parity conservation in the whole system introduces a further restriction on the allowed l_n-values.

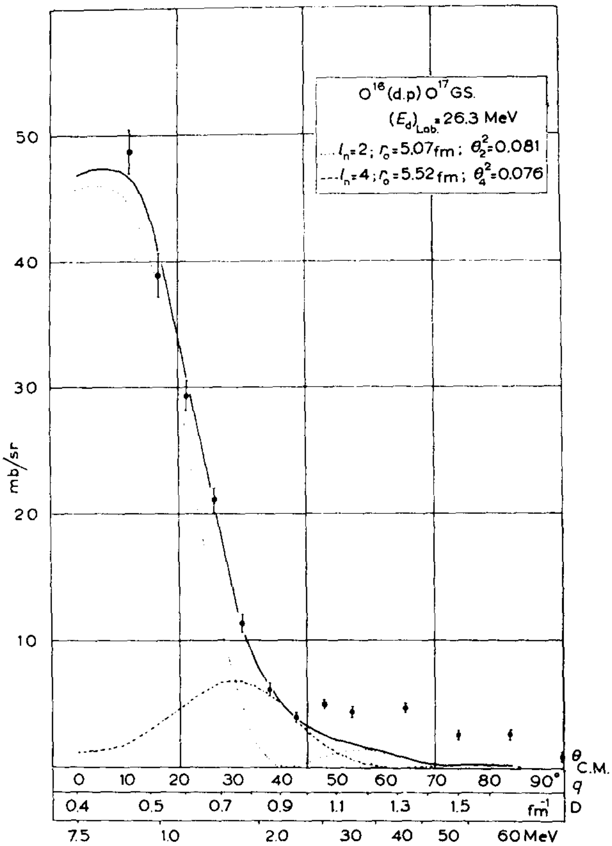

Fig. 4. Angular distribution in the reaction O^{16}(d, p)O^{16} ground state at $E_d = 26.3$ MeV. Vertical bars indicate relative errors. Solid line results in Butler theory from the addition of $l_n = 2$ and $l_n = 4$ contributions. Interaction radii and reduced widths are indicated for different contributions Horizontal scales are centre-of-mass scattering angle, transferred momentum and the "distance" to the stripping pole of the reaction, respectively.

The extra l_n contribution is only allowed by the more general selection rule:

$$|\mathbf{J}_f+\mathbf{J}_0+\mathbf{s}_d+\mathbf{s}_p|_{min} \leqq l_n \leqq J_f+J_0+s_d+s_p,$$

which is derived under the assumption of a possible spin-flip of the departing proton, though its orbital angular momentum remains unchanged through the reaction process.

In a j-j coupling shell model scheme, the neutron belonging to the main $l_n = 1$ contribution is captured by the Ni^{58} target in the ($2p_{\frac{3}{2}}$) shell.

To explain the presence of the extra $l_n = 3$ contribution, we make a tentative hypothesis considering the (d, p) reaction as proceeding in 2 steps, via the intermediate Ni^{58} 1.45 MeV state in the following way: (i) the incoming deuteron prior to the stripping process would excite the target nucleus to its first excited

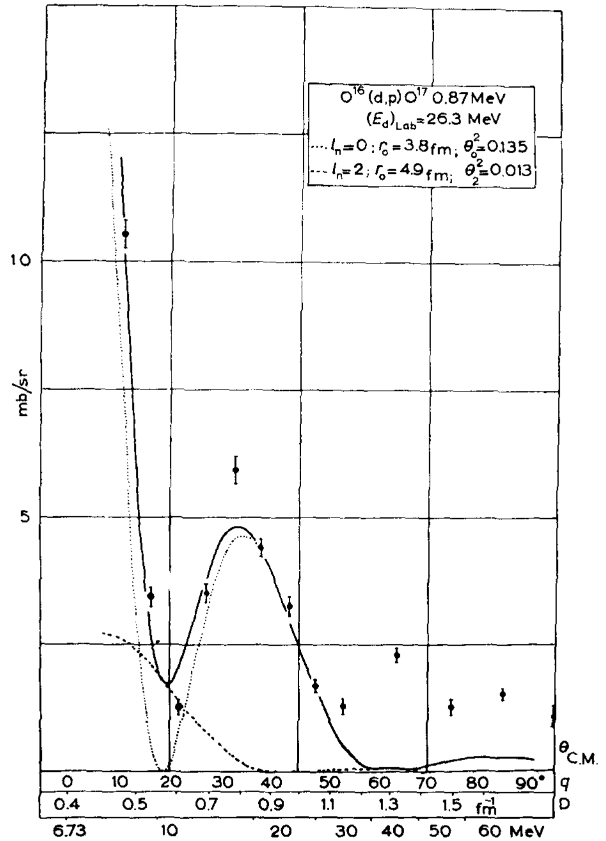

Fig. 5. Angular distribution in the reaction O^{16}(d, p)O^{17} 0.872 MeV state at $E_d = 26.3$ MeV. Vertical bars indicate relative errors. Solid line results in Butler theory from the addition of $l_n = 0$ and $l_n = 2$ contributions. Interaction radii and reduced widths are indicated for different contributions. Horizontal scales are centre-of-mass scattering angle, transferred momentum and the "distance" to the stripping pole of the reaction, respectively.

state with a configuration like ($2p_{\frac{3}{2}}$) ($1f_{\frac{5}{2}}$) coupled to a total spin 2; (ii) a normal deuteron stripping will be now accomplished in the common way connecting the "initial" Ni^{58} 1.45 MeV state with the final Ni^{59} ground state by an $l_n = 3$ wave which couples a ($1f_{\frac{5}{2}}$) particle to an equivalent particle in the initial state giving a final state with total spin $\frac{3}{2}^-$ corresponding to the Ni^{59} ground state.

In a similar fashion, the reactions O^{16}(d, p)O^{17} ground and 0.872 MeV state can be described as proceeding via the 2^+, O^{16} 6.91 MeV state [26]) (fig. 4).

In the former reaction, the initial and final states are 0^+ and $\frac{5}{2}^+$, respectively. An $l_n = 2$ and an $l_n = 4$ contribution seems to be necessary in order to obtain a good fit. Neutrons belonging to the former non-spin-flip contribution are captured in a ($d_{\frac{5}{2}}$) state [21]); neutrons belonging to the later spin-flip contribution should go through the O^{16} 6.91 MeV state, for which a configuration ($1d_{\frac{5}{2}}$) ($1g_{\frac{9}{2}}$) is assumed. Therefore when a neutron is captured in the ($1g_{\frac{9}{2}}$) state it couples with an equivalent particle producing the $\frac{5}{2}^+$ state in O^{17}.

This configuration seems rather improbable from the shell model prediction due to the high energy corresponding to the ($1g_{\frac{9}{2}}$) shell; however, it is the only configuration capable of admitting an $l_n = 4$ value in our reaction mechanism hypothesis.

In the O^{16}(d, p)O^{17} 0.872 MeV reaction, an $l_n = 2$ spin-flip contribution added to the $l_n = 0$ non-spin-flip contribution improves the fit obtained with a single contribution (fig. 5). The $l_n = 0$ contribution is explained as a 2s particle captured by O^{16} to give a final state [5]) with total spin $\frac{1}{2}^+$. The $l_n = 2$ contribution should proceed via the above-mentioned 2^+ state in O^{16} for which a configuration like ($1d_{\frac{5}{2}}$) (2s) is assumed, so that the complete wave function for this level should include at least the components ($1d_{\frac{5}{2}}$) ($1g_{\frac{9}{2}}$) and ($1d_{\frac{5}{2}}$) (2s).

It can be pointed out that the present experimental data depart from simple Butler theory when using a unique l_n-wave and that the departure increases when larger Q values are used.

Although more information is required before drawing general conclusions, such Q-values dependence is in good agreement with qualitative and quantitative discussions [6–9]), which state that the distance Δr between neutron and proton at the direct reaction occurrence depends on Q-values through a magnitude:

$$D \approx 3E_d + 2Q + 2.226 - 2(2E_d^2 + 2QE_d)^{\frac{1}{2}} \cos\theta,$$

where E_d is the centre-of-mass deuteron energy and θ is the scattering angle. As was pointed out in sect. 1, the magnitude D is called "distance" to the stripping pole.

For our deuteron energy and Q-values, $\Delta r \approx 4.6\, D^{\frac{1}{2}}$ fm is about 1.5 fm.

When using two l_n-waves, we found the following range of D values: for the Ni^{58}(d, p)Ni^{59} reaction $\approx$ 11—32 MeV, for the O^{16}(d, p)O^{17} ground and 0.872 MeV state reactions $\approx$ 11—25 MeV and $\approx$ 9—28 MeV, respectively.

Better agreement is obtained on greater distances to the stripping pole than reported elsewhere [9]).

To compute stripping reduced widths the following expression was used [5]):

$$\frac{d\sigma}{d\Omega} = 61.19 \left(\frac{A+1}{A+2}\right)^2 \frac{2J_f+1}{2J_0+1} \left(\frac{E}{E_0}\right)^{\frac{1}{2}} \{C[T_0 \tfrac{1}{2} T_f;\, M_{T_0} M_{T_f} - M_{T_0}]\}^2 \sigma^l_{\text{tab}}(xy) r_0^3\, \Theta^2.$$

The cross-section $d\sigma/d\Omega$ is in mb/sr, A is the target mass number, J_0 and J_f are the initial and final spins, E_0 is the laboratory energy of the bombarding particle in MeV, E is the free particle energy in the rest frame of $[A+1]$ nucleus in MeV, C is a Clebsch-Gordan coefficient equal to unity in the present examples, $\sigma^l_{\text{tab}}(xy)$ is the Lubitz's tables stripping cross-section, x and y are 2 convenient variables to tabulate cross-sections ($x = qr_0$ and $y = \kappa r_0$), r_0 is the interaction radius in fm, and Θ^2 is the stripping reduced width measured in units of the Wigner limit $(3\hbar/2\mu_n r_0^2)$, where μ_n is the reduced mass of the captured neutron.

TABLE 3

Strippping reduced widths

Reaction	E_d (MeV)	Q (MeV)	l_n	r (fm)	$\Theta^2_{l_n}$	$\Theta^2_{l_n+2}/\Theta^2_{l_n}$
O^{16}(d, p)O^{17} G.S.	26.3	1.912	2	5.07	0.081	0.94
			4	5.52	0.076	
O^{16}(d, p)O^{17} 0.872 MeV	26.3	1.042	0	3.8	0.135	0.1
			2	4.9	0.013	
Ni^{58}(d, p)Ni^{59} G.S.	27.5	6.78	1	5.5	0.030	1.06
			3	5.2	0.032	

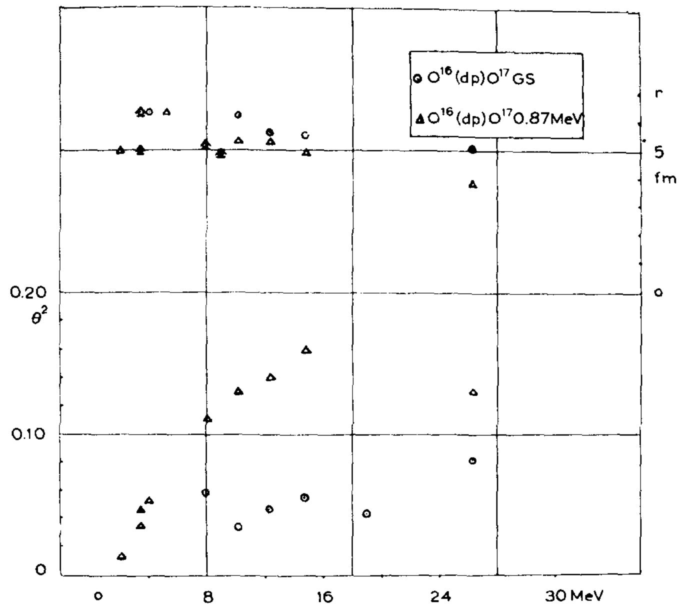

Fig. 6. Interaction radii and reduced width as a function of bombarding energy in the reaction O^{16}(d, p)O^{17}. Data below 20 MeV are quoted in refs. [5, 27]).

In table 3 the absolute and relative values of reduced widths are shown. It is seen that the contributions to stripping cross-section from the different l_n values are almost the same in each case, indicating that the proton spin-flip mechanism suggested should contribute appreciably.

However, it should be remembered that due to kinematic relations part of the main stripping forward peaks cannot be measured in our experiments because they fall in the unphysical region. Comparison between theoretical and measured cross-sections can only be done at the angular regions practicable in the laboratory system to which correspond small absolute values. This introduces an extra ambiguity in evaluating reduced widths making rather critical (within a few tenths fm) the choice of the cut-off radius.

Fig. **6** gives cut-off radii and absolute reduced widths corresponding to the $l_n = 2$ contribution in the reaction O^{16}(d, p)O^{17} ground state and for the $l_n = 0$ contribution in 0.872 MeV state as a function of the bombarding energy.

It is seen that while the cut-off radius is rather insensitive to great changes in the deuteron energies, the absolute reduced widths (calculated with the abovementioned expression) are changing by factors up to 1.5 within the region 10-27 MeV.

Neglecting the reduced widths obtained from experiments done at lower energies, it seems that a satisfactory "constant" Θ^2 value results for these reactions.

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