

SCATTERING AND STRIPPING OF 27.0 MeV DEUTERONS ON NITROGEN

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Abstract: The angular distributions of protons from the reaction $N^{14}(d, p)N^{15}$ and of the elastically scattered deuterons were measured. The experimental results of the first reaction were analyzed in terms of the theory of Butler with undistorted waves. The reaction takes place between the ground states of N^{14} and N^{15} , and their spins and parities are known. In order to fit the experimental points it was necessary to superimpose the theoretical curves of $l_n = 1$ and $l_n = 3$, l_n being the orbital angular momentum of the captured nucleon, with interaction radii $a = 3.7$ fm and $a = 3.2$ fm. No appreciable contribution from compound nucleus, exchange, or heavy particle stripping processes seems to be present in the angular distribution. The stripping reduced width is $\theta^2 = 0.31$. The $l_n = 3$ value of the orbital angular momentum implies the spin flip of the outgoing nucleon. The elastic scattering angular distribution exhibits a typical diffraction structure. Using a simple optical analogy that implies the scattering of waves from a black disk, an interaction radius was calculated for the deuteron-nucleus system: $r_0 = 6.5$ fm.

1. Introduction

The main object of present investigation was to obtain information about the reaction $N^{14}(d, p)N^{15}$, presumably due to a "stripping" process corresponding to the mechanism of Butler's theory¹⁾, and also about elastic and inelastic deuteron scattering. Recently Macfarlane and French²⁾ pointed out the lack of data for the "stripping" process and other deuteron induced direct reactions, above 20 MeV laboratory energy.

The ground state of N^{15} has been studied by means of the deuteron stripping reaction on N^{14} at various energies. Booth *et al.*³⁾ found that between 0.6 and 1 MeV the contribution due to stripping was small, whereas Jongerius *et al.*⁴⁾ had found previously that there was a reasonable agreement of the experimental angular distribution at 0.4, 0.5 and 0.6 MeV and the curves of the Butler theory, corresponding to $l_n = 1$, although they point out that the compound nucleus contribution is not negligible. Gibson and Thomas⁵⁾ found a good agreement of the theory with the experimental data at 7.9 MeV, using again the curve corresponding to $l_n = 1$. Analogous results were also obtained by various authors at 11.9 MeV (ref. 6), 14.8 MeV (ref. 7), 16.2 MeV and 16.7 MeV (ref. 8). Taking into account the spin and parity of the N^{14} ground state

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$(1+)^9$), it follows that the ground state of N^{15} is $\frac{1}{2}-$, corresponding to a configuration s^4p^{11} , a nucleon hole in the proton shell of O^{16} .

There is only little experimental information also on elastic scattering of deuterons in the range from 20 to 30 MeV¹⁰⁾, although recently several light elements have been studied around 28 MeV¹¹⁾.

2. Experimental Procedure

The experiment was performed using the external deuteron beam of the Buenos Aires 180-cm synchrocyclotron. The angular distributions were measured with a scattering chamber described elsewhere¹¹⁾. The target was gaseous nitrogen, 99.9 % pure. At every detection angle brass collimators were used to define the reaction volume. The reaction products were detected with a CsI(Tl) crystal, a phototube EMI 6097 and a single-channel pulse-height analyzer. The proton spectra were obtained by filtering the reaction products with an adequate thickness of aluminium to stop all particles with the exception of protons. The aluminium was placed immediately in front of the crystal to avoid multiple scattering effects. The optimum resolution was 2.8 % for deuterons around 27 MeV. The gas pressure used was lower than atmospheric, about 700 mm of Hg. The target volume was a function of angle, and the equivalent thickness varied between 1.2 mg/cm² for $\theta = 90^\circ$ and 6.9 mg/cm² for $\theta = 10^\circ$. The cross section was calculated following a treatment due to Silverstein¹²⁾ for the geometry corrections, as a consequence of the use of a gaseous target and a target volume defined by collimation.

3. Results

3.1. STRIPPING REACTION

Fig. 1a) contains a typical proton spectrum corresponding to the reaction $N^{14}(d, p)N^{15}$. The absolute differential cross section is shown in fig. 2, in which the relative errors are also shown. The conversion to the centre-of-mass system was effected with the help of tables prepared by Marion *et al.*¹³⁾. The theoretical angular distributions, using the plane wave undistorted form of direct interaction theory, were obtained using the usual formulas as they are presented by Macfarlane and French²⁾ and the tables of functions prepared by Lubitz¹⁴⁾.

The experimental angular distribution was adequately fitted by superimposing the theoretical curves of $l_n = 1$ and $l_n = 3$, the interaction radii being respectively $a = 3.7$ fm and $a = 3.2$ fm. According to the stripping theory of Butler, the so-called "nuclear approximations" involve the neglect of the interaction potential V_{xp} between the proton and the target nucleus, and also the interaction V_{np} between the captured neutron and the proton of the deuteron. As a consequence one obtains the well known rule for the possible values of

the orbital angular momentum

$$|\mathbf{J}_i + \mathbf{J}_f + \mathbf{s}_n|_{\min} \leq l_n \leq J_i + J_f + \frac{1}{2}, \quad (1)$$

where J_i and J_f are the spins of the target and residual nuclei, and s_n is the spin of the captured nucleon. For the reaction under discussion, expression (1)

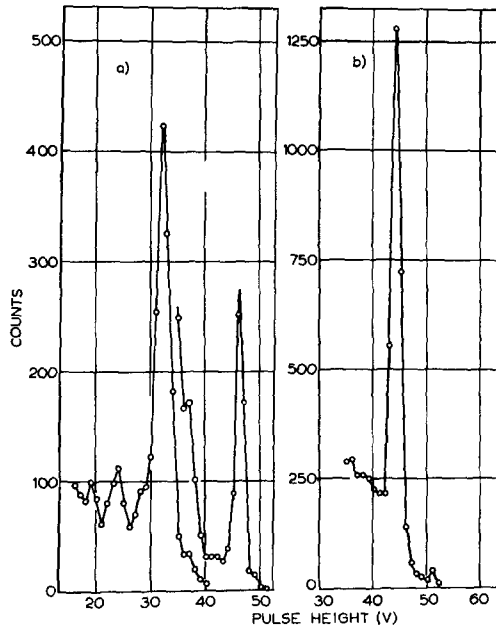


Fig. 1. a) Proton spectrum due to the reaction $N^{14}(d, p)N^{15}$ at $\theta_{lab} = 25^\circ$ (the first part of the spectrum is reduced by a factor of 4). b) Spectrum of reaction products at $\theta_{lab} = 25^\circ$.

together with the parity rule

$$\Pi_i \Pi_f = (-1)^l \quad (2)$$

yields as the only possible value $l_n = 1$. Therefore the $l_n = 3$ contribution to the cross section, tentatively assumed here to fit the experimental points, is not permitted by rule (1). If the "stripping approximations" are not valid, one should apply the following general rule derived from the law of conservation of angular momentum:

$$|\mathbf{J}_i + \mathbf{J}_f + \mathbf{s}_d + \mathbf{s}_p|_{\min} \leq l_n \leq J_i + J_f + s_d + s_p, \quad (3)$$

where s_d is the spin of the projectile (the deuteron), and s_p is the spin of the emergent proton. This rule together with (2) yields $l_n = 1$ and $l_n = 3$ as possible values. The second value of l_n corresponds to the spin-flip of the outgoing proton. Taking into account the energy of the deuterons, appreciably higher than those used previously to study stripping reactions, the assumption that

the stripping approximations cease to be valid seems plausible. The use of the undistorted form of the theory seems to be justified on account of the higher bombarding energy, although the observed effect could also be due to wave distortion. Similar results were already obtained for other elements ^{11, 19}).

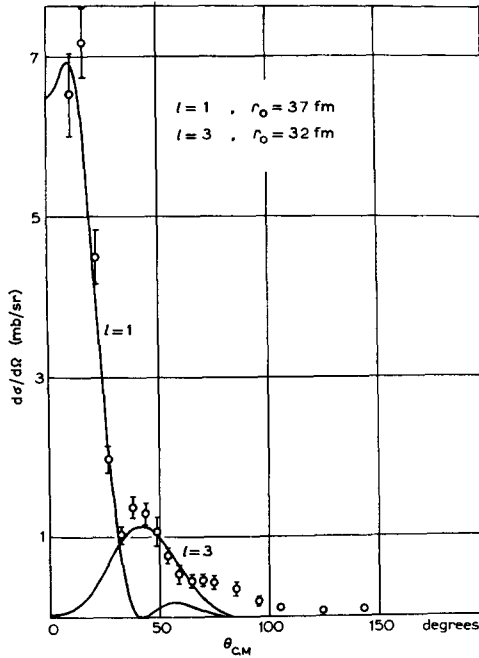


Fig. 2. Angular distribution of protons from the reaction $N^{14}(d, p)N^{15}$.

A straightforward consequence of the appearance of the $l_n = 3$ value, in the light of the shell model of the nucleus, is that the levels connected by the reaction are not pure. The captured neutron should be a $1p$ nucleon (l_n should be 1), and therefore it should be necessary to add an f component to the configuration in order to explain the higher l_n value.

It may be interesting to note that the ample second oscillation of the angular distribution, interpreted in terms of the $l_n = 3$ theoretical curve, seems to be present at lower energies but with smaller amplitude, and in phase with the second oscillation of the $l_n = 1$ curve. With increasing energy the second oscillation of the experimental angular distribution closes up towards the first maximum, getting out of phase with respect to the second oscillation of the theoretical curve. It is worth while to mention the experiments performed at 7.9 MeV by Gibson and Thomas ⁵), at 11.9 MeV by Eby ⁶), and especially at 14.8 MeV by McGruer ⁷) where the disagreement is already significant. It would be desirable to obtain the angular distributions at intermediate energies between 27 MeV and 14.8 MeV.

The reduced widths in units of $3\hbar^2/(2\mu a^2)$ are $\theta_1^2 = 0.11$ for $l_n = 1$ and $\theta_3^2 = 0.20$ for $l_n = 3$. The total reduced width is therefore $\theta^2 = 0.31$ (ref. 2). There is some difficulty related with the obtention of reduced widths, because the energy dependence of the cross section predicted by the theory of Butler is not in agreement with the experimental results¹⁵).

3.2. ELASTIC SCATTERING

Fig. 1b) contains a typical spectrum of reaction products where the elastically scattered deuterons predominate. The absolute differential cross section, its ratio to Rutherford cross section, and also the latter are shown in fig. 3. The

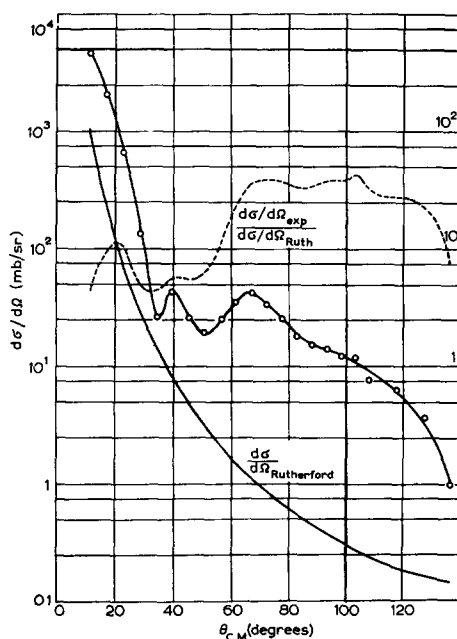


Fig. 3. Angular distribution of the elastically scattered deuterons.

elastic scattering cross section obtained by considering the scattering of the particle associated waves by a "black disk" is given by^{10, 16})

$$d\sigma/d\Omega \approx R^2 \{J_1^2[2kR \sin \frac{1}{2}\theta] / 4 \sin^2 \frac{1}{2}\theta\}, \quad (4)$$

where k is the wave number of the scattered particle, R is the interaction radius and J_1 is the first order Bessel function. The black disk model neglects Coulomb scattering, and therefore it should yield better results when the ratio of the observed cross section to the Rutherford one is large. As a consequence of (4) it can be shown that approximately¹⁶)

$$2kR \Delta(\sin \frac{1}{2}\theta) = \pi, \quad (5)$$

where $\Delta(\sin \frac{1}{2}\theta)$ is the difference of the values of $\sin \frac{1}{2}\theta$ for two adjacent maxima (or minima) of the diffraction pattern. By means of (5) an average interaction radius $r_0 = 6.5$ fm for the deuteron nucleus system was obtained. Calculating the nuclear radius through the usual expression $R_N = 1.3 \times A^{\frac{1}{3}}$ fm, one obtains a value $R_d = 3.36$ fm, for the deuteron radius, lower than the relaxation radius of the deuteron wave function $\rho = |\hbar|^{-1} = \hbar/(2\mu B)^{\frac{1}{2}} = 4.31$ fm (ref. ¹⁷), where μ is the reduced mass of the neutron-proton system forming the deuteron and B is the binding energy.

The diffraction pattern is similar to those obtained at lower energies by various authors ¹⁰). No significant inelastically scattered deuteron group was observed. This may be a confirmation of the isospin assignment $T = 1$ of the 2.31 MeV level of N^{14} , according to the isospin selection rule ¹⁸).

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