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SCATTERING OF 27.7 MeV DEUTERONS ON BERYLLIUM AND BORON

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Abstract: Beryllium and natural boron targets were bombarded with 27.7-MeV deuterons. The outgoing particles were analysed with a scintillation spectrometer. The absolute differential cross section for the elastic scattering was measured. The resulting angular distributions exhibit the usual diffraction pattern. Employing an optical analogy, interaction radii were calculated for the deuteron-nucleus system. The results are: $R_{DN} = 4.56$ fm for beryllium and $R_{DN} = 5.65$ fm for boron. The angular distribution of the inelastic process $\text{Be}^9(d, d')$ $\text{Be}^{9*} - 2.43$ MeV was also obtained and it was fitted with a direct reaction curve, using the theory of Huby and Newns, of $l = 2$ and $a = 4.8$ fm, where l is the angular momentum change and a is the interaction radius. The ground state of Be^9 is $\frac{3}{2}^-$ odd, and therefore present results yield for the 2.43 MeV level an odd parity assignment, together with the following possible spin values: $\frac{1}{2}^-$, $\frac{3}{2}^-$ and $\frac{5}{2}^-$. Better agreement with the experimental results is obtained by adding a theoretical curve of $l = 0$ with $a = 4.0$ fm, a fact which possibly implies the presence of deuteron spin-flip. No significant inelastic process was observed with the natural boron target (18.8 % of B^{10} and 81.2% of B^{11}).

1. Introduction

The Be^9 nucleus has been extensively studied by Summers-Gill¹⁾, who bombarded it with 12-MeV protons, 24-MeV deuterons and 48-MeV alpha particles. He obtained the angular distributions of the elastically scattered particles and of the excitation of the 2.43-MeV level, producing a parity and spin assignment for it. Previously Ribe and Seagrave²⁾, and Benveniste, Finke and Martinelli³⁾ obtained contradictory parity assignments for the above mentioned level. The Be^9 nucleus is still controversial mainly due to the limited experimental information.

The B^{11} nucleus was the object of considerable amount of experimental work, mainly through the $\text{B}^{10}(d, p)\text{B}^{11}$ stripping reactions. The 2.14-MeV level aroused considerable interest because according to the usual "stripping approximation" selection rules, the $\frac{1}{2}^-$ odd spin and parity assignment, confirmed by Wilkinson⁴⁾, was in apparent contradiction with the stripping angular distribution. This fact gave rise to Wilkinson's "spin-flip" hypothesis and to several theoretical and experimental papers⁵⁾

† This paper is based on communications to the Asociación Física Argentina during the following meetings: XXXVII (May 1961) and XXXVIII (September 1961).

The purpose of the experiments described here was primarily the measurement of the elastic scattering angular distribution, in order to obtain the deuteron-nucleus interaction radii, secondly the inelastic scattering angular distributions, in order to obtain information about the reaction mechanism and the excited levels of the target nuclei. Previous work on elastic and inelastic scattering on Li^7 , C^{12} and Al^{27} can be found elsewhere ⁶). The elastic scattering data will be submitted in the future to an optical model analysis with an electronic computer.

2. Experimental Procedure

2.1. MACHINE AND FACILITIES

The 28-MeV external deuteron beam facilities of the Buenos Aires 180-cm synchrocyclotron have been described elsewhere ⁷). The scattering chamber and the auxiliary equipment were described in detail in the just mentioned paper on elastic and inelastic deuteron scattering ⁶). The particle detection and spectrometry was achieved with CsI(Tl) crystals, a phototube (EMI 6097) and a single-channel pulse-height analyser. The details concerning the particle identification and separation procedure, as well as the background subtraction routine, are described in ref. ⁶). Some minor changes in the electronics were adopted during the measurements on the boron target, in order to obtain the integral of the particle spectrum above the lower window limit, during the measurement of each point of the differential spectrum. The integral was registered simultaneously on a second scaler, thus permitting a constant cross-check of the collected data.

2.2. TARGETS

The beryllium target was a chemically pure foil 20 mg/cm² thick, measured at 45° with respect to the incident beam. The thickness measurement was performed as described by Conzett ⁸) in order to avoid the target destruction.

The boron target was prepared using the chemically pure element in powder form with the following procedure: A boron emulsion in water was poured on a very thin cellulose acetate backing. The liquid was evaporated naturally in the open air, without turbulence. Some targets of very good uniformity were obtained after several trials. The thickness of the boron target was also measured using the beam transmission technique described in Conzett's paper ⁸). The boron targets backing thickness was negligible with respect to their 20 mg/cm² average thickness.

2.3. ERRORS AND EXPERIMENTAL UNCERTAINTIES

A full discussion can be found elsewhere ⁶). The error in the target thickness measurements was determined using aluminium targets of known thickness: it is not larger than 5 %. The beam energy was found to be 27.7 MeV \pm 1 %.

This value is somewhat lower than the one determined previously ^{6,7}), and it may be due to some iron configuration changes performed to raise the beam intensity. The beam energy can be maintained very stable with little precaution on the parameters of the deflector and the magnetic field of the machine.

The absolute differential cross sections reported here are known within an error of 8 %, besides the relative errors indicated on the experimental curves. The quoted value is due to the error in current integration, in solid angle and in target thickness.

The scintillator particle detection efficiency was taken to be one, because all the particles accepted by the defining apertures were counted.

3. Results and Conclusions

3.1. GENERAL

Figs. 2, 3 and 5 contain the experimentally determined absolute differential cross sections, referred to the centre-of-mass system; the conversion was effected with the help of tables prepared by Marion *et al.* ⁹). The elastic scattering curves are shown together with the Rutherford differential cross section and the ratio to it. The relative errors are the ones indicated on the curves as they are the ones to define the shape of the angular distribution. The differential cross section of the elastically scattered deuterons were analysed using a simple optical analogy ^{1,10}), in order to obtain the deuteron-nucleus interaction radii. The elastic scattering cross section obtained by considering the scattering of the particle associated waves by a black disk is given by

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

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" approximation neglects Coulomb scattering, and it should yield good results when the ratio of the observed cross section to Rutherford is large.

The number of levels of the compound nucleus excited in the reaction was calculated using the usual expression of the level density

$$w(E) = C \exp [2(aE)^{\frac{1}{2}}], \quad (2)$$

where E is the excitation energy, C and a are constants (cf. Blatt and Weisskopf ¹¹). The energy spread of the incident beam is estimated to be 56 keV, the beryllium target thickness is some 600 keV, and that of the boron target is some 700 keV. The cross section for the formation of the compound nucleus was estimated with the asymptotic expression

$$\sigma_c \approx (R + \lambda)^2 \left[1 - \frac{V(R + \lambda)}{E} \right], \quad (3)$$

where R is the nuclear radius, E is the centre-of-mass energy of the projectile, V is the Coulomb potential and λ is the particle associated wave length divided by 2π . Instead of $R + \lambda$ it is also plausible to use the deuteron-nucleus interaction radius determined experimentally. Table 1 condenses the results of the calculations employing the last-mentioned idea.

TABLE 1

Excitation energy of the compound nucleus using deuterons as projectiles, cross section for the formation of the compound nucleus calculated with the asymptotic expression (3), and number of levels of the compound nucleus involved in the reaction due to the spread in energy of the incident beam and to the finite target thickness

Target nucleus	Compound nucleus	Excitation energy (MeV)	Cross section (mb)	Number of levels
Be ⁹	B ¹¹	40.3	617	214
B ¹¹	C ¹³	42.1	905	506

The angular distribution of the inelastic process Be⁹(d, d')Be^{9*}—2.43 MeV was fitted using the Huby and Newns theory¹²⁾, that is, with spherical Bessel functions. The Huby and Newns differential cross section is given by

$$d\sigma/d\Omega = \sum_i |A_i|^2 [(4\alpha/k) \operatorname{arctg} (k/4\alpha) j_i(ka)]^2, \quad (4)$$

where $k = [(k_i - k_f)^2 + 4k_i k_f \sin^2 \frac{1}{2}\theta]^{\frac{1}{2}}$ (k_i and k_f are the initial and final wave numbers, respectively), $\alpha = (M_n E_b)^{\frac{1}{2}}/\hbar$ (the deuteron wave function relaxation length being $1/\alpha$), the A_i are constants, a is the "interaction radius" and $j_i(ka)$ is a spherical Bessel function.

3.2. ANGULAR DISTRIBUTIONS

3.2.1. The Be⁹(d, d)Be⁹ Reaction

Fig. 1 contains a typical spectrum of reaction products due to the incident deuterons. One observes two well defined peaks, corresponding to the elastic scattering and to the excitation of the 2.43-MeV level of Be⁹. The particle groups of higher energy than the elastic peaks are protons from (d, p) reactions.

Fig. 2 contains the elastic scattering absolute differential cross section, Rutherford cross section and the ratio of the former to it which yields a measure of the nuclear interaction. The curve exhibits a typical diffraction pattern common to other particles and similar to the curves obtained earlier at the same energy and at lower energies^{1, 6, 13)}. A simple analysis has been carried out through the use of expression (1), because the spacing between adjacent maxima (or minima) of the cross section is approximately π . The

interaction radius R_1 can be obtained simply as

$$R_1 = \pi/2k(\sin \frac{1}{2}\theta_{1+1} - \sin \frac{1}{2}\theta_1), \tag{5}$$

where k is the wave number of the scattered particles, θ_1 is the angle where the

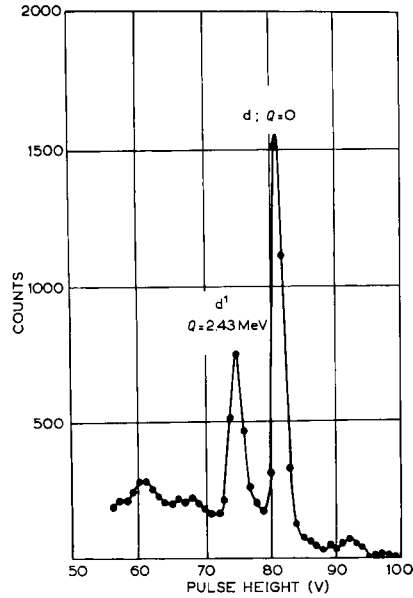


Fig. 1. Charged particle spectrum from beryllium $\theta_{lab} = 45^\circ$.

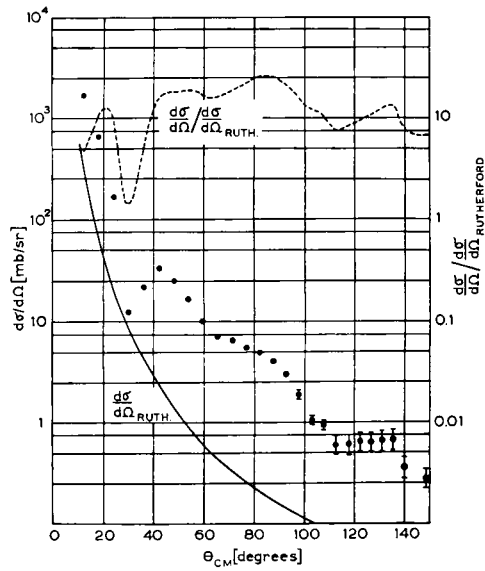


Fig. 2. Angular distribution of deuterons elastically scattered from beryllium.

i^{th} maximum is observed; a similar equation applies for the minima. Table 2 condenses the information obtained by means of this analysis. The average interaction radius $R_{1(\text{av})} = 4.56$ fm. Utilizing the expression

$$R_N = 1.3A^{\frac{1}{3}} \text{ fm} \quad (6)$$

for the nuclear radius, one obtains an interaction radius of 1.68 fm for the deuteron. Calculating the latter through the same expression (6), one finds 1.61 fm. Both values are significantly lower than the so called "deuteron radius": $R_d = 4.31$ fm (the relaxation length of the deuteron radial wave function is $R_d = \hbar/(M_n E_b)^{\frac{1}{2}}$, where M_n is the average nucleon mass and E_b is the deuteron binding energy¹⁴).

TABLE 2

Interaction radii obtained through diffraction analysis of the elastic scattering angular distributions of 27.7 MeV deuterons

Element	Maxima (degrees)	Minima (degrees)	Interaction radius (fm)	Average inter- action radius (fm)
Beryllium	22			
	51		4.77	
	85		4.77	
	135		4.70	
		30		4.56
		62	4.47	
		112	3.65	
Boron	21		4.9	
	43		6.1	
	73			5.65
		35	5.8	
		59		

3.2.2. The $\text{Be}^9(\text{d}, \text{d}')\text{Be}^{9*}$ (2.43 MeV) reaction

Fig. 3 contains the angular distribution of the cross section corresponding to the inelastic process $\text{Be}^9(\text{d}, \text{d}')\text{Be}^{9*}$ (2.43 MeV). As stated previously, the experimental points were fitted using the theory of Huby and Newns¹²), with a curve of $l = 2$ and $a = 4.8$ fm. As the ground state spin and parity of Be^9 are $\frac{3}{2}$ and odd, respectively, it follows that the parity of the 2.43-MeV level is odd and that the possible spin values are $\frac{1}{2}$, $\frac{3}{2}$, $\frac{5}{2}$ and $\frac{7}{2}$, using the current selection rules that imply an interaction of the deuteron through one of its nucleons. The angular momentum change is therefore $\Delta J = l$. Nevertheless a better agreement with the experimental results is obtained adding a contribution of the $l = 0$ curve, with a smaller interaction radius, $a = 4.0$ fm. Both theoretical curves are drawn separately on fig. 3 for the sake of clarity. Using

the same selection rule mentioned previously a single value results for the spin of the level $\frac{3}{2}$ and odd parity. Instead, if one assumes that the deuteron interacts as a whole with the nucleus, and taking into account the possibility of the flip of the deuteron spin, the selection rule ⁶⁾ should be $\Delta J = l, l \pm 2$. In that case one obtains the same set of possible spin values, for both l values, excluding the unusually high $\Delta J = 4$ angular momentum change.

The interaction radii for the direct reaction curves are consistent with the one obtained through diffraction analysis of the elastic scattering. This is certainly to be expected because the direct reaction is predominantly a surface

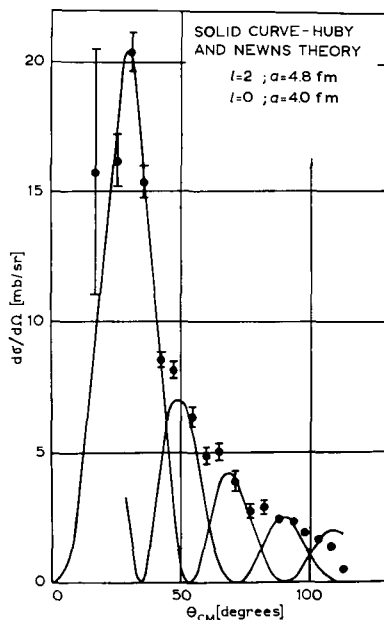


Fig. 3. Angular distribution of deuterons from the reaction $\text{Be}^9(d, d')\text{Be}^9^*$ (2.43 MeV).

reaction. The results obtained here do not contradict the shell model predictions ¹⁵⁾, either in the extreme L - S or j - j coupling schemes. The conclusions of present investigation agree with those of Summers-Gill ¹⁾ and of Ribe and Seagrave ²⁾.

The particle spectra were followed down to 150° in the laboratory system, and the cross section for the excitation of the 2.43-MeV level remains certainly lower than that of the last angle drawn in fig. 3. As no backward rise of the cross section was observed, it is concluded that there is no significant contribution due to a process that is symmetrical with respect to 90° in the centre-of-mass system, like the most common compound nucleus process through a single level or through many levels in the continuum region. Analogously exchange processes can be excluded.

Finally it is worth while mentioning that one may extend the treatment of Butler¹⁶⁾ to deuteron scattering, either in the quantum mechanical form or in the semiclassical approach, thereby assuming the deuteron to interact as a whole. In this way one may obtain a good fit of the angular distribution, using again two l values with interaction radii that are close to the ones employed with the Huby and Newns theory.

3.2.3. The B(d, d)B reaction

Fig. 4 contains a typical spectrum due to the incident deuterons. The isotopic composition of the target rendered an identification impossible of the weak inelastic group below the elastic peak. As a consequence only the elastic scattering angular distribution was measured. It is shown in fig. 5, and it was

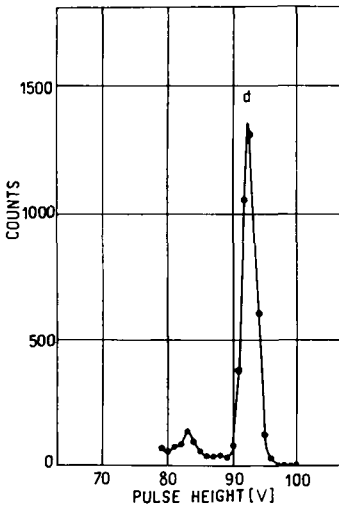


Fig. 4. Charged particle spectrum from boron $\theta_{lab} = 15^\circ$.

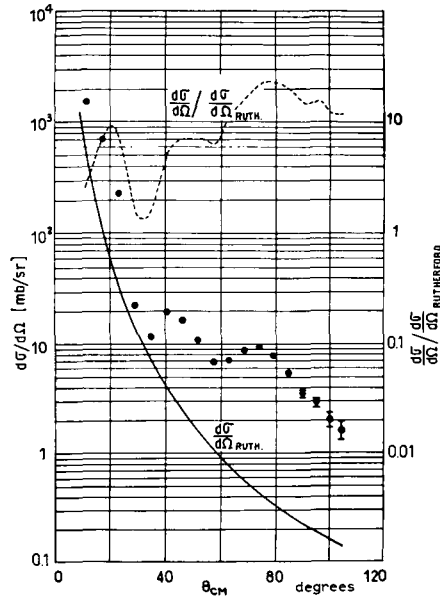


Fig. 5. Angular distribution of deuterons elastically scattered from beryllium.

attributed to B¹¹, the most abundant isotope, when performing the transformation to the centre-of-mass system. A completely similar diffraction analysis as described for the beryllium nucleus was carried out with the present angular distribution. Table 2 contains the resulting information. The average interaction radius $R_{i(av)} = 5.65$ fm. Using expression (6) for the nuclear radius, a value of 2.76 fm for the deuteron is obtained. This value is still appreciably smaller than the deuteron radius R_d .

3.3 CONCLUSIONS

Due to the high excitation energy of the compound nucleus (table 1), there are many competing channels for the decay of the system. Multiple reactions are favoured and the incident particle reemission is not likely to occur. It is then logical to expect that simple reactions would proceed through a direct type of mechanism. This seems to be the case with the inelastic scattering angular distribution reported here. The cross section is rather high taking into consideration that the deuteron is a loosely bound structure, and would more likely break up than interact as a whole. Nevertheless, the tentative explanation of the experimentally determined angular distribution through the contribution

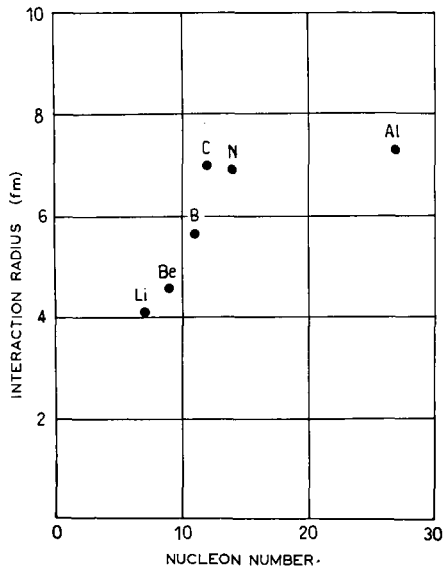


Fig. 6. Deuteron-nucleus interaction radii as a function of the nucleon number.

of two l values to the cross section, and subsequently the hypothesis of the total spin flip of the deuteron, implies that it really interacts as a whole. Otherwise it would be hard to explain a spin flip with a significant cross section. If it were due to the spin flip of each nucleon of the deuteron interacting independently with the target nucleus, its cross section should be of higher order with respect to the "non-flip" process. As is well-known, the treatment of inelastic deuteron scattering of Huby and Newns relies on the assumption that only one nucleon of the projectile interacts with the target nucleus. Therefore it precludes from the beginning the possibility of the interaction of both nucleons of the deuteron with the target, and also its interaction as if it were a particle of spin 1. Taking into account earlier results⁶⁾ together with the ones reported here, the general conclusion is that a good fit of the angular distributions of inelastic processes, leaving the target nuclei in a low lying level, is

obtained by superimposing the theoretical curves of two different l values allowed by the usual parity rule, and that presumably the appearance of the second l value is due to the "flip" of the deuteron spin.

The elastic scattering angular distributions do not exhibit any striking features. The interaction radii obtained from the angular distributions do not correspond to the same centre-of-mass energy, although they are comparable among themselves because the overall variation of energy is less than 20 % from Li up to Al. Fig. 6 contains a plot of the radii as a function of the target nucleon number, including data obtained in other experiments ^{6,17}); a definite general trend of the interaction radii is obvious for the light nuclei. The extrapolation to zero should formally yield the deuteron interaction radius. The data obtained so far are judged to be too distant from the origin to perform such extrapolation. Nevertheless it should lie somewhere between 1.25 fm and 3.5 fm, that is, smaller than the deuteron radius calculated as the relaxation length of the deuteron wave function. The set of radii obtained through the simple diffraction analysis can be useful as a starting point for the machine computations to be performed in the future.

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References

- 1) Robert G. Summers-Gill, *Phys. Rev.* **109** (1958) 1591
- 2) F. L. Ribe and J. D. Seagrave, *Phys. Rev.* **94** (1954) 934
- 3) J. Benveniste, R. G. Finke and E. A. Martinelli, *Phys. Rev.* **101** (1956) 655
- 4) D. H. Wilkinson, *Phys. Rev.* **105** (1957) 666
- 5) A. P. French, *Phys. Rev.* **107** (1957) 1655;
N. T. S. Evans and A. P. French, *Phys. Rev.* **109** (1958) 1272;
J. C. Hensel and H. C. Parkinson, *Phys. Rev.* **110** (1958) 128;
J. E. Bowcock, *Phys. Rev.* **112** (1958) 923
- 6) R. J. Slobodrian, *Phys. Rev.* (to be published), CNEA Report Nr. 54 (1961) (unpublished)
- 7) P. A. Lenk and R. J. Slobodrian, *Phys. Rev.* **116** (1959) 1229;
J. Rosenblatt and R. J. Slobodrian, *Rev. Sci. Instr.* **31** (1960) 863
- 8) Homer E. Conzett, *Phys. Rev.* **105** (1957) 1324
- 9) J. B. Marion, T. I. Arnette and H. C. Owens, Oak Ridge National Laboratory Report ORNL-2574
- 10) R. M. Eisberg, G. Igo and H. E. Wegner, *Phys. Rev.* **99** (1955) 1606;
Robert G. Summers-Gill, University of California Report, UCRL 3388 (unpublished);
R. M. Eisberg and C. E. Porter, *Revs. Mod. Phys.* **33** (1961) 190
- 11) J. M. Blatt and V. F. Weisskopf, *Theoretical nuclear physics* (John Wiley & Sons, Inc., New York, 1952)
- 12) R. Huby and H. C. Newns, *Phil. Mag.* **42** (1951) 1442

- 13) G. E. Fischer and V. K. Fischer, Phys. Rev. **114** (1959) 533;
J. L. Yntema, Phys. Rev. **113** (1959) 261;
N. Cindro, M. Cerineo and A. Strzalkowski, Nuclear Physics **21** (1960) 38
- 14) Robley D. Evans, The atomic nucleus (McGraw Hill Book Co. Inc., New York, 1955)
- 15) D. Kurath, Phys. Rev. **101** (1956) 216
- 16) S. T. Butler, Phys. Rev. **106** (1956) 272;
S. T. Butler, N. Austern and C. Pearson, Phys. Rev. **112** (1958) 1227
- 17) H. J. Erramuspe and R. J. Slobodrian, Communication to the XXXVIII Meeting of the Asociación Física Argentina (September 1961) (to be published)