Elastic Scattering of ^{14}N on ^{9}Be at 25 MeV and ^{16}O on ^{11}B at 30 MeV

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Dedicated to Professor Dr. W. GENTNER *on the occasion of his 60th birthday*

The elastic scattering of ^{14}N on ^{9}Be at 25 MeV and ^{16}O on ^{11}B at 30 MeV has been measured and analyzed with Optical Model and Ingoing Wave Boundary Condition calculations. Acceptable fits were obtained for the angular region below 100° c.m. The reflection coefficients derived from these calculations are compared with the Diffraction Model calculations of DAR to the corresponding p- and α-transfer reactions, in which a WOODS-SAXON distribution of the reflection coefficients is used.

During the measurement of transfer reactions [1, 2] with the Heidelberg Tandem VAN DE GRAAFF accelerator angular distributions of the elastic scattering of heavy ions have been obtained. In this note the analysis of the elastic scattering of ^{14}N on ^{9}Be at 25 MeV and of ^{16}O on ^{11}B at 30 MeV (E_{lab}) with the Optical Model (OM) and the Ingoing Wave Boundary Condition (IWB) [3] will be described. Only few heavy ion elastic scattering data in this energy region have been published [4, 5] and only in some cases optical model calculations have been done. The calculations of KUEHNER and ALMQVIST [5] with the optical model gave good fits to the elastic scattering of ^{16}O on ^{12}C, ^{14}N on ^{12}C and ^{14}N on ^{9}Be at energies smaller 10 MeV ($E_{c.m.}$), but the physical interpretation of the parameters (especially of the imaginary potential depth) obtained led to difficulties. Such calculations however are of great interest, because they yield the parameters required to interpret the experimental transfer reactions [1, 2] by means of DWBA and Diffraction Model calculations.

Discussion of experimental Data

The experimental procedure of the measurements with a $dE/dX-E$ counter telescope has been described in ref. [1]. The absolute cross sections result from a measurement in a special isolated chamber and have an uncertainty of 15%. The experimental curves are shown in Fig. 1 and 2 together with the calculated curves. The $^{14}N-^{9}Be$ data at 25 MeV agree within 10 – 15% with the excitation function of KUEHNER and ALMQVIST [5] measured at 90° c. m.

For the compound-elastic contribution an upper limit can be estimated from the cross sections of the $^{9}Be(^{14}N, ^{6}Li)^{17}O$ and $^{9}Be(^{14}N, ^{7}Li)^{16}O$ reactions at

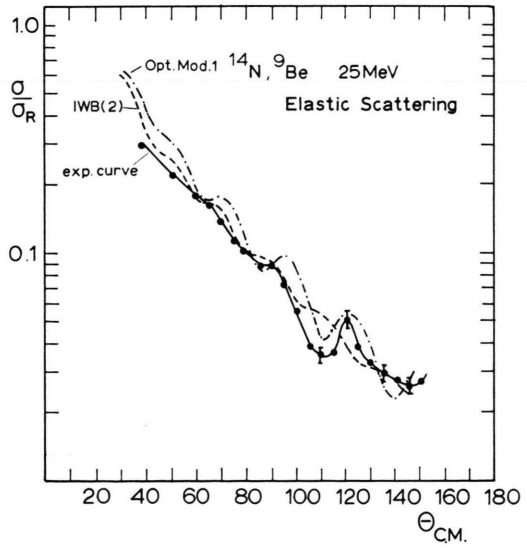

Fig. 1. Optical model and IWB calculations of the elastic scattering of ^{14}N on ^{9}Be at 25 MeV.

Parameters:

opt. Mod. 1: $V_0=-70.0$ MeV, $a_1=0.476$ f, $R_1=5.80$ f, $W_0=-10.2$ MeV, $a_W=0.45$ f, $R_W=5.88$ f;

IWB 2: $V_1=-80\,000$ MeV, $a=0.7$ f, $W_0=-1.8$ MeV, $a_W=1.2$ f, $R_W=7.0$ f.

[1] R. BOCK, H. H. DUHM, M. GROSSE-SCHULTE, and R. RÜDEL, Nucl. Phys. **70**, 481 [1965].

[2] R. BOCK, M. GROSSE-SCHULTE, W. v. OERTZEN, and R. RÜDEL, Phys. Letters **18**, 45 [1965].

[3] G. H. RAWITSCHER, Phys. Rev. **135**, B 605 [1964]. — J. S. MCINTOSH, S. C. PARK, and G. H. RAWITSCHER, Phys. Rev. **134**, B 1010 [1964] and Max-Planck-Institut für Kernphysik, Heidelberg, Preprint 1966/V/4.

[4] M. L. HALBERT and A. ZUCKER, Phys. Rev. **115**, 1635 [1959].

[5] J. A. KUEHNER and E. ALMQVIST, Phys. Rev. **134**, B 1229 [1964].

25 MeV as shown in ref. [1]. The cross sections are smaller than the elastic cross section by a factor of 80 (90° c. m.) and 20 (120° c. m.). If these reactions are taken as purely compound nuclear reactions (the cross section for the emission of a ^{9}Be nucleus should be even smaller) a negligible compound-elastic contribution can be expected.

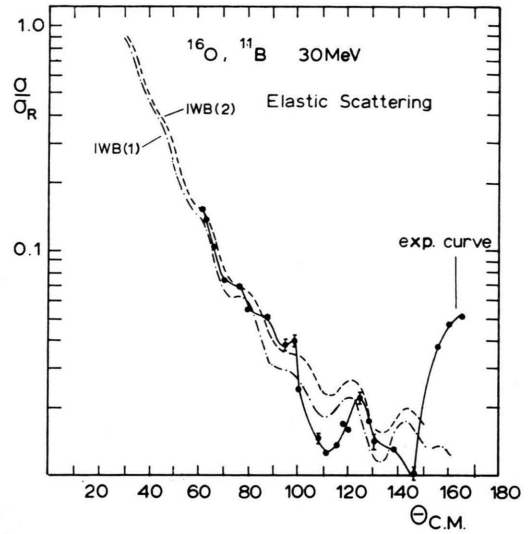

Fig. 2. IWB calculations for the elastic scattering of ^{16}O on ^{11}B at 30 MeV.
Parameters: (1) $V_0 = -80\,000$ MeV, $a = 0.72$ f, $W_0 = -1{,}0$ MeV, $a_W = 0{,}6$ f, $R_W = 7.0$ f;
(2) $a = 0.71$ f, other parameters unchanged.

The optical model for heavy ion elastic scattering

In the case of elastic scattering of heavy ions the optical model should be regarded just as an useful parametrisation of the nuclear phase shifts. Nevertheless the choice of the parameters is a physical question. KUEHNER and ALMQVIST [5] noted, that when they choose real potentials of WOODS–SAXON form with different depth, but identical surface form (as it was done by IGO [6] for the elastic scattering of α-particles), then the goodness of fit did not change, as long as the depth of the real potential was greater than some minimum value ($\sim$30 MeV for ^{16}O on ^{12}C at 10 MeV). The calculations of RAWITSCHER [3] showed also that the angular distribution of low energy elastic scattering of heavy ions is independent of the depth and form of the interior part of the real potential, if the heavy ions are strongly absorbed. In this case only the surface of the nuclear potential can be determined from the elastic cross sections. This point also follows from the observations of DRISKO, BASSEL, and SATCHLER [7] concerning the ambiguities in the optical model for strongly absorbed particles. The

$$V_0 \cdot e^{R/a_1} = C_1 \text{ and } W_0 \cdot e^{R/a_2} = C_2$$

(V_0, R and a being the depth, radius and diffuseness of a WOODS–SAXON potential) relations for the V and R parameters, which give essentially the same nuclear phase shifts mean, that it is the surface of the nucleus which determines scattering. Therefore a definite set of parameters for the nuclear potential can not be extracted from the elastic scattering of strongly absorbed particles. Since the IWB form of the optical model analysis is particularly suited when the condition of strong absorption is fullfilled and only the surface of the optical potential needs to be specified, this method of analysis is employed in the present case. In this model at small distances a boundary condition is imposed on the partial waves (formulated in WKB Approximation). With this procedure volume absorption for the partial waves is obtained and outgoing waves from the interior of the potential are eliminated. Standing waves at small distances are therefore impossible in this model.

Calculations

For the optical model calculations the WOODS–SAXON form has been used for the real and imaginary part of the potential.

$$V(r) = \frac{V_0}{1+\exp\{(r-R)/a\}}\,,$$
$$R = r_0(A_1^{1/3} + A_2^{1/3})\,.$$

The potential for the calculations with the ingoing wave boundary condition was of the form

$$V(r) = V_1 \cdot e^{-r/a} + i\,W_0 \cdot e^{-\{(r-R)/a\}^2}\,.$$

The connection with the WOODS–SAXON potential at the surface of the nucleus, when $e^{(r-R)/a} > 1$, can be achieved by neglecting the 1 in the denominator. Then

$$V(r) = V_0 \cdot e^{R/a} \cdot e^{-r/a}\,.$$

The V_1 of the IWB-potential is $V_0 \cdot e^{R/a}$ and the ambiguity of the optical model with the WOODS–SAXON

[6] G. J. IGO, Phys. Rev. Letters **1**, 72 [1958]; Phys. Rev. **115**, 165 [1959].

[7] R. M. DRISKO, G. R. SATCHLER, and R. H. BASSEL, Phys. Letters **5**, 347 [1963].

potential is absorbed in the new V_1. The COULOMB potential used is

$$V^c = Z_1 \cdot Z_2 e^2/r .$$

The deviation of this point charge potential from a finite charge distribution is non-negligible only in the interior region for $r < R_b$, R_b being the radius where the Ingoing Wave Boundary Condition is placed. In this region changes in the potential have practically no effect on the cross section and therefore this simpler form was chosen.

The IWB potential was at first taken without the imaginary part. But without surface absorption the theoretical curves fell off too steeply with angle. The fit, which was at least accepted as the best is shown in Fig. 1. The parameters are given in the figure legend. The diffuseness of the real potential is determined by the absolute cross section, because for smaller diffuseness and the right slope of the angular distribution a cross section results, which is much too large.

For the ^{16}O, ^{11}B elastic scattering at 30 MeV the best IWB fit is shown in Fig. 2. The small difference between the parameters in the two cases is not astonishing, as the difference in radius of the both systems is about 5%, and some changes in the real potential can be compensated by adequate changes in the imaginary potential. But a diffuseness smaller than 0.65 could not be taken in both cases. As the IWB analysis is formulated in WKB approximation, the radius where the IWB condition was placed is determined by this approximation. In the present calculations the WKB approximation was valid at about 3.5 fermis. Any change in this radius in the realm of validity of the WKB approximation had no effect on the angular distribution, as demanded by the model [3]. This radius was kept fixed at 3.0 fermis.

For the optical model analysis the depth of the real potential was chosen to have the fixed value of either 70 MeV or 200 MeV. In both cases the curves did not agree very well with experiment. The use of surface absorption (GAUSS-form of imaginary potential) gave no improvement. In Fig. 1 a fit for the ^{14}N, ^{9}Be elastic scattering at 25 MeV is shown. The parameters are given in the figure legend.

Discussion

The smooth decreasing part of the angular distributions can be satisfactory described by both OM and IWB calculations. It was not possible, however, to describe at the same time the strong structure at large angles. Calculated curves, which have strong oscillatory structure at about 120° c. m. had oscillations at smaller angles too. And smooth curves at small angles did not have this strong oscillation at larger angles. This difficulty is most pronounced in IWB calculations, in which less parameters are used. The position of the strong minimum corresponds to roughly the same momentum transfer for the 20 [8], 25 [1], 27.3 [4] and 30 [8] MeV ^{14}N, ^{9}Be angular distributions. A similar structure occurs in the ^{16}O on ^{11}B elastic scattering at 30 MeV and 32.5 MeV [8]. A possible interpretation could be an interference between scattering due to a complex potential (with absorption, which begins at large distances) and some other process, which takes place at distances between the nuclei, which are smaller than the WOODS–SAXON radius. Contributions from He^5 transfer can also not be excluded at large angles ($> 120°$).

For the comparison of the IWB and the usual optical model it must be mentioned, that they should give the same results, when the same form of the real potential and an adequate imaginary potential is chosen [3]. But as the IWB condition simulates volume absorption, the optical model should be taken with both volume and surface absorption in the present case.

For the comparison with the diffraction model calculations of DAR [9] we chose OM parameters (curves), which fit the angular distributions at angles smaller than 100° c. m. In Fig. 3 the modulus of the reflection coefficients corresponding to the calcu-

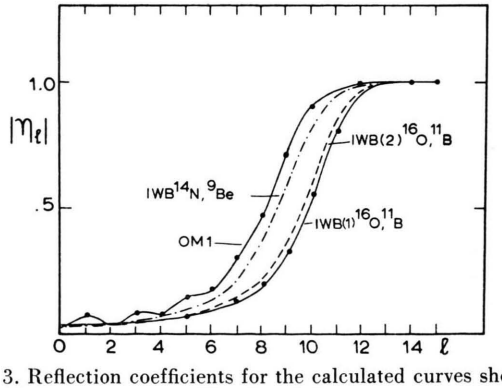

Fig. 3. Reflection coefficients for the calculated curves shown in Figs. 1 and 2.

[8] Unpublished data.

[9] A. DAR and B. KOZLOVSKY, Phys. Rev. Letters **15**, 1036 [1965], and private communications published in: Jahresbericht des Max-Planck-Instituts für Kernphysik, Heidelberg 1965.

lations in Fig. 1 and 2 is shown. These curves can be compared with the parameters L_0 and δ of DAR's [10] diffraction theory for transfer processes. In this theory a WOODS–SAXON form is chosen for the distribution of the reflection coefficients. These should be taken as an average over the elastic scattering in the ingoing and outgoing channels of the transfer reaction:

$$|\eta_l| = [1 + \exp\{(L_0 - l)/\delta\}]^{-1},$$

$$|\eta_l| = V|\eta_{i,l}| \cdot |\eta_{f,l}|.$$

Diffraction model calculations have been done by DAR for the proton and α-transfer data of ref. [1, 2]. The parameters used in these calculations are listed in Table 1.

No.	Reaction	Energy MeV	L_0	δ
1	^{11}B(^{16}O, ^{15}N)^{12}C	30	10.5	0.62
2	^{11}B(^{16}O,^{15}N*)^{12}C	30	10.5	0.62
3	^{11}B(^{16}O, ^{12}C)^{15}N	30	7.0	0.47
4	^{9}Be(^{14}N, ^{13}C)^{11}B	25	8.2	0.27
5	^{9}Be(^{14}N, ^{11}B)^{13}C	25	8.2	0.27

Table 1.

These parameters were obtained without any consideration of elastic scattering data. The L_0 used in cases 1, 2, 4 and 5 agrees with the L-value for which the reflection coefficients, derived from elastic scattering, have a value of about 0.5 (Fig. 3). The only disagreement occurs in case 3 for the α-transfer. The diffuseness δ in L-space agrees in cases 1 and 2 with the diffuseness derived from the elastic scattering analysis. In the other cases the diffuseness δ in L-space is by a factor $1.5 - 2.5$ greater than for the elastic scattering, but in these cases the diffraction structure is not pronounced. The proton and α-transfer reactions should be calculated again with the parameters derived from elastic scattering.

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[10] A. DAR, Phys. Rev. **139**, B 1193 [1965].