Refractive Effects in the Elastic Scattering of Light Heavy Ions between 5 and 10 MeV/n : the $^{16}\text{O} + ^{16}\text{O}$ Reaction

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Refractive Effects in the Elastic Scattering of Light Heavy Ions between 5 and 10 MeV/n : the $^{16}\text{O}+^{16}\text{O}$ Reaction

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Complete angular distributions of the $^{16}\text{O}+^{16}\text{O}$ elastic channel have been measured at the 9 following bombarding energies : $E_{lab} = 75.0, 80.6, 87.2, 92.4, 94.8, 98.6, 103.1, 115.9$ and 124 MeV using at forward angles ($\theta_{lab} = 5^\circ$ to 20°) the Q3D spectrometer and at backward angles ($\theta_{lab} = 20^\circ$ to 50°) two Position Sensitive Silicon detectors in kinematical coincidence. Refractive effects giving rise to nuclear rainbows and the associated Airy structures have been observed for this system. An optical model analysis has been done where the real part of the potential has been determined with no ambiguity over the whole energy range whereas the absorption (imaginary part) changed drastically around $E_{lab} = 90$ MeV.

1. INTRODUCTION

The interaction between heavy ions is dominated by strong absorption effects leading to compound nucleus formation. But for certain light heavy ions, the number of open reaction channels [1] is small and the absorption is thus weaker. From this weaker absorption, refractive effects and nuclear rainbows can arise and their observation permits to extract the Nucleus-Nucleus potential at smaller interaction radii that is usually the case. These effects have been studied in the $^{16}\text{O}+^{16}\text{O}$ system. From the elastic scattering excitation function of the $^{16}\text{O}+^{16}\text{O}$ reaction at $\theta_{cm} = 90^\circ$ reported in the literature two regimes are observed : the resonant regime at lower energy ($\leq 5\text{MeV/n}$) which corresponds to narrow structures [2], followed by the refractive regime at higher energy with larger structures [3]. In the higher energy regime, the measurement of accurate and extensive $^{16}\text{O}+^{16}\text{O}$ elastic scattering differential cross sections, obtained by the Jaeri [4] and Berlin [5] groups, have allowed the observation of strong refractive effects (the first A_1 and second A_2 Airy

minima have been identified) which in turn have permitted a better understanding of the interior part of the interaction potential and to extract "unique" optical potentials : strongly attractive (deep) with relatively weak energy dependent absorption. The aim of our work was to find a link between the high energy regime ($\geq 10\text{MeV/n}$) where deep potentials have been obtained and the low energy regime ($\leq 5\text{MeV/n}$) where the data are usually described with unrealistic shallow potentials [2] and also to see how far down does this high energy description work by using an optical model analysis. In the present study, the chosen energies correspond essentially to maxima and minima of the 90° excitation functions reported by Halbert et al. [3].

2. RESULTS

The $^{16}\text{O}+^{16}\text{O}$ reaction was carried out at the Strasbourg Tandem accelerator Vivitron which is well suited for our studies in the intermediate energy domain between 5 and 10 MeV/n requiring frequent and precise changes of bombarding energies. The 9 following bombarding energies have been chosen : $E_{lab} = 75.0, 80.6, 87.2, 92.4, 94.8, 98.6, 103.1, 115.9$ and 124 MeV . The oxygen targets used in our experiments were self supporting BeO films of $\sim 20\mu\text{g/cm}^2$ thickness [6]. Complete angular distributions have been measured for the $^{16}\text{O}+^{16}\text{O}$ elastic channel using a magnetic spectrometer (Q3D) covering the forward angles ($5^\circ \leq \theta_{lab} \leq 20^\circ$) with a proportionnal counter in its focal plan and two Position Sensitive Silicon detectors in kinematical coincidence covering the larger angles ($20^\circ \leq \theta_{lab} \leq 50^\circ, -68^\circ \leq \theta_{lab} \leq -38^\circ$).

On Figure 1 are shown the elastic angular distributions and fits obtained with the code Ptolemy [7-8] for the higher energies of our work. The optical potential ($U=V+iW$) used has a real part (V) which describes the nuclear interaction and an imaginary part (W) which describes the absorption (the flux carried away by all reaction channels). Woods-Saxon squared potentials have been used where the real part has the same behavior as the folded potential [9].

For this analysis, a monotonous variation of the volume integrals J_v and J_w [9] as a function of energy has been imposed and we have also adopted the convention that the experimental errors should be the same ($\sim 10\%$) all over the angular domain in order to increase the data weight of the backward angles which are essential for the observation of refractive effects. In Figure 1, the fits seem to be satisfactory as much for the amplitude as for the position of the structures. Of course, all details are not well reproduced and in particular the deep minima at the forward angles because the experimental step of $\Delta\theta_{lab} = 0.5^\circ$ was not small enough.

In Table 1, the parameter values of the optical potentials obtained by the code Ptolemy are indicated. A global analysis has been done where we have kept as constant as possible the real part, and we have rather varied the imaginary part. The real part has the same behaviour for all energies with $V_R \sim 420\text{ MeV}$, R_R fixed and a_R varying only a little. For the higher energies, the imaginary part remains almost the same. This not the case for the lower energies, where the absorption changes drastically around 90 MeV : W_I increases, R_I is smaller and a_I is larger. These differences are better seen by representing the ratio W/V as a function of the interaction radius, this is shown on Figure 2. For the higher energies, the curves are quite identical with a maximum around 7 fm which

Figure 1. Elastic angular distributions and fits obtained by the code Ptolemy for the higher energies of the present work. The differential cross sections are divided by the Mott cross sections.

corresponds to the strong absorption radius. The absorption is weak compared to $V(r)$ at interaction radii inferior to 7 fm and at interaction radii beyond the surface. For the lower energies, this maximum disappears and the absorption survives at interaction radii beyond the surface.

From the optical potentials obtained by the theoretical analysis, the Nearside and Farside decompositions of the scattering amplitudes have been extracted and are shown on Figure 3, where the Airy minima are indicated. The dashed lines correspond to the Nearside components and the others lines to the two Farside components. In these curves, the antisymmetrisation has been removed in order to eliminate the interference around $\theta_{cm} = 90^\circ$ due to the collision between identical bosons. In the forward angular region, the Nearside and Farside amplitudes are quite similar and their interference corresponds to Fraunhofer diffraction. In the larger angular region, the Farside amplitude is much larger than the Nearside amplitude which gives rise to interference between the two Farside components which are associated with refractive effects. Minima are observed which move as a function of energy. From the first A_1 and the second A_2 Airy minima [10] determined by the Berlin [4] and the Jaeri [3] groups respectively, our work has permitted us to identify A_3 , A_4 and A_5 which correspond to the three deep minima at $E_{cm} = 40, 47$ and 62 MeV in the $\theta_{cm} = 90^\circ$ excitation function reported by Halbert et al. [3].

Table 1

Parameter values of the optical potential obtained by the code Ptolemy for the real part (V_R , R_R , a_R) and imaginary part (W_I , R_I , a_I) from an analysis of the $^{16}\text{O}+^{16}\text{O}$ elastic scattering between 75 and 124 MeV.

E_{lab}	V_R (MeV)	R_R (fm)	a_R (fm)	W_I (MeV)	R_I (fm)	a_I (fm)	χ^2
124	420	3.97	1.58	15.13	7.10	0.90	27.9
115.9	412.0	3.97	1.50	14.77	6.85	0.85	27.1
103.1	409.6	3.97	1.56	15.68	6.80	1.25	36.8
98.6	414.0	3.97	1.56	15.44	6.59	1.13	32.2
94.8	419	3.97	1.55	12.24	7.02	0.69	27.1
92.4	420.7	3.97	1.65	11.53	7.24	0.51	41.1
87.2	420	3.97	1.54	10.90	7.01	0.73	47.3
87.2	414.8	3.97	1.56	31.14	4.53	2.35	43.3
80.6	412.2	3.97	1.54	27.34	4.38	2.15	20.3
80.6	412.6	3.97	1.54	50.98	2.69	2.64	20.8
75.0	412	3.97	1.49	67.89	2.26	2.26	24.5

Figure 2. The ratio $W(r)/V(r)$ as a function of the interaction radius at $E_{lab} = 75.0, 87.2$ and 115.9 MeV.

Figure 3. Nearside(dashed lines) and Farside decompositions of the scattering amplitudes at $E_{lab} = 94.8, 98.6, 103.1, 115.9$ and 124 MeV which have been calculated from the obtained optical potentials (see Table 1). Airy minima A_3 to A_5 are indicated.

3. CONCLUSION

Refractive effects have been observed in elastic scattering angular distributions of the $^{16}\text{O}+^{16}\text{O}$ reaction between $E_{lab} = 75$ and 124 MeV. An optical model analysis allowed us to interpret the beating observed in the angular distributions in terms of refractive effects where the contribution of low partial waves is essential and characterizes the transparency of the internal interaction. For the energies above 90 MeV, we have obtained a non ambiguous determination of the potentials where the depth of the real part is about 400 MeV and that of the imaginary part lies between 10 and 20 MeV. For energies below 90 MeV, the real part remains practically the same but the absorption part shows the well known "Igo" ambiguity with depth values between 10 and 70 MeV.

For the $^{16}\text{O}+^{16}\text{O}$ system, the rainbow supernumeraries A_1 to A_5 have now been identified and allow us to fix the nuclear potential depth for bombarding energies between 5 and 40 MeV/n at interaction radii down to 4 fm.

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