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HOW STRONG IS THE ABSORPTION IN THE $^{12}\text{C} + ^{20}\text{Ne}$ SYSTEM ? (*)

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Résumé. — Un calcul de la contribution du noyau composé à la diffusion élastique $^{12}\text{C} + ^{20}\text{Ne}$ a été exécuté avec le modèle statistique. Les résultats indiquent que la contribution du noyau composé peut rendre compte de la plus grande partie de la section efficace observée aux angles supérieurs à 90° c.m., ce qui renforce l'hypothèse d'un potentiel optique beaucoup plus absorbant dans le système $^{12}\text{C} + ^{20}\text{Ne}$ que dans le système $^{16}\text{O} + ^{16}\text{O}$.

Abstract. — A statistical model calculation of the compound nuclear contribution to the $^{12}\text{C} + ^{20}\text{Ne}$ elastic scattering reaction has been performed. The results indicate that compound elastic scattering may account for most of the cross-section observed at angles larger than 90° c.m., supporting the proposal that the optical potential for the $^{12}\text{C} + ^{20}\text{Ne}$ system is considerably more absorptive than for the $^{16}\text{O} + ^{16}\text{O}$ system.

We reported recently [1] on the elastic scattering of ^{12}C by ^{20}Ne . This study was motivated by a desire to elucidate the relative importance of direct and compound channels in determining the surface transparency responsible for the pronounced structure and large cross-sections for elastic scattering of ^{16}O by ^{16}O . We had suggested previously [2] that these features of $^{16}\text{O} + ^{16}\text{O}$ scattering are primarily a consequence of the difficulty for the direct reaction channels (rather than compound nuclear channels) to carry away the angular momentum brought in by the entrance channel. The inhibition of the direct channels in this case is due to unfavorable Q values associated with the closed shell structure of both the target and projectile. This circumstance is no longer present in the $^{12}\text{C} + ^{20}\text{Ne}$ system, where the Q values for inelastic scattering and transfer reactions are more favorable. Thus if the direct channels are important one would expect to see a difference in the absorption for the $^{12}\text{C} + ^{20}\text{Ne}$ system compared to the $^{16}\text{O} + ^{16}\text{O}$ system, whereas if the compound nuclear channels are important the absorption should be similar since the same compound nucleus is formed for both systems. An excitation function measured [1] at 70° c.m. for $^{12}\text{C} + ^{20}\text{Ne}$ indeed showed considerably smaller cross-sections and less structure compared to $^{16}\text{O} + ^{16}\text{O}$ scattering, consistent with expectations if direct channels are dominant in determining the absorption.

In a recent communication [3] to this journal results

of another study of $^{12}\text{C} + ^{20}\text{Ne}$ elastic scattering were reported. In this work the excitation functions at more backward angles, 90° and 130° , were measured as well as at 70° c.m. At the more backward angles and higher energies the observed cross-sections are considerably larger than the quite small cross-sections predicted by the optical potential obtained [1] in the fit to the earlier data. The back-angle cross-sections were intermediate in magnitude between those predicted by the $^{12}\text{C} + ^{20}\text{Ne}$ potential and $^{16}\text{O} + ^{16}\text{O}$ potential [4]. It was thus suggested that the $^{12}\text{C} + ^{20}\text{Ne}$ potential was somewhat too absorptive and that the absorption in the $^{12}\text{C} + ^{20}\text{Ne}$ system is intermediate between that in the $^{16}\text{O} + ^{16}\text{O}$ and the $^{18}\text{O} + ^{18}\text{O}$ systems.

It seemed likely to us that the observed cross-sections at back angles in the $^{12}\text{C} + ^{20}\text{Ne}$ system were of the approximate magnitude to be expected from compound nuclear processes. (A compound nuclear contribution of this approximate magnitude had been previously established [5] in the $^{16}\text{O} + ^{16}\text{O}$ system.) The excitation functions also exhibited structure suggestive of Ericson fluctuations. We have therefore performed a Hauser-Feshbach calculation to see if indeed compound nuclear cross-sections of the magnitude observed are expected. The calculations have been performed with the code STATIS [6], using the level density [7] and optical model parameters given in table I.

The exit channels considered were chosen so as to include all of the important heavy ion exit channels which compete most effectively with the compound

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TABLE I

Optical model and level density parameters used in Hauser-Feshbach calculation. The level density notation is that of reference [8]. The spin cut-off parameter was given by $\sigma^2 = dt/\hbar^2$ with $d = \frac{2}{5} mR^2$ where $R = r_0 A^{1/3}$ and $r_0 = 1.4$ fm

	$^{12}\text{C} + ^{20}\text{Ne}$	$^8\text{Be}_{\text{g.s.}} + ^{24}\text{Mg}$	$^8\text{Be}_{2.94}^* + ^{24}\text{Mg}$	$^{16}\text{O} + ^{16}\text{O}$	$\alpha + ^{28}\text{Si}$	$p + ^{31}\text{P}$
a/A (ref. [7])	0.165	0.149	0.149	0.149	0.116	0.130
Δ (ref. [10])	5.00	5.13	5.13	5.13	3.88	1.67
E_{cut} (°)	11.87	9.97	9.97	12.05	9.70	5.99
V (MeV)	17.0	17.0	17.0	17.0	85.0	$62.8 - 0.3 E_{\text{c.m.}}$
R_0 (fm)	6.76	6.76	6.76	6.80	4.68	4.68
a_0 (fm)	0.57	0.57	0.57	0.49	0.60	0.57
W (MeV) (°)	$1.0 + 0.54 E_{\text{c.m.}}$	$1.0 + 0.54 E_{\text{c.m.}}$	$1.0 + 0.54 E_{\text{c.m.}}$	$0.8 + 0.2 E_{\text{c.m.}}$	9.0	$0.3 + 0.64 E_{\text{c.m.}}$ (°)
R_i (fm)	6.76	6.76	6.76	6.40	4.68	4.68
a_i (fm)	0.57	0.57	0.57	0.15	0.60	0.50
R_{Coul} (fm)	6.76	6.76	6.76	6.80	4.68	4.68
Ref. for optical model	(°)	(°)	(°)	(°)	(°)	(°)

(°) E_{cut} = energy above which discrete levels were *unknown* and continuum level densities were used.

(°) Surface type for $p + ^{31}\text{P}$, volume type otherwise.

(°) Ref. [1].

(°) Ref. [4].

(°) CRAMER, J. G., private communication.

(°) For $E_{\text{c.m.}} < 13.8$; for $E_{\text{c.m.}} > 13.8$, $W = 9.9 - 0.06 E_{\text{c.m.}}$.

(°) WATSON, B. A., SINGH, P. P. and SEGEL, R. E., *Phys. Rev.* 182 (1969) 977.

elastic channel. The neutron exit channel was not included in the final calculation after it was shown that its contribution was approximately an order of magnitude smaller than the proton exit channel. The angular momentum dependence of the denominator of the Hauser-Feshbach expression for

$$E_{\text{c.m.}} = 24.7 \text{ MeV}$$

is shown in figure 1. Also shown are the relative probabilities for making the compound nucleus with different J values. The calculations are sensitive to the assumption as to whether an yrast level cut-off is assumed for the compound nucleus. Such a cut-off may be expected if more angular momentum can be brought in by the entrance channel than the compound nucleus (assumed to be spherical) can accommodate as rotational energy. Hanson *et al.* [8] have reported that such a cut-off is necessary in order to reproduce the observed cross-sections in the $^{12}\text{C} + ^{14}\text{N}$ system. On the other hand Klapdor *et al.* [9] report that such a cut-off is unnecessary, particularly at lower energies. We therefore have performed calculations both with and without an yrast level cut-off for the compound nuclear spin distribution. The yrast level cut-off was determined by

$$E = \frac{\hbar^2 J(J+1)}{2d} \quad \text{with} \quad d = \frac{2}{5} mR^2$$

and $R = 1.4 A_2^{1/3}$. For $E_{\text{c.m.}} = 24.7$ MeV this cut-off is at $J > 22$.

FIG. 1. — The open circles are the values of the Hauser-Feshbach denominator as a function of the compound nuclear angular momentum J for $E_{\text{c.m.}} = 24.7$ MeV. The dashed curve gives $(2l+1)T_l$ which is proportional to the probability for forming the compound nucleus with angular momentum $J = l$.

The results are shown in figure 2 together with the results of Doubre *et al.* [3]. It is seen that the observed cross-sections at 90° and beyond are of the order of the two estimates of the compound nuclear cross-sections. In figure 3 we compare the angular distribution of reference [3] with the Hauser-Feshbach predictions. The calculations reproduce the absolute magnitude of the cross-sections but underestimate

FIG. 2. — Excitation functions for elastic scattering of ^{12}C by ^{20}Ne at three angles. The connected full circles are the data of Dobre *et al.* The connected triangles give the results of the compound elastic cross-section calculations with and without an yrast level cut-off in the compound nucleus spin distribution. The upper smooth curve and the dashed curve are the optical model prediction of the potentials of refs. [4] and [1], respectively.

the structure. It is not clear to us whether the observed structure is due to Ericson fluctuations or whether the Hauser-Feshbach calculation underestimates the structure expected in the angular distributions. The expected structure as well as the magnitude of the compound nuclear contribution depends on the absorptiveness of the optical potential. A less strongly absorbing potential introduces more structure and decreases the absolute compound cross-section while increasing the direct cross-section. For example if the weakly absorbing $^{16}\text{O} + ^{16}\text{O}$ potential is used the compound nuclear cross-section is decreased by more than an order of magnitude while the direct cross-section is increased by an even larger factor near 90° . It might be possible to find a potential slightly less absorbing than the previous $^{12}\text{C} + ^{20}\text{Ne}$ potential which would give more structure at back angles and still be consistent with the direct cross-sections forward of 90° . A more complete angular distribution with sufficient data to determine whether the structure is periodic and with what period might clarify this situation. We believe that these compound nuclear cross-section estimates are uncertain to approximately

FIG. 3. — Elastic scattering angular distribution at 24.7 MeV (c.m.). The full circles are the data of Dobre *et al.* and the dashed and dotted curves are the compound elastic cross-sections calculated with (dotted curve) and without (dashed curve) an yrast level cut-off in the compound nucleus spin distribution. The smooth curve is the optical model prediction of ref. [1].

a factor of two due to uncertainties in level density and optical model parameters. For example, an increase of 40 % in the level density parameter for the α decay channel, one of the most important channels, leads to a cross-section decrease of about a factor of 3.

These results indicate that the observed cross-section at angles of approximately 90° or larger is most likely primarily of compound nuclear rather than direct origin and thus are not inconsistent with the optical model potential of reference [1]. Up to 90° the cross-sections are reasonably described by this absorptive potential. We have previously shown [5] that the compound elastic contribution to the $^{16}\text{O} + ^{16}\text{O}$ system is small. We therefore conclude that there are significant differences in the absorptive potentials for the $^{12}\text{C} + ^{20}\text{Ne}$ and $^{16}\text{O} + ^{16}\text{O}$ systems.

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