

## Alpha Transfer Reactions Between Oxygen Isotopes

D. Kalinsky<sup>†</sup>, D. Melnik<sup>††</sup>, U. Smilansky,  
N. Trautner<sup>‡</sup> and S. Weisrose<sup>#</sup>

Dept. of Physics

Weizmann Institute of Science  
Rehovot, Israel

and

O. Dietzsch

Inst. de Fisica

Universidade de Sao Paulo  
Sao Paulo, Brazil

E

<p>NUCLEAR REACTIONS <math>^{16}\text{O}(^{16}\text{O}, ^{12}\text{C})^{20}\text{Ne}</math>, <math>^{16}\text{O}(^{18}\text{O}, ^{14}\text{C})^{20}\text{Ne}</math>,  <math>^{16}\text{O}(^{18}\text{O}, ^{22}\text{Ne})^{12}\text{C}</math>, <math>^{16}\text{O}(^{17}\text{O}, ^{13}\text{C})^{20}\text{Ne}</math>,  <math>^{16}\text{O}(^{17}\text{O}, ^{21}\text{Ne})^{12}\text{C}</math>, <math>E_{\text{CM}} = 17</math> MeV.  measured <math>d\sigma/d\Omega</math>.</p>
---

<sup>†</sup>Present address: MG Electronics Ltd., Rehovot, Israel.

<sup>††</sup>Present address: Dept. of Physics, Rutgers University,  
New Brunswick, N.J. 08903, USA.

<sup>‡</sup>Present address: Niels Bohr Inst., 19 Blegdamsvej, Copenhagen Ø,  
Denmark.

<sup>#</sup>Supported in part by a Royal Society Fellowship.

Abstract

Alpha transfer reactions between  $^{16}\text{O}$  and  $^{16,17,18}\text{O}$  isotopes have been measured at  $E_{\text{cm}} \sim 17$  MeV. The cross sections are analyzed by assuming a cluster transfer within the DWBA. The good qualitative agreement between the experimental and the calculated results, support the assumption that these reactions proceed via a direct cluster-transfer process. The interference between the possible processes which lead to the final products determine the observed structure in the cross-sections.

## I. Introduction

For some time our group at the Weizmann Institute Tandem Laboratory has been engaged in the measurement of cross sections for reactions between all the possible Oxygen isotopes at Tandem energies<sup>(1-6)</sup>. Previous reports have discussed the cross section for elastic, inelastic and one-neutron and two-neutrons transfer reactions. Our main conclusion was that the observed patterns in most of the measured cross sections can be accounted for by considering the interference between the various processes which lead to the same outgoing channel. The spectroscopic factors which were extracted from the one-neutron data were found to be consistent with results from previous investigations.

In this paper we discuss the cross sections for the reactions between  $^{16}\text{O}$  and the three stable Oxygen isotopes, in which the products are composed of C and Ne isotopes. Our main goal has been to gain insight into the mechanism governing these reactions, and to check whether the methods which were applied successfully for the other reactions between Oxygen isotopes, are applicable also in the present case.

We propose that these reactions are direct, and can be described in terms of the DWBA, allowing the interference of the various processes which yield the same reaction products. In all the reactions investigated one possible mechanism was the transfer of two neutrons and two protons - an  $\alpha$  cluster. Depending on the particular outgoing channel, the other process could be the transfer of two protons and N neutrons, with  $N = 0, 1, 2, 3, 4$ .

In Chapter II we shall briefly outline the experimental set up and the theoretical model used in the present work. We shall then proceed to compare the measured and calculated cross-sections in order to test the validity of the proposed mechanism.

## II. Experimental and Theoretical Results

Beams of the three stable Oxygen isotopes from the Tandem van-de-Graaf of the Weizmann Institute were focused on self-supporting Si  $^{16}\text{O}$  targets of  $\sim 20 \mu\text{g}/\text{cm}^2$ . The reaction products were identified and counted in a kinematic coincidence system which has been described in ref. (1). The resulting cross sections are displayed in figs. (1), (3)-(6). (The low lying level schemes of the relevant Ne isotopes are also displayed for further reference.)

The theoretical calculations were carried out within the DWBA framework. It was shown by R. de Vries that recoil effects are very important in the description of heavy cluster transfer reactions<sup>(8)</sup>. We used therefore the code LØLA<sup>(8)</sup> throughout. The transfer form factors were calculated under the assumption that the nucleons are transferred in clusters which occupy their intrinsic ground states. The wave functions which describe the bound states of the clusters to the cores are specified by the quantum numbers which follow Glendenning's prescription<sup>(9)</sup>. Their asymptotic behaviour is determined by the binding energy of the cluster to the core. The binding potential was characterized by a radius parameter  $R = 1.25 (A_{\text{core}}^{1/3} + A_{\text{trans}}^{1/3}) \text{fm}$  and a diffusivity parameter of  $a = 0.6 \text{fm}$ . The optical potentials which determine the scattering wave functions in the entrance and exit channels were chosen in the following way.

For the  $^{16}_{0+}^{16}\text{O}$  case we used Gobbi's shallow potential<sup>(10)</sup>, whereas for the  $^{16}_{0+}^{17}\text{O}$  and the  $^{16}_{0+}^{18}\text{O}$  reactions we took the shallow potentials used in ref. (1). In all the C+Ne channels we used the shallow potential recommended in ref. (11). Several calculations were repeated with the shallow potentials replaced by deep ones which reproduce the elastic scattering data. The shapes of the transfer cross sections were not affected.

The final cross sections were obtained after the various amplitudes which describe different processes were summed up coherently, and squared. This coherent summation is carried out using the methods developed in ref. (6).

We shall now discuss the various cross sections individually.

(a)  $^{16}_{0+}^{16}\text{O}, ^{12}_{\text{C}}^{20}\text{Ne}$

The cross sections to the lowest  $0^+$  and  $2^+$  states in  $^{20}\text{Ne}$  were measured and are displayed in Fig. (1). The choice of a bombarding energy of  $E_{\text{cm}} = 17.5$  MeV was somewhat unfortunate since the  $^{16}_{0+}^{16}\text{O}$  elastic cross section displays its first irregular structure exactly at this energy. Singh et al.<sup>(12)</sup> measured the  $^{12}_{\text{C}}^{20}\text{Ne}$  channel in the  $^{16}_{0+}^{16}\text{O}$  system at higher energies. They found that the irregularities observed in the transfer cross section are correlated with those of the elastic scattering data. The optical model potential used in the present case cannot reproduce the observed structures and this may also lead to discrepancies in the calculated transfer cross sections. The calculations predict rather well the positions of the maxima and minima. This is a consequence of the

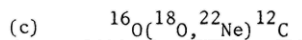
symmetry of the entrance channel, and has little to do with the reaction dynamics.

(b)  $^{16}_0(^{18}_0, ^{14}_6)^{20}_{10}\text{Ne}$

The transfer reactions which populate the lowest  $0^+$ ,  $2^+$  and  $4^+$  states in  $^{20}\text{Ne}$  were measured at  $E_{\text{cm}} = 17$  MeV. In the theoretical analysis we included the results of ref. (13), where the transitions to the  $0^+$  state were measured for  $E_{\text{cm}} = 13.18$  and  $15.06$  MeV (Fig. (2)).

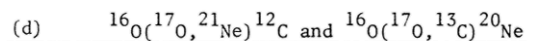
The two possible processes which populate the exit channel  $^{14}_6+^{20}_{10}\text{Ne}$  are the  $\alpha$  and  $2p$  transfers. Figs. (2) and (3) display the results of the DWBA calculations together with the experimental data. In all the cases the best fit to the observed pattern was achieved when the ratio of the  $\alpha$  and  $2p$  spectroscopic amplitudes were of the order 1:2. The overall normalization factors which were applied to the theoretical results depend on the bombarding energy and the particular final state. Their variation is limited to within one order of magnitude. The overall agreement between experiment and theory is rather good. The quality of the theoretical fits to the  $^{16}_0(^{18}_0, ^{14}_6)^{20}_{10}\text{Ne}(0^+)$  data deteriorates as the bombarding energy increases. This is probably due to the fact that at the lowest bombarding energy, the grazing angles for the two transfer processes are nearer to  $90^\circ$ . (See broken lines in fig. (2).) The interference patterns are constructed from those parts of the individual amplitudes which are the least sensitive to the details of the assumed bound wave functions. At the highest energy the corresponding partial cross sections peak at  $\sim 50^\circ$  and  $120^\circ$ . (See broken lines at the bottom of fig. (3).) The interference now occurs between the wings of the

transfer amplitudes, which are much more sensitive to the inaccuracies introduced because of our simple picture of the transfer mechanism.



The various reactions which populate the  $0^+$ ,  $2^+$  and  $4^+$  states in  $^{22}\text{Ne}$ , as well as the sum of the cross sections for populating the second  $2^+$  state in  $^{22}\text{Ne}$  and the first  $2^+$  state in  $^{12}\text{C}$ , were measured at  $E_{\text{cm}} = 17$  MeV. In the present case, we assumed that the  $\alpha$  cluster transfer interferes with the  $^6\text{He}$  transfer mechanism. The DWBA fits are displayed in fig. (4). Again, satisfactory agreement is achieved between the measured and calculated cross sections. In the present case the best fit is obtained when the spectroscopic amplitudes for the  $^4\text{He}$  and  $^6\text{He}$  are of roughly the same magnitude, but with opposite signs. In the theoretical calculation for the reactions populating the second  $2^+$  state in  $^{22}\text{Ne}$  or the first  $2^+$  state in  $^{12}\text{C}$ , we assumed a pure excitation of the  $2^+$  state in  $^{12}\text{C}$ .

The rather good agreement between the data and the calculated cross sections for the four different transitions, again support the assumptions which underly the theoretical model.



The cross sections for the various excited states were measured at  $E_{\text{cm}} = 17$  MeV and they are displayed in figs. (5) and (6). There are several factors which hamper the theoretical study of these reactions. The first is the dense spectrum of the  $^{21}\text{Ne}$  product, which could not be resolved in our experimental set-up. Most of the results which relate to excited  $^{21}\text{Ne}$  states are therefore sums of

cross-sections. Because of the high spin of the  $^{17}\text{O}$  projectile, the individual cross-sections comprise several contributions which correspond to the various allowed transferred  $\ell$  values. This number increases with the outgoing channel spin. The resulting cross sections display much less structure than was observed in the  $^{16}\text{O}+^{16}\text{O}$  or the  $^{16}\text{O}+^{18}\text{O}$  experiments and it renders the study of interference effects rather difficult. The large number of amplitudes also increases the computation time beyond any practical limit. For these reasons, we concentrated only on one representative reaction, namely  $^{16}\text{O}(^{17}\text{O}, ^{13}\text{C}(1/2^-))^{20}\text{Ne}(0^+)$  and tried to reproduce the observed cross section by assuming interference between  $\alpha$  and  $^3\text{He}$  transfers, in the spirit of the preceding discussion. The results of the calculations are displayed in fig. (5), and they appear to agree with the data. The ratio of spectroscopic amplitudes required for the  $\alpha$  and  $^3\text{He}$  transfers are 2:1.

(e) Estimates of Compound Nucleus Contributions

As a final stage of the theoretical investigations we estimated the contribution of the compound nucleus process to the cross sections. Using the code STATIS<sup>(7)</sup> we found that the compound nucleus mechanism can account for less than 10% of the measured cross sections. This result cannot unambiguously exclude the role of this mechanism. However, the observed angular dependence of the cross sections on the one hand, and the predicted magnitude on the other hand favours the assumption that the direct processes play the prominent role.

### III. Conclusions

The overall qualitative agreement which was obtained for the reactions which we studied in the present work seem to support the proposition that these reactions proceed via direct cluster transfer mechanism, and that the decisive factor which determines the observed structures is the interference of processes which lead to the same final products. In contrast to some previous studies (e.g. ref. (14)), the positions of the maxima and minima were reproduced rather well without introducing any new assumptions in the model. The fact that the calculations did not reproduce the normalization of the cross sections is probably due to the primitive cluster transfer approximation. The ratios of the spectroscopic amplitudes for the bound states of the  $\alpha$  and the other Helium clusters vary between 2:1 and 1:2. One should exercise much caution in assigning to these values any physical significance.

References

1. D. Kalinsky, D. Melnik, U. Smilansky, N. Trautner, B.A. Watson, Y. Horowitz, S. Mordechai, G. Baur and D. Pelte, Nucl. Phys. A252 (1975) 364.
2. D. Kalinsky, D. Melnik, U. Smilansky, N. Trautner, Y. Horowitz and S. Mordechai, in press Nucl. Phys. (1977).
3. D. Kalinsky, D. Melnik, U. Smilansky, N. Trautner, S. Weisrose and O. Dietzsch, European Conf. on Nucl. Phys. with Heavy Ions Caen (1976) p. 44.
4. D. Kalinsky, D. Melnik, U. Smilansky, N. Trautner and S. Weisrose, Weizmann Inst. preprint WIS-77/27 Ph (1977).
5. D. Kalinsky, D. Melnik, U. Smilansky and N. Trautner, Proceedings of the Int. Conf. on Nucl. Structure, Supp. Jour. Phys. Soc. Japan, to be published (1977).
6. D. Melnik, Ph.D. Thesis (1977) unpublished.
7. R.G. Stokstad, Proceedings of the Nashville Conf. on Nucl. Reactions between Heavy Ions, Ed. R.L. Robinson, F.K. McGowan, J.B. Ball and J.H. Hamilton, North Holland Publishing Co. (1974) p. 327.
8. R.M. DeVries Phys. Rev. C8 (1973) 951, and Nucl. Phys. A212 (1973) 207.
9. N.K. Glendenning, Phys. Rev. 137B (1965) 102.
10. A. Gobbi, Symposium on Heavy-Ions Scattering, Argonne National Lab. Rep. ANL-7837 (1971) p. 63.
11. R. Vandenbosch, M.P. Webb and M.S. Zisman, Phys. Rev. Lett. 33 (1974) 842.

12. P.P. Singh, D. A. Sink, P. Schwandt, R.E. Malmin and R.H. Siemssen,  
Phys. Rev. Lett. 28 (1972) 1714.
13. P.H. Barker, P.M. Bockburn, A. Huber, H. Knoth, U. Matter,  
H.P. Seiler and P. Marmier, Ann. of Phys. 66 (1971) 705.
14. W.F.W. Schneider, B. Kohlmeyer, F. Pühlhofer and R. Bock,  
Phys. Lett. 46B (1973) 195.

Figure Captions

- Fig. 1. Cross sections for the  $^{16}\text{O}(^{16}\text{O}, ^{12}\text{C})^{20}\text{Ne}$  reactions populating the  $0^+$  and  $2^+$  levels in  $^{20}\text{Ne}$ . The curves are results of DWBA calculations.
- Fig. 2. Cross sections for the  $^{16}\text{O}(^{18}\text{O}, ^{14}\text{C})^{20}\text{Ne}(\text{g.s.})$  reactions at  $E_{\text{cm}} = 13.18$  and  $15.06$  MeV, from ref. (13). The full lines are the results of the DWBA calculations. The broken lines are the partial cross sections for the two transfer processes which contribute to the total cross sections.
- Fig. 3. Cross sections for the  $^{16}\text{O}(^{18}\text{O}, ^{14}\text{C})^{20}\text{Ne}$  reactions at  $E_{\text{cm}} = 17$  MeV, as measured in the present experiment. The full lines are the DWBA calculations. The broken lines denote the partial cross sections for the two transfer processes which contribute to the full cross section.
- Fig. 4. Cross sections for the  $^{16}\text{O}(^{18}\text{O}, ^{22}\text{Ne})^{12}\text{C}$  reactions at  $E_{\text{cm}} = 17$  MeV. The lines are the DWBA calculations.
- Fig. 5. Cross sections for the  $^{16}\text{O}(^{17}\text{O}, ^{13}\text{C})^{20}\text{Ne}$  reactions at  $E_{\text{cm}} = 17$  MeV. The line is the result of a DWBA calculation.
- Fig. 6. Cross sections for the  $^{16}\text{O}(^{17}\text{O}, ^{21}\text{Ne})^{12}\text{C}$  reactions at  $E_{\text{cm}} = 17$  MeV. The various doublets and triplets are indicated in the level scheme of  $^{21}\text{Ne}$ .

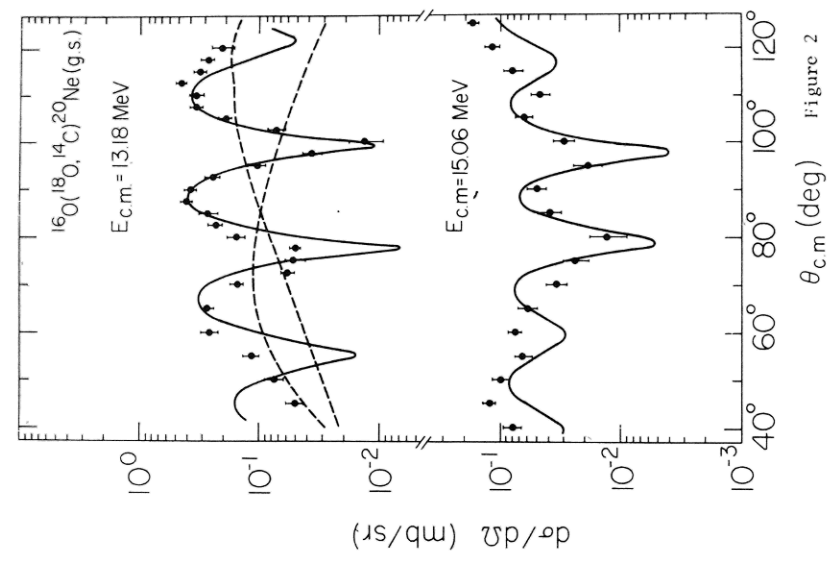


Figure 2

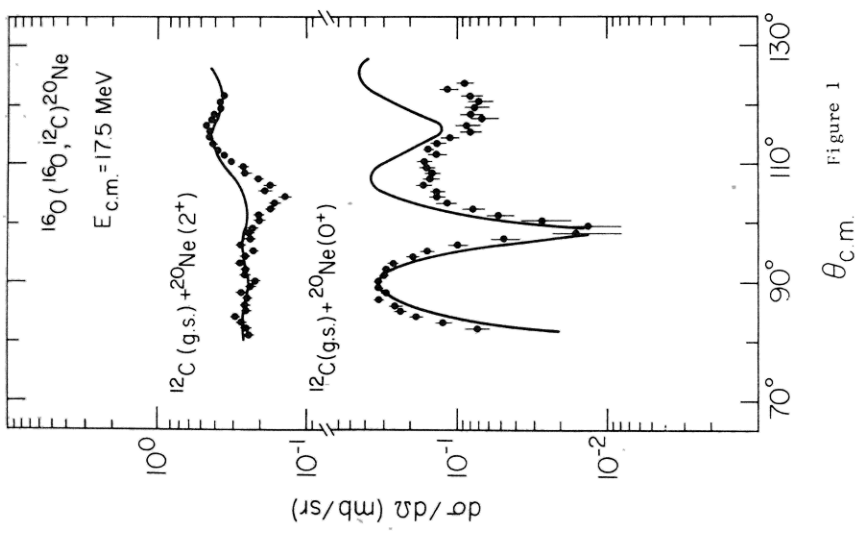


Figure 1

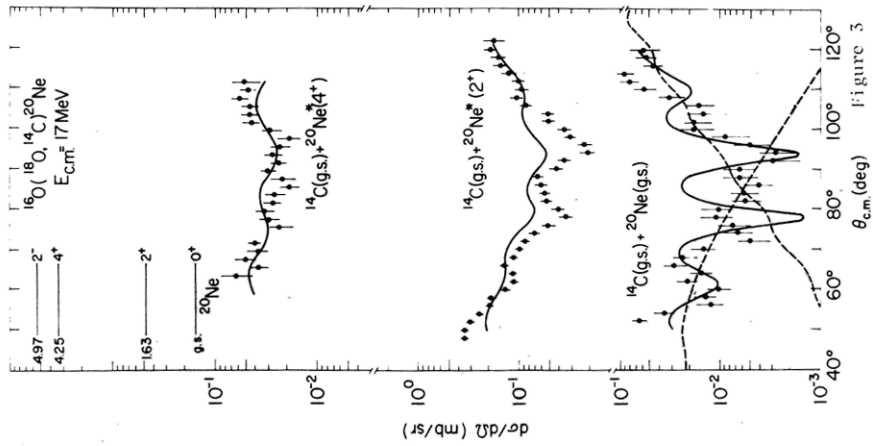


Figure 5

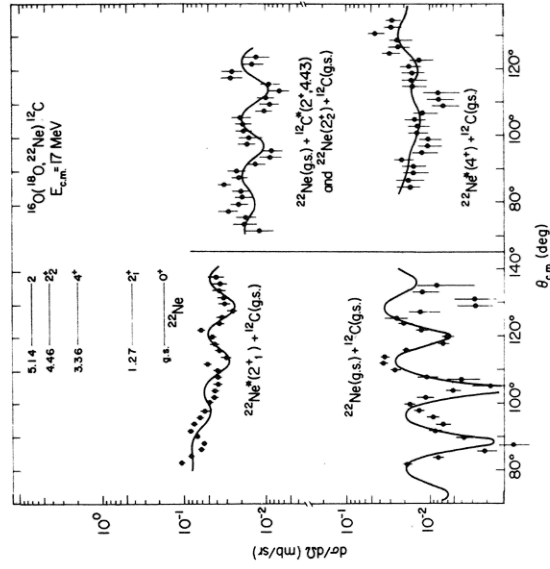


Figure 4

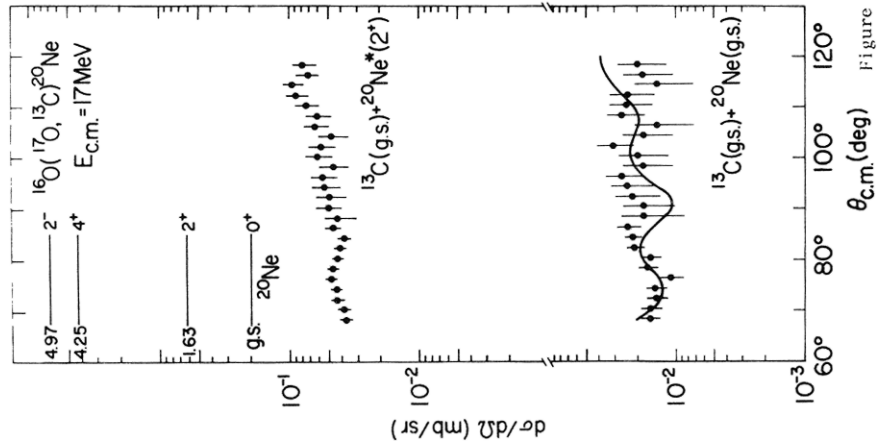


Figure 5

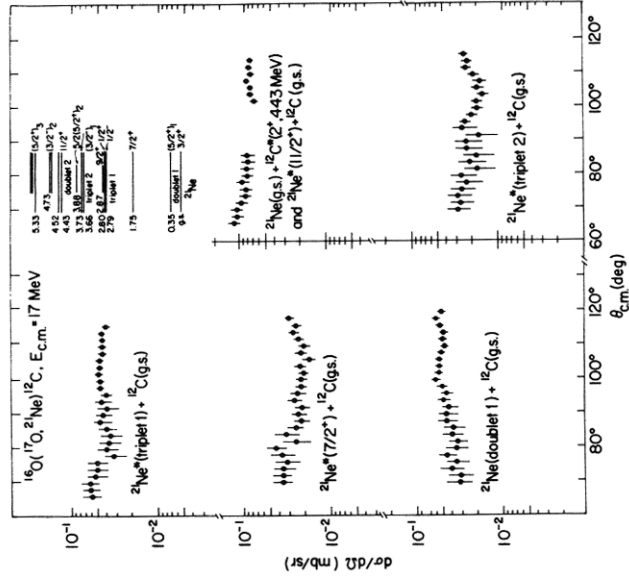


Figure 6