^{12}C and ^{16}O nuclei, which all have negative Q values, are not important in the low-energy nucleosynthesis region. This conclusion is supported by Kozlovsky[7] for the α-transfer reaction $^{12}C(^{12}C, ^{8}Be)^{16}O$. In the case of $^{12}C + ^{16}O$ it has been suggested that the α-transfer reaction producing ^{20}Ne accounts for $\lesssim 3\%$ of the total reaction cross section at 10 MeV[8] and that at even lower energies this contribution may be greater. Our calculations show that the transfer process may increase in proportion to the total reaction cross section as the energy is lowered but below 6 MeV the nonoptimum nature of the Q value drastically reduces the transfer cross section. At 7.2 MeV (the effective energy for explosive nucleosynthesis[9] at temperatures around 3.6×10^9 °K) our calculations and more exact distorted-wave calculations of Nilsson and Barnes[10] yield an upper limit of 10% to the fraction of the cross section proceeding by transfer. This contribution is less than the uncertainties in the measured absolute reaction cross section for $^{12}C + ^{16}O$ (Ref. 6 and Patterson *et al.*[11]).

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Entrance-Channel Effects in the ^{32}S System: Comparison of $^{12}C + ^{20}Ne$ and $^{16}O + ^{16}O$ Elastic Scattering*

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$^{12}C + ^{20}Ne$ elastic-scattering angular distributions have been measured at several energies, and an excitation function has been obtained at 70° center of mass from $E_{c.m.} = 17$ to 28 MeV. The $^{12}C + ^{20}Ne$ data are greatly damped compared with $^{16}O + ^{16}O$ data in this energy range. This demonstrates that the absorption is not determined primarily by compound-nuclear properties. The differences are interpreted in terms of the more favorable angular-momentum matching conditions for the $^{12}C + ^{20}Ne$ direct-reaction channels.

The observation[1,2] of prominent gross structure in $^{16}O + ^{16}O$ elastic scattering has led to considerable interest in the nature of the mechanisms and interaction potentials in heavy-ion reactions. The periodicity of the structure is readily understood in terms of shape resonances. The most dramatic aspect of the structure, however, is the large peak-to-valley ratio together with the large absolute magnitude of the cross sections at angles near 90°. A conventional optical-model analysis[1] easily reproduced the periodicity but not the magnitude of the oscillations. Chatwin and co-workers[3,4] showed that the magnitude of the oscillations could also be reproduced if the imaginary potential was made explicitly l dependent. They introduced a smooth cutoff in the strength of the absorptive potential as l gets larger than a certain critical value. This cutoff becomes important if the heavy nuclei in the entrance channel bring in a greater amount of angular momentum than any of the exit channels can carry away. The parameters of the l-dependent potential were

chosen empirically[4] to reproduce the experimental data, resulting in a smaller critical angular momentum (the parameter characterizing the angular-momentum form factor) than the grazing angular momentum from a conventional optical potential. Chatwin *et al.*[3] found that the maximum entrance-channel angular momentum associated with the grazing partial waves could not be carried away by the neutron, proton, or α-particle channels of the compound nucleus.

Explanations of the origin of the l dependence in the $^{16}O+^{16}O$ system have concentrated mainly on considerations based on compound-nuclear level densities. Low and Tamura[5] directly relate the l dependence of the imaginary potential to the angular-momentum-dependent level density of the compound nucleus. Gobbi *et al.*[6] have considered an imaginary potential which has a volume part dependent on the compound-nuclear level density plus a surface part describing the direct processes. Helling, Scheid, and Greiner[7] have proposed that it is the precompound states, corresponding to nuclear configurations where the overlap of the two heavy ions is small, which determine the strength and angular-momentum dependence of the imaginary potential. On the other hand, an investigation of the $^{18}O+^{18}O$ system[8] (which exhibits characteristics of the more usual strongly absorptive heavy-ion interaction) suggested that the l dependence is determined not by compound-nuclear properties, but rather by the angular-momentum-matching properties of the reaction channels coupled *directly* to the entrance channel, e.g., the inelastic and α-particle transfer channels.

We report here the results of an experiment designed to distinguish between effects due to compound-nuclear level densities and decay widths and those due to angular-momentum-matching conditions between the entrance channel and the directly coupled reaction channels. We compare the elastic scattering of ^{12}C by ^{20}Ne with that for ^{16}O by ^{16}O. Both systems form the same compound nucleus and do so with very similar angular-momentum populations. This is illustrated in Fig. 1(a) where the grazing angular momentum as a function of excitation energy in ^{32}S is shown. The two curves are within approximately a single unit of each other throughout the energy range shown. An angular-momentum dependence dictated by the nuclear level density or decay widths would thus lead to similar predictions for the cross section as a function of energy or angle for both systems. If, however, angular-momentum-

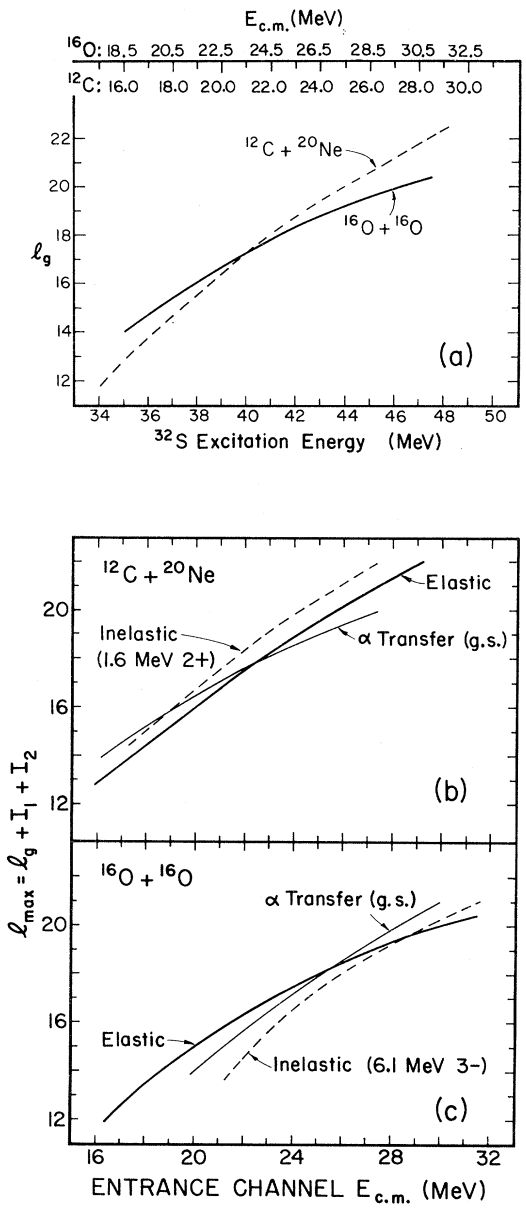

FIG. 1. (a) Plot of the grazing angular momentum, l_g, brought in by $^{16}O+^{16}O$ and $^{12}C+^{20}Ne$ as a function of the compound-nucleus excitation energy. The center-of-mass energies for the two systems are indicated at the top of the figure. The l_g values, defined as the l value for which $T_l=0.5$, were calculated with the $^{12}C+^{20}Ne$ optical potential given in Fig. 2 and with the six-parameter $^{16}O+^{16}O$ potential of Gobbi, Webb, and Zisman (Ref. 9). (b), (c) Plot of l_{max}, the maximum angular momentum which can be carried off by a particular exit channel, compared with the grazing angular momentum brought in by the entrance (elastic) channel. I_1 and I_2 are the spins of the outgoing fragments. For the cases shown here $I_1=0$ always and $I_2=0$ except for the "inelastic" curves which refer to the ^{16}O (3^-) and ^{20}Ne (2^+).

matching conditions in the entrance channel are important, the more favorable Q values for direct reactions, particularly for inelastic scattering, in the $^{12}C+^{20}Ne$ system would lead to an expectation of considerably stronger absorption in this case.

Carbon beams from the University of Washington FN tandem Van de Graaff were used to bombard a specially designed[9] gas cell containing 0.13 atm of isotopically enriched ^{20}Ne (99.45%). The detector arrangement consisted of a transmission mounted E counter backed by a veto counter and a monitor counter at $\theta_{lab}=24.5°$. The angular acceptance of the E counter was 0.4° (lab). Particle identification was not required since only one reaction product (^{16}O from the $^{12}C+^{20}Ne \rightarrow {}^{16}O+{}^{16}O$ reaction) interferes with the elastic peak and this can be shown to be weak by applying detailed balance to the measured cross sections[10-12] for the inverse reaction. The absolute cross sections were obtained by normalization to the optical-model calculations at forward angles. The normalization was checked by filling the cell with Kr and assuming the scattering to be Rutherford at all energies. Various consistency checks indicate that the cross sections reported have an overall uncertainty of 15–20%.

Angular distributions for the elastic scattering of ^{12}C by ^{20}Ne were measured[11] at $E_{c.m.}=13.9$, 17.0, 20.2, 23.3, and 26.7 MeV. The 23.3-MeV data, along with $^{16}O+{}^{16}O$ data taken under identical experimental conditions, are shown in Fig. 2. Clearly, the two systems exhibit qualitatively different behavior. Although the excitation energy in the compound nucleus was not matched in the two measurements shown in Fig. 2 (both measurements were made at the same $E_{c.m.}$), an examination of the $^{16}O+{}^{16}O$ behavior[2] over a range of energies spanning the energy required to match the compound-nucleus excitation energy shows that this qualitative difference persists. The solid line in Fig. 2 results from an optical-model fit to all five angular distributions. The parameters, shown in the figure, describe a more strongly absorbing potential in the case of $^{12}C+^{20}Ne$ scattering compared to $^{16}O+{}^{16}O$ scattering. It can be shown that the qualitative difference between the angular distributions is not a consequence of one system consisting of identical bosons while the other does not. The dotted curve in Fig. 2 is a calculation using the $^{12}C+^{20}Ne$ potential but assuming that identical spinless bosons were involved. The identical-particle effects are small at all angles for which we have $^{12}C+^{20}Ne$ elastic data. Similarly, it can be shown that the potentials[2,6] which fit the $^{16}O+{}^{16}O$ data[2] predict a very strongly oscillating angular distribution for a nonidentical particle system.

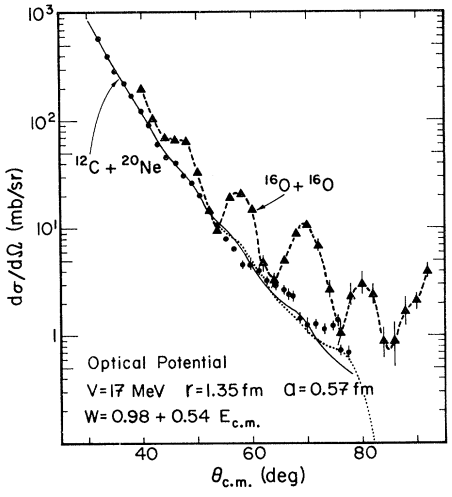

FIG. 2. Angular distributions for $^{12}C+^{20}Ne$ and $^{16}O+{}^{16}O$ elastic scattering at $E_{c.m.}=23.3$ MeV. The full and dotted curves are optical-model calculations assuming nonidentical and identical bosons, respectively (see text).

In addition, we have measured an excitation function for the elastic scattering of ^{12}C by ^{20}Ne at 70° (c.m.) for center-of-mass energies from 17 to 28 MeV in 250 keV steps. These measurements are shown in Fig. 3 along with the ^{16}O elastic data of Maher *et al.*[2] The solid curve is the prediction of the optical potential given in Fig. 2. The excitation function for $^{12}C+^{20}Ne$ scattering

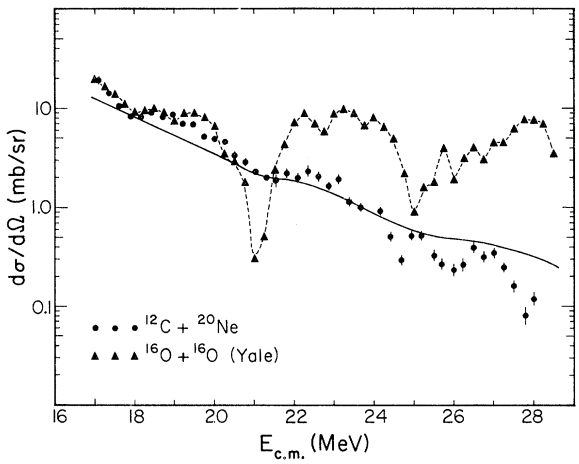

FIG. 3. Elastic-scattering excitation functions for $^{12}C+^{20}Ne$ and $^{16}O+{}^{16}O$ at $\theta_{c.m.}=70°$. The solid curve is the predicted excitation function using the optical-model parameters shown in Fig. 2.

is much less structured and lower in absolute magnitude than for $^{16}O+^{16}O$ scattering.

The differences between the $^{16}O+^{16}O$ and $^{12}C+^{20}Ne$ scattering are unlikely to be related to compound-nuclear level densities or decay widths since, for a given excitation energy, the maximum entrance-channel angular momenta are very similar for the two systems. We believe the differences between the two systems can be correlated with the momentum mismatch between the entrance channel and the most important direct-reaction channels. This is illustrated in Figs. 1(b) and 1(c) where we have plotted the maximum outgoing angular momentum as well as the entrance-channel (elastic) grazing angular momentum. In order for an exit channel to be able to carry away the entrance-channel angular momentum the l_{max} curve must coincide with or lie above the elastic curve. The inability of the $^{16}O+^{16}O$ direct channels to carry off enough angular momentum at low energies is a consequence of the large excitation energy of the first 3^- (6.1 MeV) and 2^+ (6.9 MeV) states in ^{16}O, as compared to the lower lying 2^+ (1.6 MeV) and 4^+ (4.3 MeV) states in ^{20}Ne, and of the more negative Q value for α transfer. The importance of angular-momentum mismatch in determining the strength of various exit channels has recently been demonstrated for the $^{16}O+^{16}O$ system by Rossner *et al.*,[12] who find that there is a strong correlation between momentum mismatch as we have defined it, and the experimental cross sections for a number of inelastic and single-nucleon and multinucleon transfer channels.

It is important to note that, to the extent that it is possible to form the compound nucleus with the same angular momentum at a given excitation energy by two different entrance channels, the channel which can carry away the most angular momentum will correspond to different processes for the two systems. For example, the $^{12}C+^{20}Ne$ (1.63 MeV) channel corresponds to α transfer for the $^{16}O+^{16}O$ entrance channel and to inelastic scattering for the $^{12}C+^{20}Ne$ entrance channel. We have measured the inelastic scattering cross section to this state in the course of these measurements and find it to be about an order of magnitude stronger than the corresponding α-transfer cross section reported by Rossner *et al.* This observation is consistent with the recent finding[13] that the inelastic channels play a dominant role in determining the difference in absorption in the $^{16}O+^{16}O$ and $^{18}O+^{18}O$ systems.

We have emphasized here the angular-momentum-matching conditions in the direct-reaction exit channels. One also expects the less tractable precompound doorway states to play a role in determining the absorption from the entrance channel. It does, however, seem possible to understand qualitatively the differences between the two systems considered here in terms of the direct-reaction channels.

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