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Search for a fusion L window in the $^{16}O + ^{16}O$ system at $E_{c.m.} = 34$ MeV

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(Received 17 February 1981)

We have measured the inelastic scattering cross section for the reaction $^{16}O(^{16}O, ^{16}O')^{16}O$. The inelastic yield is dominated by single and double excitation of the group of states with $6.1 \leq E_x \leq 7.1$ MeV in ^{16}O. The yield for energy losses greater than 15 MeV is 5.9 mb. This is significantly less than time-dependent Hartree-Fock calculations indicate for this system where nonfusion for low partial waves is predicted.

[NUCLEAR REACTIONS $^{16}O(^{16}O, ^{16}O')$, $E_{c.m.} = 34$ MeV, $\sigma(E_x, \theta_{c.m.})$; $\theta_{c.m.} = 30°-90°$, $E_x = 0-20$ MeV, inelastic yields compared to TDHF.]

Time-dependent Hartree-Fock (TDHF) calculations[1-5] indicate that the collision between two heavy ions does not lead to compound nucleus formation for the smallest impact parameters if the center of mass energy is sufficiently high. The reaction proceeds instead to a two-body final state with a total kinetic energy determined by the Coulomb barrier for the two ions. Unlike symmetric fission, the angular distribution does not increase towards smaller scattering angles.

TDHF calculations by Koonin and Flanders[6] predict that for the $^{16}O + ^{16}O$ reaction at $E_{c.m.} = 34$ MeV the partial waves $L \leq 6$ do not lead to fusion. The corresponding deep inelastic cross section is expected to be 132 mb. Recent publications by Dhar and Nilsson[7] and also by Wolschin[8] point out that the occurrence of nonfusion at lower bombarding energies depends sensitively on the assumptions used in TDHF calculations. It is of experimental interest to determine if this novel reaction mechanism does, indeed, occur in nature or whether the effect is an artifact of the calculations and the approximations used therein. Several attempts to use the energy dependence of the fusion-evaporation cross section to infer the presence of nonfusion for low partial waves have relied on model predictions to infer results, and, in some cases, have not been conclusive.[9-11] Results of a study of the $^{27}Al + ^{32}S$ system[12] have been interpreted by the authors to be in support of the TDHF predictions, although recently Hartmann and Dünnweber[13] have pointed out that what was seen may simply reflect the near mass symmetry in the entrance channel. Since the $^{16}O + ^{16}O$ system is inherently simpler and the nuclei less deformable, and since it has been the subject of much theoretical study we looked for evidence of the presence of nonfusion in this system. We report here on that direct test and find no experimental evidence for the occurrence of such a process in $^{16}O + ^{16}O$.

The experimental arrangement allowed for an unambiguous and kinematically complete identification of the final state reaction partners over a large domain in the center of mass. Preliminary results obtained in earlier measurements[14,15] indicated the presence of an appreciable inelastic yield for a Q value of ≈ -13 MeV, which turned out, in the present experiment, to be due to the double excitation of the states at $E_x = 6.1-7.1$ MeV in ^{16}O. Our present data are in agreement with later measurements by Tserruya[16] and, apart from a normalization discrepancy, are also consistent with our earlier data.

The bombarding energy of 68.5 MeV (68 MeV after energy loss in the target) was chosen to keep the excitation in the outgoing ^{16}O nuclei sufficiently low ($E_x \leq 10$ MeV per fragment for equally distributed excitation energy) to avoid dominant subsequent particle decay of the excited residual nuclei. A 75 $\mu g/cm^2$ self-supporting ^6Li foil was allowed to oxidize in a pure oxygen atmosphere, producing a $^6Li_2O$ target of ≈ 150 $\mu g/cm^2$ areal density. The beam consisted of $^{16}O^{7+}$ ions from the University of Washington tandem Van de Graaff accelerator. Coincident events were observed in two gas ΔE, solid state E position sensitive telescopes based on the Markham *et al.*[17] design. In this manner the energies (E_1,E_2), angles (θ_1, θ_2), and atomic numbers (Z_1,Z_2) for two-body final state products could later be determined off line. One counter with a large acceptance was placed at two separate settings ($\theta_2 = 36.39° \pm 7.5°$; $49.3° \pm 7.5°$), while the other instrument served as the angle defining detector for the coincident fragment angular correlation measurements.

In the subsequent analysis, O + O coincidences were studied for which the total momentum in the exit channel was equal to the incident momentum of the beam. In this manner it was possible to further discriminate against misidentified particles and O + O events originating from degraded, slit-scattered beam particles. For the more backward angular setting of the recoil detector it is possible to observe elastic scattering near $\theta_{c.m.} = 90°$ in kinematic coincidence. The simultaneous observation of elastic and inelastic scattering allows for a normalization of our data to existing[18] elastic scattering measurements.

The angular distributions were compiled to produce a contour plot of double differential cross section, $d^2\sigma/d\theta\, dE$ (a Wilczynski plot), for the $^{16}O + ^{16}O$ system. The extensive information we obtained is presented in Fig. 1. The dashed line delimiting the data reflect the limits defined by the kinematic coincidence requirement. It is difficult to extend these limits any further because of the rather low kinetic energies involved for either one or both coincident fragments. The surface is reflection symmetric about $\theta_{c.m.} = 90°$ by virtue of the identical boson nature of the entrance channel. The yield to the $^{16}O + ^{16}O$ final state is seen to be dominated by single excitation of the states between 6.1 and 7.1 MeV. The integrated cross section over the angular range observed here corresponds to $\sigma_{6-7} = 35.9$ mb. The cross section for the double excitation of these same states in both nuclei is $\sigma_{12-14} = 19.8$ mb. The elastic yield over its limited range is $\sigma_{0.0} = 4.6$ mb. By comparison, the total inelastic yield for Q values more negative than 15 MeV is $\sigma_{Q<-15} = 5.9$ mb. This value may include up to $\approx 30\%$ of less inelastic events due to the experimental energy resolution.

The trajectory of the theoretically calculated deflection function for the partial waves $L = 2-6$ is shown by the "×" marks in Fig. 1. The progression from $L = 2-6$ goes along a path of increasing experimental cross section; this would be expected considering the relative contributions, $(2L + 1)$, from the various partial cross sections. However, the integrated cross section for $Q < -15$ MeV is only 5.9 mb; this is less than 5% of the expected yield. We interpret this result as experimental evidence that the presence of a fusion L window is not borne out, at least at the order of magnitude expected from TDHF[3,4,6] calculations. Figure 2(a) presents a projection of the Wilczynski plot onto the total kinetic energy axis (TKE), showing the relative strength of the cross section at all Q values. Since the partial waves above the fusion window contribute to smaller energy losses

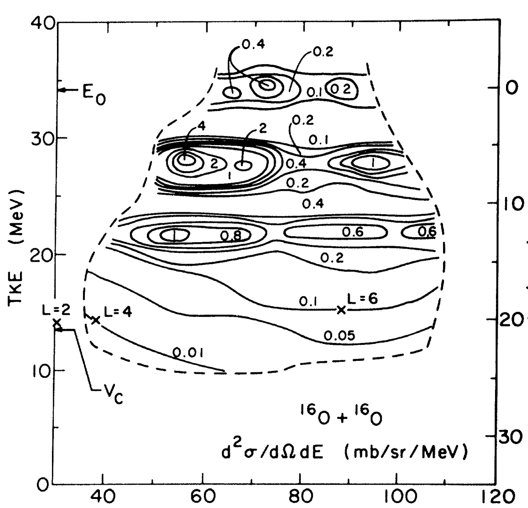

FIG. 1. A Wilczynski plot for the $^{16}O + ^{16}O$ system. The incident energy, E_0, and Coulomb barrier, V_C, for the system are indicated. The "×" marks denote TDHF predictions for the scattering angles for ions suffering nearly head-on collisions. The dashed lines show the detection limits for the present experiment.

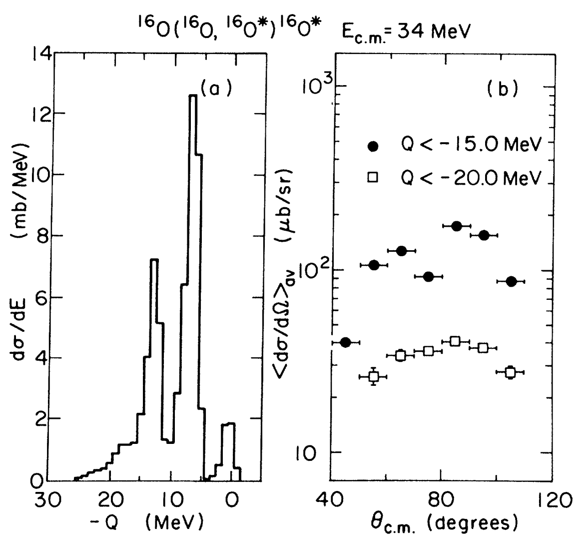

FIG. 2. (a) A projection of the Wilczynski plot onto the TKE axis. (b) Angular distributions for selected Q-value ranges. The points represent averages over 10° intervals in the center of mass.

than those below the window, a gap is expected in the energy spectra that arises from a difference in the centrifugal potentials between high and low partial waves that is independent of the details of the energy loss calculation. No evidence for such a gap is observed; the only structure is that associated with single and double excitations of the first few states in ^{16}O. Figure 2(b) shows the angular distributions for the yields $Q < -15$ and -20.0 MeV. Whereas the angular distributions for more positive Q values (see Fig. 1) increase towards forward angles, we observe that the distributions for these larger energy losses peak toward 90° in the center of mass. This behavior would be expected from TDHF. It is also possible, however, as Hartmann and Dünnweber[13] have pointed out that for a symmetric entrance channel there would be an enhancement of the inelastic yield at 90° for energy losses where the folding together of the θ and π-θ deflection functions results in an intersection; the magnitude of this rise is dependent on the slope of the deflection function at 90°.

We now address ourselves to the possible reasons for observing a small deep inelastic yield. Because of the mean field approximation that is used in current TDHF calculations, mass transfer to an asymmetric exit channel is suppressed.[19] Undoubtedly, though, transfers—especially α transfer to $^{12}C + ^{20}Ne$—will take place and will compete with the symmetric exit channel for the deep inelastic yield. We have taken a brief look at the $^{12}C + ^{20}Ne$ coincidences (but by no means in as great a detail as our study of the $^{16}O + ^{16}O$ final state) and find the α transfer yield to be at most comparable to that observed for the inelastic channel. It is improbable that the predicted cross section may be fractionated among several two-body final states. The observed drop in cross section at forward angles also makes it unlikely that the missing yield occurs at angles $\theta_{c.m.} \leq 30°$; if this were the case the differential cross section would have to increase by a factor of ≈ 1000 in the unobserved angular range. Experimental evidence on deeply inelastic collisions indicates that the excitation imparted to the two fragments is shared in proportion to their masses, indicating thermal equilibration in the final state. For identical particles this finding implies the equipartition of the excitation energy. One expects, of course, a dispersion about this average result. The TDHF calculations indicate that it should be small.[6] Independently, by assuming that the excitation is imparted to the fragments statistically, the energy dependence of the level densities for the two nuclei can be used to estimate the spread. For $-Q = 18$ MeV one obtains $\langle E_x \rangle = 9 \pm 4.5$ MeV. Folding in the γ-decay branching ratio for ^{16}O, one expects that the two-body final state should still reflect ≈ 15–20% of the binary yield, which in terms of cross section represents ≈ 27 mb. Our observed yield is still much smaller than this lower estimate to the expected yield. In terms of partial waves contributing to nonfusion, our result implies a lower cutoff $L_{min} < 2$.

Recently, refinements have been suggested to TDHF calculations by several authors.[8,20,21] The work of Grangé *et al.*[8] involves the treatment of the time evolution of the equation for the Wigner transforms of the density matrix supplemented with a collision term to account for two-body dissipation. Although no *a priori* calculations have been made for finite nuclei, the direction of the effect is to significantly reduce the probability of nonfusion for head on collisions. Similarly, the choice of potential used in a standard TDHF calculation has been shown[7] to be able to alter the threshold at which nonfusion at small impact parameters occurs. Experimentally we see that there is no evidence for the occurrence of such a phenomenon in the $^{16}O + ^{16}O$ system at $E_{c.m.} = 34$ MeV at the level that would be expected from conventional calculations. Our result provides a constraint against which possible extensions of TDHF can be tested.

The authors wish to thank S. E. Koonin and B. Flanders for their assistance in providing us with the TDHF calculations and also I. Tserruya for very helpful discussions. This work was supported in part by the U.S. Department of Energy.

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