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EXCITATION-FUNCTION STRUCTURE IN $O^{16}+O^{16}$ SCATTERING*

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In recent years excitation functions and angular distributions for heavy-ion–induced reactions and scattering have been studied extensively at low and medium incident energies. The observation of resonances, correlated in energy, in all open channels of the $C^{12}+C^{12}$ system in the region of the Coulomb barrier led to the discovery and study[1,2] of nuclear molecular states. Structure at higher energies in the excitation curve for both elastic scattering and alpha-particle emission from this system was shown to exhibit no cross correlations and was successfully explained[3,4] as reflecting fluctuation phenomena.

A particularly interesting result of the early experiments[5,6] was the total lack of apparent structure in the $O^{16}+O^{16}$ elastic-scattering excitation functions in the same energy range. In this Letter we wish to report on extensions of the $O^{16}+O^{16}$ measurements to higher bombarding energies. In striking contrast to the earlier work we find very pronounced and regular structure in the excitation functions; we suggest that this structure may provide interesting insight into the mechanisms of heavy-ion interactions.

The experiments involved bombardment of self-supporting SiO targets with O^{16} ion beams in the energy range from 35 to 80 MeV from Yale's High Voltage Engineering Corporation Model MP tandem accelerator. Measurement of elastic scattering uncontaminated by inelastic processes was assured through requirement of kinematic coincidence between scattered and recoil O^{16} ions; a detector array allowed simultaneous coincidence measurements at five variable angles. Angles subtended by the detectors were $\pm 0.5°$ and the angle setting precision was better than $0.1°$. Absolute cross sections were determined by comparison with Mott-scattering predictions at 20 MeV and are quoted with an accuracy of $\pm 20\,\%$.

Excitation functions measured at 50°, 60°, 70°, 80°, and 90° in the center-of-mass frame are shown in Fig. 1. It should be noted that for pure Mott scattering the 90° yield function is smooth. Several angular distributions mea-

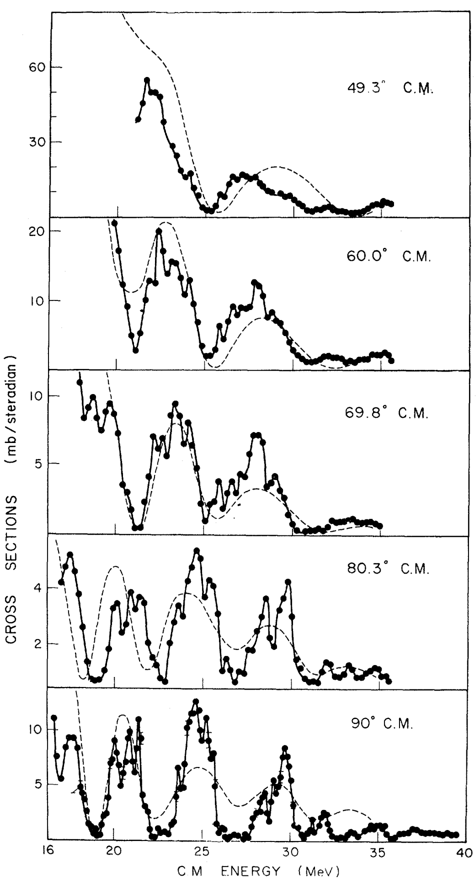

FIG. 1. $O^{16}+O^{16}$ elastic-scattering excitation functions measured at five different angles. The dashed curves represent the theoretically predicted excitation functions calculated with the potential listed in Table I. The excitation functions at 50° to 80° were measured with an effective energy resolution reflecting target thickness of 400 keV. The energy resolution for the 90° excitation function was 125 keV.

sured at center-of-mass energies in the range between 18 and 30 MeV are shown in Fig. 2. In view of the symmetry about 90° of the angular distributions from the scattering of identical particles, all measurements have been limited to angles ≤100°.

The arresting feature of the present data is the pronounced structure in the yield functions in marked contrast to the earlier[5,6] lower energy measurements. The three major gross-structure peaks at 90° have comparable widths, peak-to-valley ratios in excess of 20:1, and valley widths increasing with incident energy. A fourth peak at 17 MeV is partially submerged in the exponentially (with decreasing energy) rising cross section. Almost identical structure appears at 90° and 80° and at 70° and 60°, respectively; however, the gross-structure peaks are shifted in energy between the 80°/90° and 60°/70° curves. The gross-structure peaks themselves are fragmented partially into structure of intermediate width. Additional fine structure was observed in a measurement with 50-keV resolution over the gross-structure peak at 20.5 MeV in the 90° excitation function. Very probably the fine structure and possibly the fragmentation of the broad maxima into peaks of intermediate width reflect fluctuation phenomena which may be particularly large since a zero-spin boson system has only one statistical degree of freedom. A similar explanation of the regularities apparent in the gross structure seems highly improbable although it cannot be excluded a priori.

Instead it is believed that we are dealing with a potential-scattering phenomenon. As has been frequently suggested as, e.g., in the earlier studies[2,5] on the $C^{12}+C^{12}$ system, the interaction potential for these heavy-ion systems may be substantially modified by the Pauli exclusion principle in limiting the interpenetration of the ions at close radial separations. In effect this could give rise to "quasimolecular" interaction potentials having relatively shallow attractive regions and perhaps a repulsive core similar to the potentials found from the α–He^4 scattering.[7] On the other hand, the ordinary optical model has been successfully applied[8-10] to the analysis of heavy-ion scattering data, although the physical meaning of such an optical potential for heavy ions has always been somewhat in question. It is hoped that the present investigation of heavy-

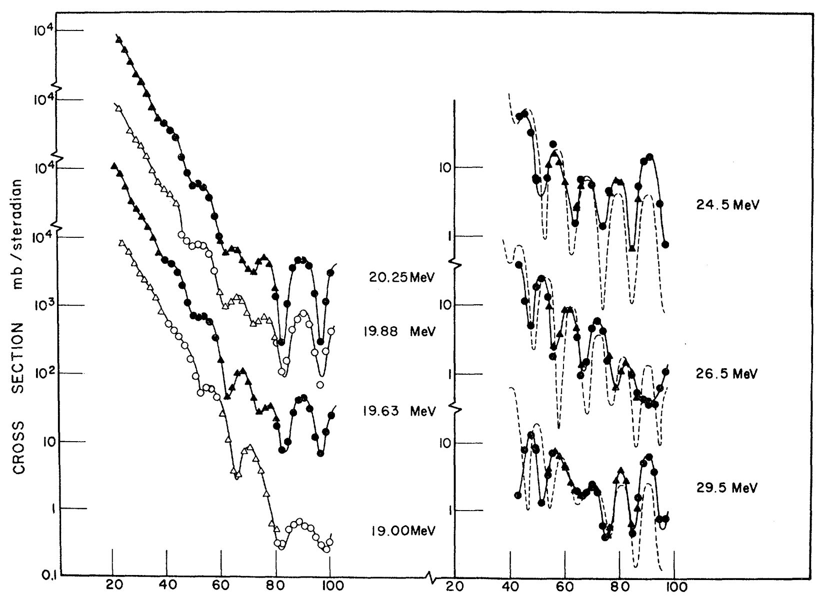

FIG. 2. $O^{16}+O^{16}$ elastic-scattering angular distributions measured at various c.m. energies between 19 and 30 MeV. The dashed curves are angular distributions calculated with the parameters listed in Table I. The effective energy resolution was 125 keV for the angular distributions measured around 20 MeV, and 400 keV for the angular distributions measured at 24.5, 26.5, and 28.5 MeV. Dots and triangles represent angles measured with different detectors. The dashed curves have been calculated with the potential listed in Table I.

ion scattering over a wide energy range may allow discrimination between these two (repulsive core versus ordinary complex potential) models in terms of the energy dependence of the potential parameters.

We have undertaken to examine the present data utilizing the standard optical-model code ABACUS,[11] which has been modified to take the identity of the colliding particles into account; calculations with what may be more realistic potentials with repulsive core are in progress.

Figure 1 shows optical-model calculations of the excitation functions using a Woods-Saxon potential with volume absorption. The parameters used are listed in Table I. Although these calculations do not fit the data in detail they succeed remarkably well in qualitatively reproducing the gross structure at all angles. The best results were obtained with a shallow real potential of 17 MeV as suggested to us by Block and Malik.[12] In addition a linear energy dependence for the depth of the imagninary potential was used ($W = 0.4 + 0.2E_{\text{c.m.}}$). The introduction of an energy-dependent W is consistent with the results obtained[9,10] from optical-model analyses of heavy-ion scattering at different energies. Attempts to fit the excitation functions with a real potential of about 40 MeV have been unsuccessful, despite a rather thorough parameter scan in this region. (A potential of about 40 MeV has been most commonly used in the optical-model analyses of heavy-ion scattering.) Although the calculations with the 40-MeV potential also predict gross structure in the excitation functions it was not possible to obtain agreement with experiment for all angles simultaneously.

We have also attempted without success to obtain equally good fits with deeper (as well as shallower) potentials by systematically moving away from the 17-MeV best-fit parameters along the locus of minimum χ^2. Moreover, calculations with a deeper real potential, which was inserted point by point into the calculations such as to reproduce faithfully the tail region of the 17-MeV potential, failed to give a satisfactory fit to the data. In these latter calculations the ratio of W to V was taken to be the same as that used for the 17-MeV potential. These results are in contrast to the observation of Kuehner and Almqvist[9] for heavy-ion scattering at energies close to the Coulomb barrier, where a continuous ambiguity in the real potential was found. Preliminary calculations with a soft repulsive core (obtained by folding a Gaussian-shaped repulsive core into the ordinary Woods-Saxon potential) have been inconclusive. It should be noted, however, that in the 17-MeV potential case the resulting real potential ($V_{\text{real}} + V_{\text{Coulomb}}$) is positive (+3 MeV), and therefore repulsive, for the main part of the nuclear interior except for a small region around 5 fm where it is weakly (<1 MeV) attractive. While we cannot completely exclude the possibility of comparable fits with other parametrizations, the good qualitative agreement obtained with the experimental results with the very shallow well is suggestive of the "quasimolecular" potentials discussed above.

Table I. Optical-model parameters for the $O^{16} + O^{16}$ system.[a]

V (MeV)	W (MeV)	R (fm)	a (fm)
17	$0.4 + 0.2E_{\text{c.m.}}$	6.8	0.49

[a]The potential is of the standard Woods-Saxon form with volume absorption.

Ideally it would be desirable to deduce from simultaneous analyses of the angular distributions and the excitation functions a self-consistent set of optical-model parameters over the energy range studied. In the present calculations we have not achieved this goal; parameters obtained from search calculations on the angular distributions do not vary systematically with energy. This failure to obtain a consistent set of optical-model parameters from a search on the angular distributions is not too surprising since the excitation functions show evidence of significant contributions from compound elastic scattering which cannot be encompassed by the optical model. Indeed some of the present data are very reminiscent of those reported[13] from alpha-particle scattering on relatively light nuclei, and as in that work we are engaging in a systematic phase-shift analysis of angular distributions measured in small energy increments to search for underlying resonances.

Angular distributions calculated with the shallow potential of Table I are compared with the data in Fig. 2. Except for the 90° minimum at 26.5 MeV, which is not reproduced by the calculations, the over-all agreement between calculated and measured angular distributions is surprisingly good.

We have also considered the possibility that the gross structure in the excitation functions could reflect resonant transfer of an alpha particle, or less probably a nucleon, between the scattering O^{16} ions in analogy with the ion-atom measurements of Everhart[14] and as discussed by Temmer.[15] We have indeed detected the conjugate $C^{12}+Ne^{20}$ reaction exit channel; these measurements, however, as well as the success of the calculations with the simple potential model, suggest that this is not the dominant reaction mode.

Of particular interest are the facts that the gross structure in the excitation function can be reproduced by a potential model and that the potential thus obtained is so shallow. In view of the well-known ambiguities of the optical model, further investigations will be necessary to establish the ultimate significance of the shallow potential. The extreme shallowness of our best potential suggests a marked restriction on the interaction of heavy ions reflecting operation of the Pauli principle and we suggest that more detailed theoretical examination of this phenomenon could be of considerable interest. The present investigation leads naturally to an extended study of additional identical and nonidentical heavy-ion systems accessible to the new energy and beam species range of the Model MP tandem accelerators. Such studies are now in progress in this laboratory.

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