RESONANT ELASTIC SCATTERING OF C^{12} BY CARBON

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(Received February 29, 1960)

The elastic scattering of C^{12} by carbon has been studied in the range $6 \leq E_{lab}{}^{C} \leq 29$ Mev, using high-resolution Au-Si surface barrier detectors[1] and carbon ion beams of precisely defined energy from the Chalk River tandem accelerator. Excitation curves have been measured for $\theta_{lab} = 45°$, 28.8°, and 19.5°; at energies above the Coulomb barrier, those at 45° and 28.8° show pronounced resonance structure corresponding to excitations in $Mg^{24} \geq 24$ Mev while that at 19.5° shows only very weak residual structure. This is believed to be the first reported example of such resonant phenomena in heavy-ion reactions. In marked contrast to these results for the C + C system, similar measurements for O^{16} ions on oxygen targets show no such resonant behavior corresponding to similar excitations in S^{32}. The binding energies in Mg^{24} and S^{32} are 14.08 and 16.54 Mev, respectively; the calculated[2] Q values for nucleon and alpha emitting reactions are equal to within ~2 Mev for the two systems.

Figure 1 shows the 45° ($\phi_{c.m.} = 90°$) excitation curves for the C + C and O + O systems. The dashed curves show the E^{-2} dependence predicted for pure Coulomb scattering. In view of the agreement between the predicted and measured energy dependence (Fig. 1) and angular dependence (to be discussed later), the cross-section scale in Fig. 1 was obtained by normalizing to the Mott predictions at low energies. In the C + C case, there is no apparent correlation between the structural features of the excitation curves at the different angles studied suggesting that interference effects may be important.

A typical heavy-ion spectrum is inset in Fig. 1. The system energy resolution made it possible to use pulse-height analysis to eliminate contributions from elastic scattering of the incident ions on target contaminants and from inelastic processes without the use of coincidence techniques. With ~50 $\mu g/cm^2$ carbon targets and 2×2 mm detector areas, system resolutions $\lesssim 2\%$ have been obtained using very simple transistorized current preamplifiers.

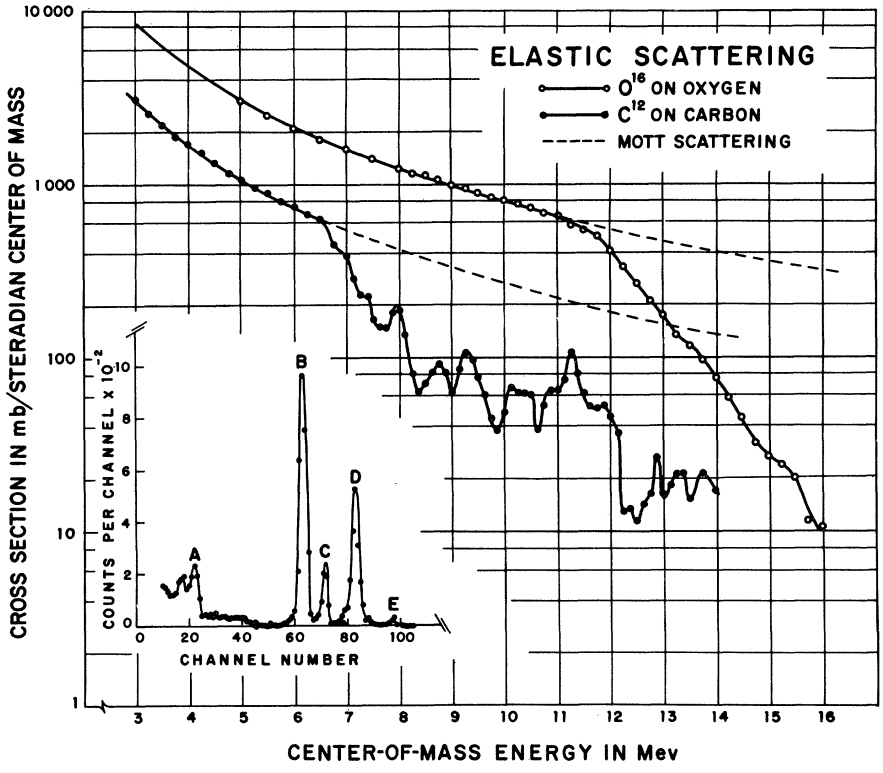

FIG. 1. Excitation curves for the elastic scattering of C^{12} by carbon and of O^{16} by oxygen. Self-supporting targets of carbon (~50 $\mu g/cm^2$) and of SiO (~70 $\mu g/cm^2$) and 5×5 mm Au-Si detectors, have been used in these measurements. The inset figure is a typical spectrum at $\theta_{lab} = 45°$ obtained for 21.0-Mev carbon ions on carbon. The peak legend is as follows: the double peak at A arises from alpha particles and protons from the reaction which completely traverse the junction and thus provide a measure of its thickness. B is from C^{12} elastically scattered by carbon; C is for C^{12} elastically scattered by oxygen; D is from C^{12} elastically scattered by a residual phosphorous contaminant from the stripping compound used in preparing the target, and E is from C^{12} elastically scattered from traces of heavier target contaminants.

Using, as a first approximation, the "quarter point" analysis suggested by Blair,[3] interaction radii of 7.8 and 8.8 f are obtained for the C+C and O+O systems, respectively; these are to be compared to the value of 8.0 f reported previously for the N+N system.[4] Assuming these interaction radii, the classical Coulomb barriers are 6.6 and 10.5 Mev, respectively. As shown in Fig. 1, the shapes of the excitation curves are in good accord with the Mott scattering predictions for energies below the barriers; however, with increasing energy the experimental cross sections are smaller than those predicted. For the O+O system, the almost exponential decrease with very weak superposed structure, is characteristic of essentially all of the previously reported elastic scattering of deuterons,[5] alpha particles,[6] and heavy ions.[7] The results for the C+C system are anomalous not only in that marked resonance structure appears, in some cases with $\Gamma \leq 200$ kev, but also in that the cross section averaged over this resonance structure decreases much less rapidly with increasing energy than in the other cases.

In order to gain further information on this resonance behavior, angular distributions of the elastically scattered carbon ions have been measured at several energies in the range studied; three typical distributions are shown in Fig. 2. As anticipated from the excitation curves, at energies below the barrier, the Mott predictions for the Coulomb scattering of identical, spin-zero Bosons is in excellent agreement with the experimental data.

As the energy is increased above the barrier, however, the shape of the angular distributions changes rapidly with energy as shown. This change is not monotonic; the distribution measured at 13.34 Mev, for example, is very similar to that at 11.25 Mev while that at 12.25 Mev is significantly different. Of particular interest is the fact that the experimental minima at $\phi_{c.m.} \simeq 78°$ and 102° do not shift in angle with changing energy as predicted for Mott scattering. Such stationary minima are, however, characteristic of the Blair model[3] predictions. In the case of the 11.25-Mev distribution, for example, the predicted shape of the angular distribution agrees well with that observed for $\phi_{c.m.} \geq 65°$ assuming total absorption of all incident waves up to and including $l_{max} = 6$; however, the predicted cross sections are a factor ~2 less than those observed in this range. This fit is superior to that obtained with $l_{max} \sim 8$, which corresponds classically to the interaction radius quoted.

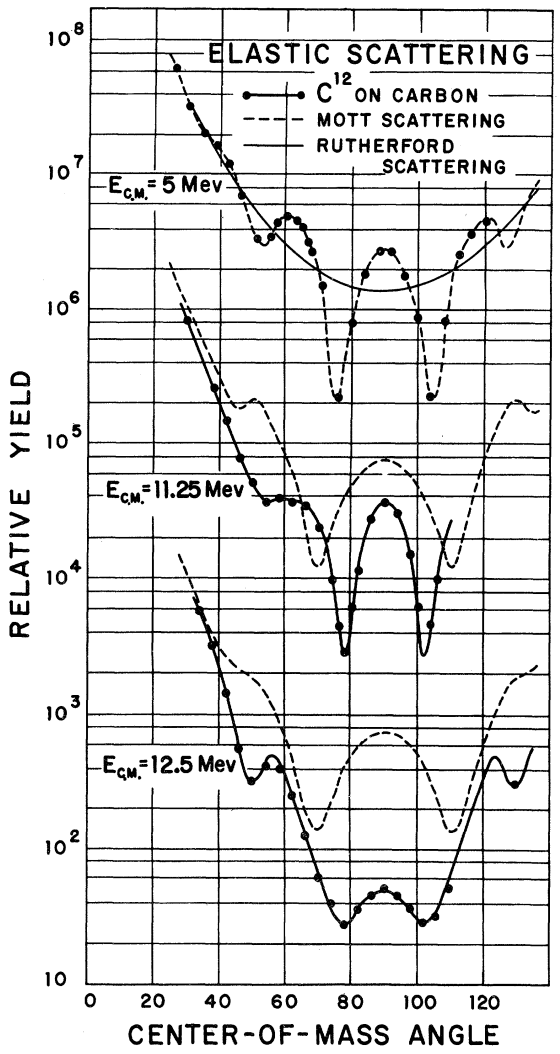

FIG. 2. Typical angular distributions for C^{12} elastically scattered from carbon. The Rutherford and Mott scattering predictions differ only in that the latter includes the quantum mechanical interference term arising from the identity of the incident and target nuclei. The three distributions have been displaced arbitrarily for presentation; however, the corresponding experimental and theoretical curves have been normalized in each case using the data of Fig. 1. An experimental angular resolution ~0.5° has been used in these measurements.

In the case of the 12.5-Mev data there is essentially no agreement for any assumed $l_{max} \leq 10$ since the predicted ratio of the cross section at $\phi_{c.m.} = 90°$ to that at $\phi_{c.m.} = 80°$ is $\gtrsim 10$. Significant improvement is obtained by assuming $l_{max} = 6$ and in addition total absorption of $l = 10$ without absorption of $l = 8$, in that the above ratio is

reduced to ~3. More sophisticated analyses of these data are clearly required to produce acceptable fits; such analyses are now in progress using an optical model. The preliminary results obtained with the Blair model do suggest, however, that the resonance structure in the carbon excitation curve reflects the selective absorption of particular incident partial waves to form high-spin states of Mg^{24}.

Any successful explanation of the C+C resonance structure must also include the lack of such structure in the O+O data at corresponding excitations. While the gross structure of the C+C curve ($\Gamma \sim$ few Mev) above the barrier may well reflect size resonances in the effective optical potential, the fine structure ($\Gamma \lesssim 200$ kev) implies the formation of high-spin, quasi-molecular states with $\tau \sim 10^{-21}$ sec. A number of different mechanisms are consistent with these results and while it is not possible to preclude any of these, that which appears most attractive involves the binding of the carbon nuclei into high-spin, dumbbell states through virtual nucleon transfer. On this basis, differentiation between the C+C and O+O systems would reflect the fact that in the energy range accessible, nucleon transfer reactions are energetically forbidden in the former and allowed in the latter, for energies above the Coulomb barrier ($Q \sim -11.5$ Mev). It should be noted however that in the latter case, the transfer reaction products must penetrate much of the Coulomb barrier for the energies involved here. Moreover, in the O+O system both virtual and real transfer reactions involve the transfer of a nucleon between the p and d shells and are thus expected to be inhibited relative to those in the C+C system which are within the p shell.

If it is assumed that the fine structure in the C+C data of Fig. 1 reflects interference between the shape-elastic amplitudes and compound-elastic amplitudes corresponding to the quasi-molecular states (i.e., $\Gamma_{C^{12}} \sim \Gamma_{\text{total}}$ for the latter), the reaction excitation curve would not be expected to show comparable structure (nucleon and alpha emission from such states is inhibited by the changes in shape and angular momentum required). Measurement of this excitation curve is in progress to further elucidate the mechanisms involved.

The results reported herein are part of a program of study of heavy-ion interactions now in progress. Later, more complete publications will present excitation curves at other angles, angular distributions at other energies, and similar measurements for other systems.

We are indebted to Dr. E. Vogt for discussions concerning these results.

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QUESTION OF NUCLEON CLUSTERS IN THE NUCLEAR SURFACE*

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(Received January 25, 1960; revised manuscript received February 23, 1960)

It has been suggested by Wilkinson[1] that strong evidence for the existence of nucleon clusters in the region of the nucleus where the density is less than 20% of its central value (defined as the periphery) is provided by the absorption of K^- mesons by nuclei in photographic emulsions. The ratio of two-nucleon to one-nucleon reactions as determined from the hyperon energy spectra is appreciable—about 20%.[2]

There is strong evidence that the K^- meson reacts with the nucleus in the periphery. The mechanism has been described by Jones.[3] The K^- meson is captured in a Bohr orbit, and cascades electromagnetically into a $5g$ orbit for heavy emulsion nuclei. (Light nuclei will not be considered here; the same considerations apply.)