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Orbiting in the $^{12}C + ^{20}Ne$ System

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An experimental study of the $^{20}Ne + ^{12}C$ systems reveals a large cross section for inelastic scattering with large negative Q values at backward angles. The differential cross section is proportional to $1/\sin\theta_{c.m.} > 100°$ and has characteristics consistent with the decay of an orbiting $^{20}Ne + ^{12}C$ dinuclear system.

The elastic scattering of heavy ions at large angles has received much attention since the measurements of Braun-Munzinger *et al.*[1] first revealed an enhanced cross section for scattering of $^{16}O + ^{28}Si$ at center-of-mass angles larger than 100°.[2] The backward-angle enhancement seems to be a general feature for projectiles and targets in this mass region, although the size of the enhancement can vary markedly from system to system. A number of explanations have been offered for this phenomenon, such as Regge poles,[3] resonances,[4] parity-dependent potentials,[5] diffraction,[6] and particle exchange.[7] The regular broad structures appearing in the excitation functions could also be explained by orbiting in the mutual potential.[8] It would be desirable to have additional experimental data which might help in distinguishing among these various pictures. Since the interpretation of backward-angle enhancement in terms of the orbiting of projectile and target should have general consequences for inelastic scattering as well,[9] we have investigated the gross features of the inelastic scattering at backward angles. Experimental data of this type are reported here for the first time. We find both for the system $^{12}C + ^{20}Ne$, on which we report here, and for other systems as well,[10] a strong enhancement of the cross section for inelastic scattering with large negative Q values at backward angles. The gross features we observe for the inelastic scattering find a natural interpretation in terms of orbiting and support this mechanism as the origin of backward-angle enhancement of elastic scattering as well.

A natural carbon target was bombarded with beams of 50- to 80-MeV $^{20}Ne^{4+}$ from the Oak Ridge isochronous cyclotron. The reaction products with $Z > 3$ were identified with a position-sensitive ΔE-E counter[11] which spanned an angular range of 9° in 1° steps. Angular distributions covering the angular range of $5° \leq \theta_{lab} \leq 40°$ were taken at 60, 72.5, 74, and 75.2 MeV, and a 22-point excitation function was measured for $12° \leq \theta_{lab} \leq 21°$.

Figure 1 shows a typical spectrum of C ions; note the sharp groups which can be identified with known states in the $^{12}C + ^{20}Ne$ system superimposed on a broad continuum centered at a Q value around -11.5 MeV. The thresholds for the production of the most likely exit channels with more than two bodies are indicated in the figure. The $^{13}C + ^{19}Ne$ and $^{11}C + ^{21}Ne$ channels have ground-state Q values of ~ -12 MeV. Clearly most of the yield in the region of enhancement is $^{12}C + ^{20}Ne$.

Given the dominance of a two-body final state, we obtained the dependence on center-of-mass angle of the average Q value ($\overline{Q}$, the centroid of the bump) and the magnitude of the cross section contained in the enhanced C yield (including the ground state). At each bombarding energy, $\overline{Q}$ was constant over the measured angular range. An almost linear variation of $\overline{Q}$ with bombarding energy was also observed (from $\overline{Q} = -5$ MeV at 50 MeV bombarding energy to $\overline{Q} = -13$ MeV at 80 MeV bombarding energy). All the angular distributions for the summed $^{12}C + ^{20}Ne$ cross section

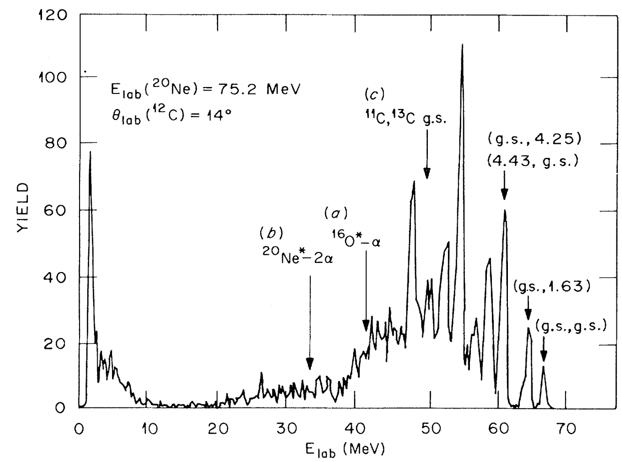

FIG. 1. Energy spectrum for outgoing C particles. The three arrows shown indicate the thresholds for the following processes:

(a) $^{12}C(^{20}Ne, ^{16}O^*)^{16}O \rightarrow \alpha + ^{12}C$

(b) $^{12}C(^{20}Ne, ^{20}Ne^*)^{12}C \rightarrow 2\alpha + ^{12}C$

(c) $^{12}C(^{20}Ne, ^{11}C)^{21}Ne$ and $^{12}C(^{20}Ne, ^{13}C)^{19}Ne$.

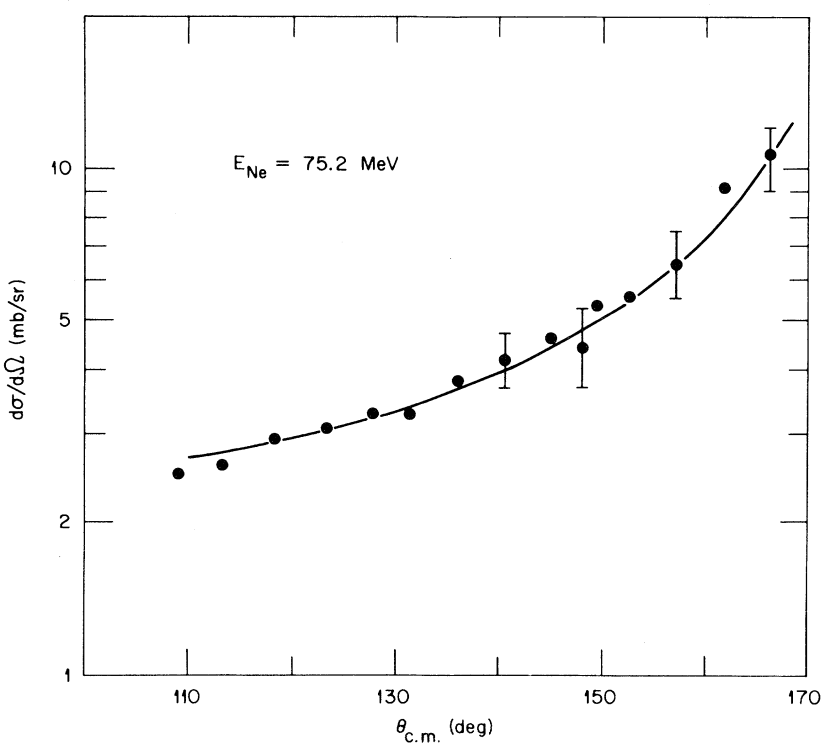

FIG. 2. The center-of-mass angular distribution for the total yield observed in the region of enhanced $^{12}C^* + ^{20}Ne^*$ events (the bump in Fig. 1). The curve is proportional to $1/\sin\theta_{c.m.}$.

(bump + low excited states + ground state) follow the pattern shown in Fig. 2. The solid curve is proportional to $1/\sin\theta_{c.m.}$. With this angular dependence, the integrated cross section (0–180°) is 54 mb at $E_{lab}=75.2$ MeV. An excitation function showing the energy dependence of this angle-integrated cross section is shown in Fig. 3. Angular distributions and excitation functions have also been measured for the particle groups corresponding to the ground state and 1.63- and 4.25- or 4.43-MeV excitations. The excitation functions for those low-lying states show regularly spaced broad structures (~2 MeV c.m.) and a high degree of cross correlation,[12] characteristic of potential scattering. The angular distributions at the maxima of the observed gross structure for the ground-state transition are reproduced by the square of a single Legendre polynomial.

These angular dependences of average Q values and summed cross sections indicate that the yield originates from relaxed events associated with the decay of a system either at complete (compound nucleus) or partial (orbiting dinuclear system) equilibrium. It is not possible, however, on the basis of the above observations, to distinguish between the two possibilities. Therefore, one must resort to a more quantitative analysis in order to differentiate between the two processes.

The possibility that the $^{12}C+^{20}Ne$ yield might arise wholly or partially from statistical evaporation of a ^{12}C ion (or an excited ^{16}O ion which decays to $^{12}C+\alpha$) has been investigated by performing a Hauser-Feshbach calculation using the code HELGA.[13] The distribution of partial waves contributing to fusion was chosen to have the same shape as the distribution determined by an optical-model fit to the elastic scattering,[14,15] except that the angular momentum for which $T_l=\frac{1}{2}$ was reduced from the grazing value of 21 to a critical value of 19. The latter value was determined by the measured cross section for evaporation residues, 1200 ± 120 mb, plus an additional 54 mb corresponding to the yield shown in Fig. 2. The optical-model parameters and densities of levels governing n, p, and α emission in our calculation have been shown to reproduce measured cross sections for evaporation of these particles in this mass region.[16] In these exit channels, as well as those for $^{12}C+^{20}Ne$ and $^{16}O+^{16}O$, low-lying levels of known excitation, spin, and parity were included explicitly. In this manner, the cross sections were calculated for all possible exit channels which produce ^{12}C, either directly in one of its bound states or through subsequent α decay. The result, 11 mb, represents only one-fifth of the observed yield (see Fig. 3). The average experimental cross sections at backward angles for the ground and first excited states of $^{12}C+^{20}Ne$ are also underpredicted by the same factor. Variation of l_{cr} by $\pm 1\hbar$ or of the level-density parameters within a range allowed by comparison to experiment[16] can affect the above prediction by about 20%. We thus conclude that statistical evaporation of ^{12}C by an equilibrated compound nucleus cannot account for the main part of the observed yields of $^{12}C+^{20}Ne$.

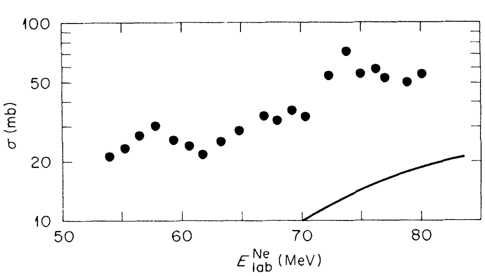

FIG. 3. The excitation function for the angle-integrated (0°–180°) yield which is illustrated in Figs. 1 and 2. Random errors are less than 8%. There is a systematic error of ±10% in absolute normalization. The solid line shows the magnitude and energy dependence predicted by the statistical evaporation model discussed in the text.

Statistical calculations for fission which consider the density of states at the fission-barrier configuration as the limiting factor predict even smaller values for the fission of ^{32}S.[17] It should be noted, however, that the program used[18] considers symmetric fission as the dominant mode; in such light systems, there might be a higher probability for asymmetric fission.

We consider next the possibility of orbiting as a mechanism for the observed inelastic yield of $^{12}C+^{20}Ne$ at large angles. In this case, the ^{12}C and ^{20}Ne nuclei are first attracted by the nuclear potential, and perform one or more rotations during which their identity is maintained although relative kinetic energy may be converted into internal excitation energy and angular momentum; the system then finally separates in an excited configuration. This picture has been discussed on a quantum-mechanical basis by Scheid *et al.*[19] for light systems and classically by Wilczyński for heavy systems.[9]

In addition to a balance of excitation energy and angular momentum which may be expressed by the equations

$$\vec{L}_{in} = \vec{J}_{out}(^{20}Ne^*) + \vec{J}_{out}(^{12}C^*) + \vec{L}_{out}, \quad (1)$$

$$E^{in}_{c.m.} + \overline{Q} = E^{out}_{c.m.}, \quad (2)$$

two necessary conditions for orbiting are the following: (a) There must exist a pocket in the combined nuclear, Coulomb, and centrifugal potentials such that

$$d(V_{nucl} + V_{Cb} + V_{cen})/dr = 0, \quad (3)$$

at a radius R for which there is a local maximum in the potential. (b) At $r = R$, the radial kinetic energy must be small, i.e.,

$$E^{out}_{c.m.} = \frac{\hbar^2 L_{out}(L_{out}+1)}{2\mu R^2} + V_{Cb} + V_{nucl}. \quad (4)$$

Condition (a) is satisfied for partial waves with $l \lesssim 19$, even with the rather shallow[20] nuclear potential deduced in Ref. 14. At $E_{c.m.} = 28$ MeV (the example of Figs. 1 and 2) the values of L_{in} which make the dominant contribution to orbiting must lie between $l_{cr} = 19\hbar$ and $l_{gr} = 21\hbar$. Application of Eqs. (1) and (4) then requires that L_{out} must have values ranging from $14\hbar$ to $11\hbar$ for Q values in the range of -11 to -14 MeV. These results together with Eq. (2) imply that the excited C and Ne ions must carry 6 to 10 units of intrinsic angular momentum. Examination of the known levels of ^{12}C and ^{20}Ne shows that states with such spins are available at these excitation energies. Thus, requirements (a) and (b) are satisfied for inelastic scattering at $E_{c.m.} = 28$ MeV and, it may be shown, also for the entire range of bombarding energies considered in this work.

A third condition for orbiting is that the absorption into channels other than $^{12}C^* + ^{20}Ne^*$ be sufficiently weak that the system has a finite probability to survive for a complete rotation. Satisfaction of this condition cannot be demonstrated quantitatively and *a priori* by simple arguments. However, the presence of broad structure in the 90° and 177° elastic excitation functions[12, 15] and in the angle-integrated excitation function shown in Fig. 3 indicates a weak absorption or surface transparency.[2] Taken together with the satisfaction of conditions (a) and (b) above, the observation of a $1/\sin\theta_{c.m.}$ dependence of the cross section for a sum of many excited states thus strongly suggests that orbiting does indeed occur.

In summary, measurements of backward-angle inelastic scattering extended to high excitation reveal a large yield of which the ground state is only a small part. The properties of this enhanced inelastic scattering provide evidence which favors the interpretation of elastic and inelastic backward-angle scattering in terms of orbiting.

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