Observation of Angular Momentum Saturation in Deep-Inelastic Processes Involving Light Heavy Ions

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The most probable value for the total kinetic energy of reaction products from strongly damped collisions of $^{28}Si + ^{12}C$ was found to increase with bombarding energy only up to a limiting value. This behavior suggests that the orbital angular momentum of the dinuclear complex formed in these collisions has reached a saturation value beyond which further increase is not possible.

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Studies of collisions between heavy ions have shown that the large incoming orbital angular momenta play an important role in determining the outcome of the collision.[1] This is true especially in collisions between lighter nuclei ($A_p, A_t < 40$) where Coulomb and centrifugal repulsion for the dominant (near-grazing) partial waves are of comparable magnitude. Fragments from deep-inelastic processes emerge from the collision with completely damped kinetic energies, i.e., energies equal to the potential energy stored in an intermediate dinuclear complex formed in that collision.[2,3] For collisions between light heavy ions it was shown that the kinetic energy of the fully damped fragments contains significant centrifugal energy contributions. The centrifugal energy depends on the relative orbital angular momentum of the two nuclei in contact $[E_{\rm rot} = Kl(l+1)]$ and accounts for the observed linear dependence of the kinetic energy of the final fragments on the bombarding energy.[4–7] Recent measurements have shown that the yield of fragments from strongly damped processes dominates the spectra at backward angles, and the angular distributions associated with this yield indicate that the fragments emerge from a *long-lived* rotating dinuclear complex (orbiting).[8] These measurements at backward angles provide a means for studying the products from deep-inelastic processes in the absence of contributions from quasielastic processes. From our study of deep-inelastic processes in $^{28}Si + ^{12}C$ at backward angles we show in this paper results which demonstrate that the orbital angular momentum of the rotating dinuclear system formed in this collision reaches a saturation value beyond which it ceases to increase with increasing bombarding energy. If orbiting of the two nuclei does occur, as has been stipulated for deep-inelastic scattering long ago,[2,3] then such a limit on orbital angular momentum is indeed expected to occur when the centrifugal force becomes large enough to cancel the attractive nuclear force. Aside from serving as additional confirmation for the long held semiclassical view of deep-inelastic scattering as an orbiting phenomenon,[2] knowledge of this angular momentum limit can also be used to learn about the strength and range of the nuclear interaction potential.

In the experiment, ^{28}Si beams at several energies ranging from 100 to 190 MeV from the Brookhaven National Laboratory tandem accelerator facility were used to bombard natural carbon foils and spectra of recoiling targetlike nuclei were studied at forward angles.[8] This is equivalent to studying projectilelike products emitted at backward angles in the bombardment of a ^{28}Si target by ^{12}C beams.[9] Two such spectra for carbon nuclei emitted at different bombarding energies are shown in Fig. 1. In Ref. 8 we have shown that all the yield in these spectra and similar spectra of boron, nitrogen, and oxygen nuclei comes from the decay of a long-lived rotating dinuclear complex formed in the collision between ^{28}Si and ^{12}C. The most probable Q value[10] ($\bar{Q}$) for these spectra does not depend on the angle of emission and has a linear dependence on bombarding energy over the energy range $30 \leq E_{\rm c.m.} \leq 40$ MeV studied in Ref. 8. Results from similar measurements at higher energies are shown in Fig. 2 for emitted carbon and oxygen nuclei, the two strongest outgoing channels. The figure shows the most probable values for the total kinetic energy of the final fragments as a function of bombarding energy. The kinetic energies were obtained by adding the most probable values of the measured Q value spectra (see Fig. 1) to the center-of-mass bombarding

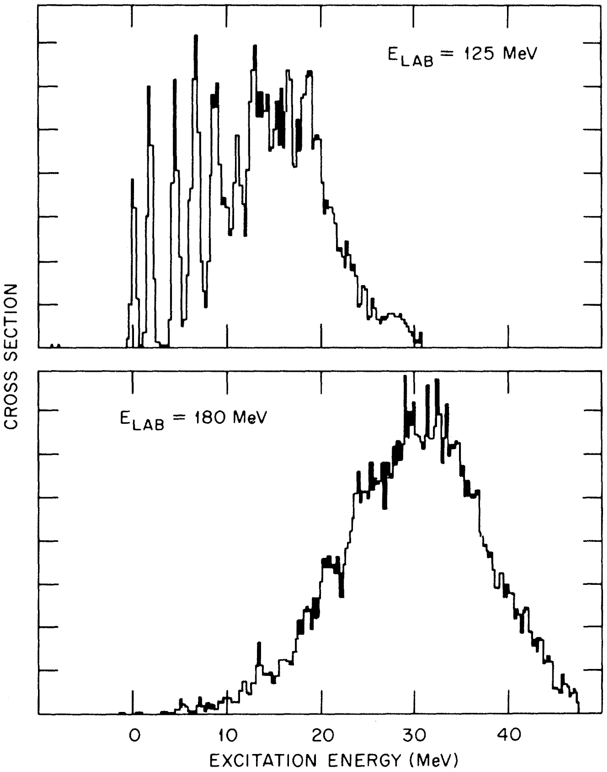

FIG. 1. Excitation energy spectra for carbon nuclei from $^{12}C + ^{28}Si$ backward angle scattering ($\theta_C \simeq 168°$).

energy ($E^f_{\text{kin}} = E_{\text{c.m.}} + \bar{Q}$). The linear dependence on bombarding energy seen at the lower energy range arises from the centrifugal energy of the rotating dinuclear system prior to scission.[4-8] Above an incident energy of 45 MeV (c.m.) we see that the final kinetic energy becomes almost independent of bombarding energy.

A simple interpretation of this sudden change stipulates that at this bombarding energy a value of the angular momentum has been reached beyond which formation of a dinuclear system is not allowed because of centrifugal repulsion. The total nucleus-nucleus potential for the two nuclei in contact can be written

$$V(d) = V_{\text{nucl}}(d) + V_{\text{Coul}}(d) + V_{\text{centr}}(d), \qquad (1)$$

where

$$V_{\text{nucl}}(d) = \frac{R_1 R_2}{R_1 + R_2} g(x), \quad V_{\text{Coul}}(d) = 1.44 \frac{Z_1 Z_2}{d},$$

$$V_{\text{centr}}(d) = \frac{\hbar^2 l_{\text{orb}}(l_{\text{orb}}+1)}{2\mu d^2}, \quad g(x) = \frac{1}{Ae^{x/a} + Be^{x/b}},$$

$d = R_1 + R_2 + x$ is the nucleus-nucleus separation at the time of scission, and l_{orb} is the angular momentum of the dinuclear rotation.

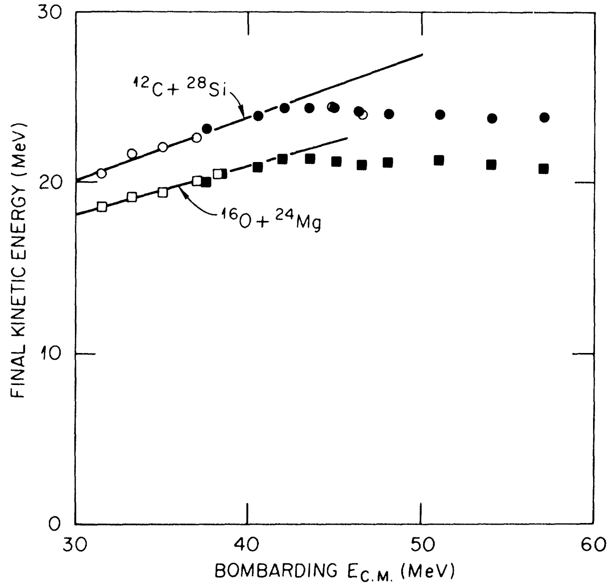

FIG. 2. Bombarding energy dependence of the most probable value of the total kinetic energy of the outgoing fragments for the $^{12}C + ^{28}Si$ and the $^{16}O + ^{24}Mg$ channels. The open and closed data symbols refer to experiments done at different times.

The saturation value for l_{orb} ($\equiv l^s_{\text{orb}}$) can be determined by equating the nucleus-nucleus radial force with zero ($dV/dr|_{r=d} = 0$). The point at which this happens depends to first order on l_{orb}, d, and the nuclear potential parameters.

The saturation value of the total kinetic energy, which equals the magnitude of the nucleus-nucleus potential at scission, was used to determine the maximum angular momentum. By use of the potential shown in Eq. (1) with $d \cong 8$ fm (see Fig. 3) and values of $A = 0.045$, $a = 3.3$, $B = 0.0061$, $b = 0.71$, and a saturation value of 24 MeV for the kinetic energy (see Fig. 2), a saturation angular momentum of $l^s_{\text{orb}} = 19$ was derived. The parameters quoted here differ from those given by Bass but are within the tolerance quoted by him.[1, 11] An additional constraint is provided by the bombarding energy for which the kinetic energy reaches saturation; it should be near 40 MeV center-of-mass bombarding energy for rolling and near 46 MeV for a sticking dinuclear system. It must be emphasized that the saturation value for angular momentum derived here is determined for the nuclei in contact. The cross section for this process comes from a range of incoming partial waves mostly larger than this saturation value. Friction brings about a reduction of the relative kinetic energy and orbital angular momentum in the entrance channel which may

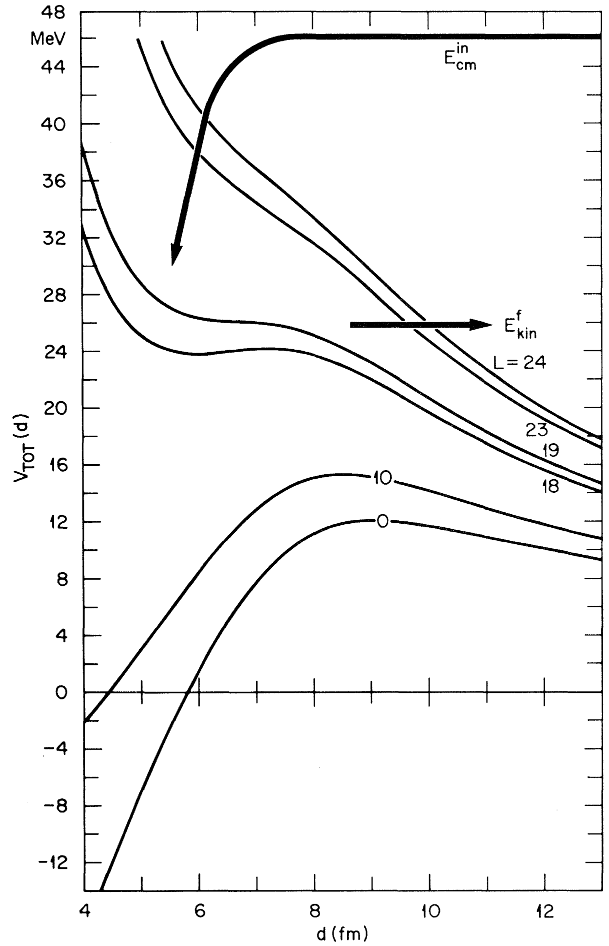

FIG. 3. The $^{12}C + ^{28}Si$ total nucleus-nucleus potential calculated with the parameters quoted in the text.

provide conditions suitable for the formation of a dinuclear system. It is therefore obvious that l^{s}_{orb} determines the value of the maximum angular momentum in the entrance channel only to the extent that dissipative forces are able to reduce the incoming angular momenta to values below l^{s}_{orb}. At higher bombarding energies, near 45 MeV in the center of mass system, the angular momentum in the entrance channel reaches a value ($l_{\mathrm{crit}} \cong 23$) which dissipation can no longer reduce to $l = 19$, a value that can lead to nucleus-nucleus attraction. This value of $l_{\mathrm{crit}} = 23$ is therefore the maximum value of angular momentum in the entrance channel which may lead to fusion or orbiting. The majority of the incoming flux leads to complete fusion; therefore the total fusion cross section will show a $1/E$ dependence at energies above $E_{\mathrm{c.m.}} = 45$ MeV and processes involving partial momentum and angular momentum transfer should become more important.[12]

The classical approach outlined above can only describe the most probable values of the measured macroscopic observables (maxima of the measured distributions). Quantum fluctuations in the shape of the nucleus-nucleus potential or in the energy dissipation process may cause the observed spread in kinetic energy (Q value) around the maximum value (see Fig. 1). A quantum mechanical treatment of the nucleus-nucleus potential must also include absorption—which to first order governs the probability of the orbiting nuclei to fuse rather than separate.

Problems may arise from the fact that only inclusive spectra for detected carbon or oxygen nuclei were measured. Sequential α emission from the projectile, if present, produces carbon nuclei with much lower energy than those observed. The effect of C ions decaying in flight will result in a spectrum where the more negative Q-value (higher excitation energies) yields are suppressed, an effect opposite to the one observed in these data. The data suggest that products from sequential decay of other channels (e.g., $^{16}O^{*} \rightarrow {}^{12}C + \alpha$) do not affect the shape of the carbon spectra significantly; throughout the whole bombarding energy range studied here the yield in the carbon channel remains at least a factor of 5 higher than the second most intense exit channel which is ^{16}O. We also note that the widths of the kinetic energy (or Q value) distributions vary only slightly, and very smoothly, with bombarding energy, and this would not be the case if over the measured energy range a new channel had suddenly opened and contributed significantly to the observed carbon yield. Finally the fact that both the ^{16}O and ^{12}C channels show the same behavior (seen in Fig. 2) indicates that while the data may be slightly weighted by secondary processes the sudden change in the slope of the data near 45 MeV indicates that a fundamental change in the reaction process has occurred.

We therefore suggest that the saturation observed in the kinetic energy of the outgoing fragments reflects a limiting value of angular momentum with which the dinuclear system can rotate. Since the fusion of nuclei must proceed via a contact configuration we expect that the limit on angular momentum derived from analysis along the lines outlined above is related to the critical angular momentum l_{crit} that can lead to fusion of these nuclei. Such information could complement the knowledge of l_{crit} derived from absolute cross sections for compound nucleus formation.[1-3] Measurements of evaporation residues from the fusion of $^{28}Si + ^{12}C$ over the same energy range could further elucidate the relation between critical angular momenta for fusion (l_{crit}) and the saturation angular momentum for the orbiting process (l^{s}_{orb}).

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