Angular Momentum Limits in Fusion Reactions Induced by Argon and Krypton Projectiles

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(Received 1 September 1977)

Evaporation-residue cross sections, A and Z distributions, and γ-ray multiplicities are reported for ^{40}Ar and ^{86}Kr reactions leading to various Er compound nuclei. When combined with previous data the results show an angular momentum limit approximately consistent with the expected onset of fission modified by contributions from charged-particle emission. No evidence is found for an absence of evaporation residues from low-l collisions in the ^{86}Kr cases.

Recently there have been several studies of heavy-ion fusion reactions[1] leading to compound nuclei in the mass region 150–160. These experiments have involved fusion and evaporation-residue (ER) cross-section measurements,[2,3] detailed studies of γ-ray multiplicities,[4-6] and excitation functions for specific xn channels.[7,8] Projectiles ranging from ^{16}O to ^{86}Kr ions were used. In general, experiments which measure average quantities such as σ_{ER} and the number of γ rays in the deexcitation of the ER products do not show significant differences between cases where similar compound nuclei are formed with a variety of bombarding particles. However, detailed studies of threshold behavior for specific xn channels[7] and of higher moments of the γ multiplicity distributions[5] seem to show definite nonequilibrium effects.

This Letter reports new experimental results for evaporation residues from Er compound systems ($A = 154–164$) at $E^* = 50–120$ MeV following ^{40}Ar and ^{86}Kr bombardments of Sn and Ge targets. Cross sections and detailed mass and charge distributions have been measured for ER products from $^{86}\text{Kr} + {}^{70,74}\text{Ge}$ reactions at the Lawrence Berkeley Laboratory SuperHILAC. At the Gesellschaft für Schwerionenforschung Unilac, γ-ray multiplicity distributions have been studied for $^{86}\text{Kr} + {}^{76}\text{Ge}$ and $^{40}\text{Ar} + {}^{122,124}\text{Sn}$. The results are combined with previous data on ER cross section, A and Z distributions[9] from $^{86}\text{Kr} + {}^{65}\text{Cu}$, and cross sections[2,3] for the ^{40}Ar bombardment of ^{109}Ag and ^{121}Sb.

The measurements of γ-ray multiplicity distributions used a multidetector array consisting of fourteen NaI detectors and two Ge(Li) detectors.[4] The σ_{ER} and the A and Z distributions resulted from direct measurements of the yield, velocity, dE/dx, and total energy of the ER products. Details are given in Refs. 2, 4, and 9.

From σ_{ER} and multiplicity measurements[5] for these same Er compound systems formed by ^{16}O and ^{32}S bombardments, it has been shown that the average angular momentum of the ER products, $\bar{l}$, can be related to the measured average γ-ray multiplicity $\bar{M}_\gamma$, by the empirical relationship

$$\bar{l} = 2(\bar{M}_\gamma - 4). \tag{1}$$

In general the ER cross section is given by

$$\sigma_{ER} = \pi\lambdabar^2 \sum_{l=0}^{\infty} (2l+1) P_{\text{fusion}} (1 - P_{\text{fission}}). \tag{2}$$

In a sharp-cutoff approximation, $P_{\text{fusion}} = 1$ for $l \leq l_{cr}$ and 0 for $l > l_{cr}$, and $P_{\text{fission}} = 0$ for $l \leq l_f$ and 1 for $l > l_f$, where l_{cr} is the critical angular momentum for fusion and l_f is the value above which the fused nuclei decay by fission instead of forming ER products. Then a quantity l_{max} for ER products can be derived from σ_{ER} using the relationship

$$l_{\text{max}} = (\sigma_{ER}/\pi\lambdabar^2)^{1/2}. \tag{3}$$

If the same $(2l+1)$ partial-cross-section distribution is assumed for the γ multiplicity measurements then l_{max} can be obtained from the relationship

$$\bar{l}_{\text{max}} = 3\bar{l}/2. \tag{4}$$

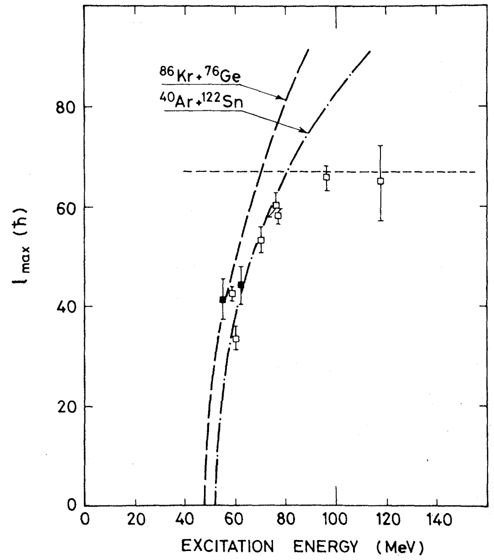

FIG. 1. Plot of l_{max} determined from γ-ray multiplicity measurements as described in the text vs the compound-nucleus excitation energy for $^{86}Kr + {}^{76}Ge$ (solid points) and $^{40}Ar + {}^{122,124}Sn$ (open points). The two heavy dashed curves indicate the predicted l_{max} vs E^* assuming the Bass potential and the incoming-wave boundary condition. The horizontal line denotes the angular momentum at which the fission barrier of a rotating liquid drop equals the B_n for ^{162}Er.

Figure 1 shows the result from the γ multiplicity measurements converted into angular momentum via Eqs. (1) and (4). The lines represent a calculation based on the Bass potential[10] and an incoming-wave boundary (IWB) condition discussed by Broda *et al.*[11] It is seen from the figure that the trend of the angular momentum input predicted by the calculation is reproduced by the data up to $l \approx 65\hbar$ only, where an apparent limit is reached from the Ar-induced reactions. The observed limit is close to the angular momentum for which the fission barrier of a rotating liquid drop[12] equals the neutron binding energy of the compound system (see Fig. 1).

Figure 2(a) shows results for l_{max} obtained using both σ_{ER} measurements and $\bar{M}_\gamma$ results from the present studies and from previous σ_{ER} mea-

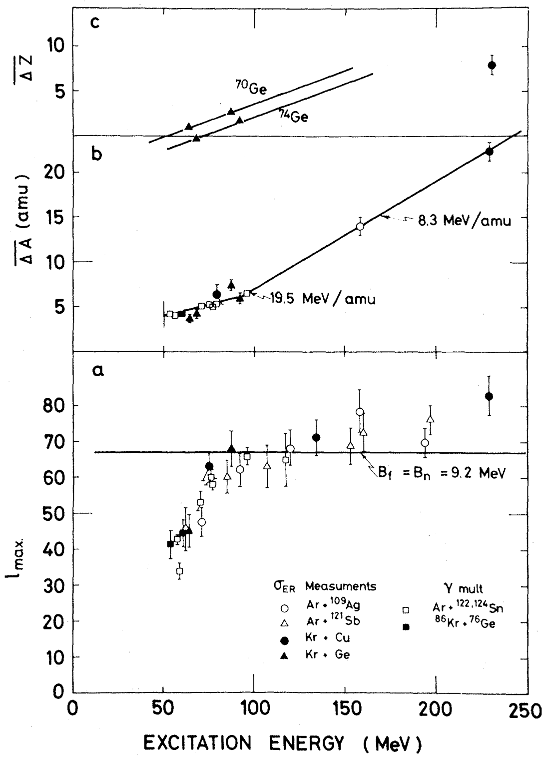

FIG. 2. Plot of (a) l_{max}, (b) average evaporated mass, and (c) average evaporated charge as a function of the excitation of the compound nucleus for evaporation residues formed by ^{40}Ar bombardments of ^{109}Ag, ^{121}Sb, and $^{122,124}Sn$, and by $^{84,86}Kr$ bombardments of ^{65}Cu, and $^{70,74,76}Ge$. The data included are from γ-ray multiplicity measurements discussed in the text and from measurements of the yield and A, Z of the evaporation residues from the present and previous measurements (Refs. 2, 3, 14). The angular momentum at which the rotating-liquid-drop fission barrier equals the B_n for ^{162}Er is indicated for comparison in (a).

surements.[2,3] Several major characteristics are illustrated: (i) The values obtained for $l_{\max}$ from the $\bar{M}_\gamma$ and σ_{ER} measurements are consistent indicating the validity of Eq. (1) for these heavier projectiles. (ii) From *both* $\bar{M}_\gamma$ and σ_{ER} measurements we find $l_{\max}$ values which agree when the same system is formed at the same excitation energy using ^{40}Ar and ^{86}Kr projectiles. This agreement reflects the experimental result that a particular E^* neither $\sigma_{\mathrm{ER}}/\pi\lambda\!\!\!^{-2}$ nor $\bar{M}_\gamma$ depend on the projectile. At $E^* > 80$ MeV it seems reasonable to postulate that $l_{\max}$ will be determined by fission competition and, therefore, reach a limit of $\sim 65\hbar$. If all l values below $40\hbar$ were excluded from fusion in ^{86}Kr but not in ^{40}Ar bombardments[13] the experiments should show $(\sigma_{\mathrm{ER}}/\pi\lambda\!\!\!^{-2})_{\mathrm{Kr}} \sim \frac{1}{2}(\sigma_{\mathrm{ER}}/\pi\lambda\!\!\!^{-2})_{\mathrm{Ar}}$ and $(\bar{M}_\gamma)_{\mathrm{Kr}} \sim (\bar{M}_\gamma)_{\mathrm{Ar}} + 5.1$. The data in Fig. 2(a) are not consistent with a low-l-value window of this magnitude. (iii) In the energy region 100–250 MeV the values of $l_{\max}$ continue to rise slowly from $\sim 65\hbar$ to $\sim 80\hbar$ indicating that at the highest energies there is significant initial population of values which might be expected to decay primarily by fission but which instead end up as ER products. This result may indicate that at the highest energies for l values of the order of $80\hbar$ particles compete favorably with fission decay so that there is a significant probability for removing angular momentum before the system becomes unstable toward fission. Significant angular momentum removal could most easily be accomplished by α-particle emission either from the equilibrated compound nucleus or possibly as a preequilibrium process occuring during the time required to fuse the two large nuclei into a compound system.

Figure 2(b) shows the average number of nucleons emitted from the ER products as a function of excitation energy. Results have been obtained from the time-of-flight measurements, from the relative cross sections for various ER products in the γ multiplicity measurements, and from a radiochemical measurement[14] for ^{40}Ar + ^{109}Ag. Results from the various techniques seem to agree quite well. In the region of $E^* = 53$–93 MeV $\overline{\Delta A}$ changes from 4 to 6.2 amu, implying a slope of 19.5 MeV/amu in this region. For $E^* > 100$ MeV the excitation energy per nucleon emitted is found to be ~ 8.3 MeV/amu. Between 50 and 100 MeV the excitation energy is divided between particle emission and the increase in γ-ray emission resulting from $l_{\max}$ changing from 0 to $65\hbar$ while above 100 MeV the estimated total γ-ray energy reaches an approximately constant value. The value of 19.5 MeV required per emitted nucleon below the angular momentum limit can be reproduced by statistical calculations using rotational energies that assume an yrast line with a rigid moment of inertia. Above 100 MeV the observed slope appears to be too small to be explained by the evaporation of nucleons alone and at ~ 230 MeV the results suggest the evaporation of 1–2 α particles. An estimate of the reaction barrier is indicated in Fig. 2(b) by the vertical solid line. At this point only low l values are allowed and the $E^* = 50$ MeV is partitioned between ~ 35 MeV for the binding energy of four neutrons, ~ 8–9 MeV for neutron kinetic energies, and ~ 6–7 MeV for statistical γ rays.

Figure 2(c) shows the results obtained from the average charge emitted $(\overline{\Delta Z})$ in the deexcitation of the compound systems formed in Kr bombardments. The results show (i) that $\overline{\Delta Z}$ increases rapidly with increasing excitation energy and (ii) at the same excitation energy $\overline{\Delta Z}$ is ~ 1.5 units greater for the deexcitation of ^{156}Er than for ^{160}Er. Both of these results are caused by the systematic decrease in B_p and increase in B_n as the products become more neutron deficient. Despite systematic changes in $\overline{\Delta Z}$ the quantity $\overline{\Delta A}$ remains approximately a function of E^* because the protons are only emitted in significant numbers when their binding energies have decreased to the point where the total energy release is similar to neutron emission. Because of the variation in $\overline{\Delta Z}$ the method of summing cross section from different systems used to obtain $\sum \sigma(xn)$ in Ref. 7 is probably not correct. As a consequence, values of $\overline{\Delta Z}$ that can be deduced from Figs. 2 and 3 of Ref. 7 are systematically lower by 1–2 amu than the results shown in Fig. 2(b).

In addition, the multiplicity measurements show the M_γ values for specific channels excited by Ar and Kr projectiles are approximately equal for systems excited to the same excitation energy. This result is again inconsistent with the postulate[13] that the lowest 40 l waves do not fuse in Kr bombardments. A similar conclusion has been stated by Simon *et al.*[6] from a comparison of γ-multiplicity results for Yb ER products formed ^{16}O, ^{40}Ar, and ^{86}Kr reactions.

The fact that $l_{\max}$ continues to rise slowly for $E^* > 100$ MeV and that there are differences[7] in cross sections and apparent thresholds for specific xn channels from Ar and Kr bombardments may indicate the presence of nonequilibrium effects in the decay of the ER products. The observed effects could be consistent with the emission of a few preequilibrium charged particles with this probability being dependent on both the excitation energy and the bombarding particle. Model calculations qualitatively consistent with this speculation have been published.[15] For the very-neutron-deficient systems studied in Ref. 7 the threshold shifts may be due to an increased preequilibrium charged-particle emission when nuclei are excited at low angular momenta with Kr projectiles. Some cross section from low l values is then shifted from xn to (yp,xn) channels. Since we are dealing primarily with neutron-deficient nuclei and since charged-particle emission is generally limited by a Coulomb barrier it may be reasonable to expect that deexcitation which might take place from a fused system before it reaches equilibrium could lead to an increase in charged-particle emission both for this low-E^*, neutron-deficient case, and for the $E^* > 100$ MeV region discussed above.

This work has been supported in part by the U. S. Energy Research and Development Administration under contract to the University of California and the Union Carbide Corp., by the Danish National Science Research Council, and by the Japan World Exposition Commemorative Fund.

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