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Fusion of heavy nuclei

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Cross sections for evaporation residue fromation following complete fusion of $^{81}Br+^{90,94}Zr$, ^{96}Mo, and ^{104}Ru and $^{90}Zr+^{90,94}Zr$ have been measured over a broad range of energies from far below to well above the classical Coulomb barrier. We observe large changes of slope and magnitude among the excitation functions for these systems at all energies. There are pronounced structural variations at sub-barrier energies, less rapid than expected increases in evaporation residue formation at near-barrier energies and declining evaporation residue formation as the systems become heavier at still higher energies.

Recent studies[1–12] of the sub-barrier fusion of heavy ions have provided new information on the nuclear physics taking place when two atomic nuclei come together. The information is contained both in the pronounced variations observed among excitation functions for different collision partners and in the overall shape and magnitude of the excitation functions. In this Rapid Communication we report results of a study of near- and sub-barrier fusion in the heavy symmetric and nearly symmetric $^{81}Br+^{90,94}Zr$, ^{96}Mo, and ^{104}Ru and $^{90}Zr+^{90,94}Zr$ systems. These systems are heavier than those examined previously in detail yet have fission barriers which were high enough to enable us to determine the complete fusion cross sections unambiguously over a broad range of energies from measurements of the evaporation residue cross sections (see Table I).

In the experiments 280 to 350 MeV ^{81}Br and 333 to 365 MeV ^{90}Zr beams were provided by the Brookhaven National Laboratory tandem Van de Graaff accelerator facility. These beams were used to bombard thin 120 to 160 $\mu g/cm^2$ $^{90,94}Zr$, 110 $\mu g/cm^2$ ^{96}Mo and 125 $\mu g/cm^2$ ^{104}Ru targets. The forward-recoiling evaporation residues were detected in a $\Delta E-E$ proportional counter telescope placed at the focus of the Massachusetts Institute of Technology–Brookhaven National Laboratory velocity selector system. Absolute cross sections were obtained by normalizing the evaporation residue yields to Rutherford scattering yields detected in a pair of silicon surface barrier detectors (monitors) placed 22° to the beam axis in the target chamber. Details concerning the experimental technique have been presented elsewhere.[2,7]

The targets were prepared by vacuum evaporation from reduced powders enriched to 99.4% (^{90}Zr), 98.6% (^{94}Zr), 96.8% (^{96}Mo), and 99.7% (^{104}Ru). Backings were typically 15 $\mu g/cm^2$ Formvar and/or carbon. The ^{90}Zr beam source was fabricated from the same sample as the ^{90}Zr targets. To insure proper beam identification, calibration measurements were performed in which various single-stripped ^{81}Br and ^{90}Zr beams were elastically scattered from ^{181}Ta targets.

TABLE I. Global fusion and fission characteristics of the systems studied. Listed in column 3 are effective entrance channel fissilities and listed in column 4 are finite-range fission barrier heights.

System	Compound Nucleus	$(Z^2/A)_{mean}$ [a]	B_{fiss} [b]
$^{81}Br+^{90}Zr$	^{171}Re	32.8	16.1
$^{81}Br+^{94}Zr$	^{175}Re	32.1	17.6
$^{81}Br+^{96}Mo$	^{177}Ir	33.4	14.4
$^{81}Br+^{104}Ru$	^{185}Au	33.6	(13.3)
$^{90}Zr+^{90}Zr$	^{180}Hg	35.6	9.9
$^{90}Zr+^{94}Zr$	^{184}Hg	34.8	11.2

[a] $(Z^2/A)_{mean}=[(Z^2/A)_{eff}(Z^2/A)_{cn}]^{1/2}$ (Ref. 13). $(Z^2/A)_{cn}$ denotes the compound nucleus value. $(Z^2/A)_{eff}=4Z_TZ_P/A_T^{1/3}A_P^{1/3}(A_T^{1/3}+A_P^{1/3})$ (Ref. 14).
[b] Reference 15.

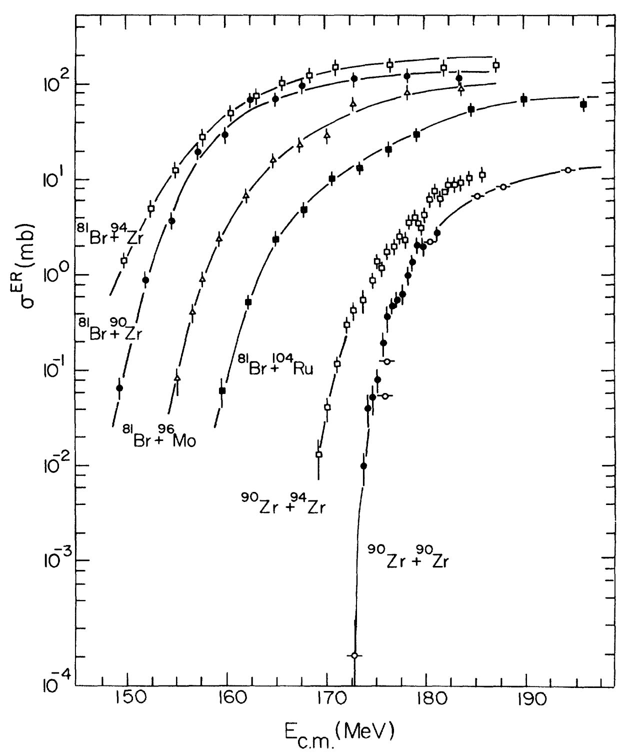

FIG. 1. Excitation functions for evaporation residue formation. The abscissa denotes the weighted average center-of-mass energies. Data for the $^{90}Zr+^{90}Zr$ system from Ref. 18 are included as open circles with horizontal bars giving the corresponding energy uncertainty. Smooth lines are visual guides and are not fits to the data.

Proper ion energy and the absence of satellite beams were confirmed during the fusion measurements by monitoring the well-separated elastic scattering from the 3 to 9% tungsten deposited in the targets during fabrication. We observed larger yields in the $^{90}Zr+^{90,94}Zr$ systems, at energies above 360 MeV, than in our first measurements.[16] The lower initial yields were found to be due to large inhomogeneities in the Formvar backings. In addition, we found that an overall numerical error had been made in Refs. 16 and 17 in the data analysis. The error is restricted to the results reported in Refs. 16 and 17.

The new plus revised cross sections for evaporation residue formation following complete fusion of $^{81}Br+^{90,94}Zr$, ^{96}Mo, and ^{104}Ru and $^{90}Zr+^{90,94}Zr$ are displayed in Fig. 1. Included in the figure are the results from Ref. 18 for the $^{90}Zr+^{90}Zr$ system. Those cross sections are in good agreement with ours. We observe in Fig. 1 that, unlike the behavior exhibited by cross sections for less massive systems, the excitation functions for the ^{81}Br and ^{90}Zr systems do not approach one another at above-barrier energies. Instead, the cross sections tend to level off at progressively lower values as the systems become heavier. For $^{81}Br+^{90,94}Zr$ the cross sections plateau in the 120 to 170 mb range; for $^{90}Zr+^{90}Zr$ the cross sections only reach the 10 mb level.

We further observe that the slopes of the excitation functions for the ^{81}Br systems become progressively shallower as we go from $^{90,94}Zr$ to ^{96}Mo to ^{104}Ru, even at energies well below those where saturation sets in. We display the data for the four ^{81}Br systems in Fig. 2 as a function of $E_{c.m.}-V_0$. We see that the changes in slope are large enough to produce crossovers of the excitation functions. To provide a quantitative measure of the slopes, phenomenological fits were done over the energy range from just above the barrier up to, but not including, the plateau region in the manner described in Ref. 6. The barrier radii r_0 which characterize the slopes were found to range from ~ 0.8 fm ($^{81}Br+^{94}Zr$) to ~ 0.6 fm ($^{81}Br+^{104}Ru$). For comparison, values for r_0 in the range 1.0 to 1.1 fm were extracted[6,7] from fits to data in the Ni+Ni to Ge+Ge region.

In Table I we have listed the finite-range fission barriers[15] for the systems under study. These barriers, together with a_f/a_ν values in the range 1.02 to 1.03, have been shown[19–21] to describe the competition between fission and evaporation residue formation in nuclei in the vicinity of $A=180$. To determine at what point fission competition sets in, and at what value evaporation residue formation saturates due to fission competition, we performed statistical model calculations using the aforementioned constants.

We also performed calculations in which an extra-push energy, dependent upon $(Z^2/A)_{\rm eff}$ and angular momentum,

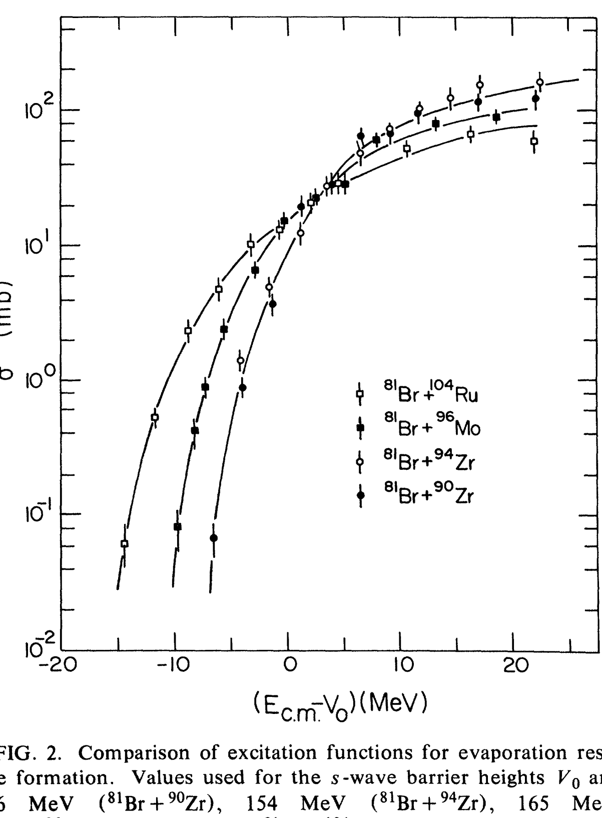

FIG. 2. Comparison of excitation functions for evaporation residue formation. Values used for the s-wave barrier heights V_0 are 156 MeV ($^{81}Br+^{90}Zr$), 154 MeV ($^{81}Br+^{94}Zr$), 165 MeV ($^{81}Br+^{96}Mo$), and 174 MeV ($^{81}Br+^{104}Ru$). Smooth lines are visual guides. To maintain visual clarity only one guide line has been drawn for $^{81}Br+^{90,94}Zr$ and several data points for $^{81}Br+^{104}Ru$ have been offset slightly to the left.

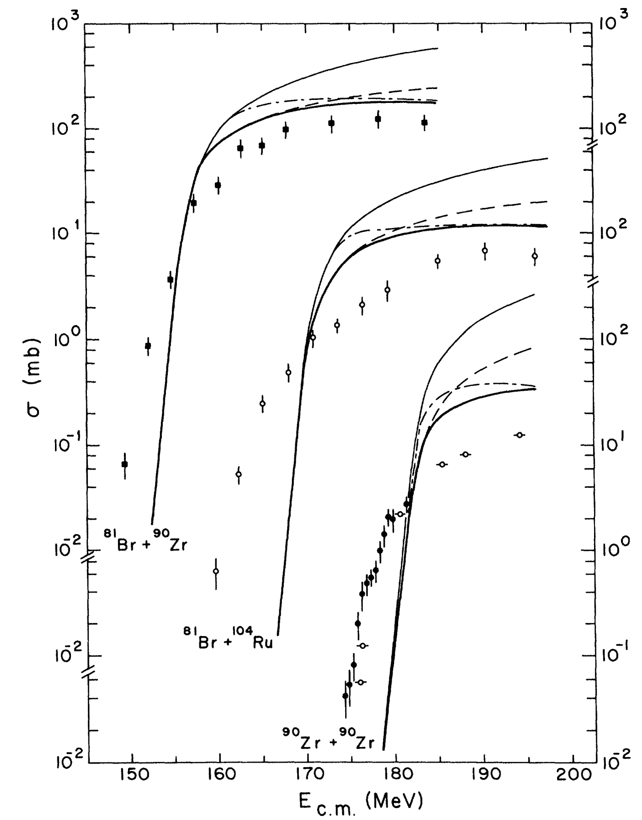

FIG. 3. Comparison of experimental and calculated excitation functions. Thin solid lines denote excitation functions for complete fusion with V_0 ($^{81}Br+^{90}Zr$) = 156 MeV, and the others scaled proportionately giving V_0 ($^{81}Br+^{104}Ru$) = 170 MeV and V_0 ($^{90}Zr+^{90}Zr$) = 182 MeV. Dashed-dotted lines denote cross sections for evaporation residue formation; dashed lines represent complete fusion including the extra push; heavy solid lines give the evaporation residue cross sections taking into account the extra push. The two lowest energy $^{90}Zr+^{90}Zr$ data points have been omitted for display purposes.

was incorporated into the standard[6] expression for the transmission coefficients. In Refs. 22–25 the behavior of fissionlike and fusion excitation functions for fairly asymmetric target-projectile combinations and energies well above the barrier was interpreted in terms of an extra-push model of dynamic deformations.[26,27] In our calculations we employed values for the threshold effective fissility $\beta = 33 \pm 1$ and corresponding slope constant $a = 12 \pm 1$ deduced in Ref. 27 from fits to the fissionlike data of Ref. 22, and examined further in Refs. 23–25.

The results of the fission and extra push calculations are compared with the data for the $^{81}Br + ^{90}Zr$, $^{81}Br + ^{104}Ru$, and $^{90}Zr + ^{90}Zr$ systems in Fig. 3. In the fusion calculations performed using the WKB method we generated interaction potentials using both Krappe-Nix-Sierk[28] and Akyüz-Winther[29] nuclear potentials. We then renormalized the s-wave barrier heights to the experimental values. Shown in Fig. 3 are fusion cross sections, fusion cross sections including extra push, evaporation residue cross sections, and evaporation residue cross sections including extra push.

We observe in the figure that the calculated excitation functions for evaporation residue formation including the extra push have the correct shape at the highest energies. However, the cross sections are predicted to saturate at values from 50% to a factor of 3 higher than observed experimentally. Fission competition sets in at cross section levels higher than those for which the small r_0 values were deduced. Extra-push influences become appreciable at lower energies than fission competition and produce a decrease in slope at energies near the barrier. These predicted influences are not strong enough to bring the calculations into agreement with the data. Finally, we note that fission competition provides the overall limit to evaporation residue formation at the highest energies.

In the above, no parameter adjustments were attempted. One can vary (decrease) the fission barrier heights until agreement with the saturation cross sections is achieved, as was done in Ref. 18.[30] Also, one can increase the strength of the extra push.[31] An alternative possibility is that the single-particle processes which are strong at sub-barrier energies (Fig. 2) extend to energies where the excitation functions were described in terms of small r_0 values. There is support for this possibility in recent studies of heavy systems in which large quasielastic proton[32] and neutron[33] transfer yields were observed at energies not too far above the barrier.

To summarize, we have measured cross sections for evaporation residue formation following complete fusion of $^{81}Br + ^{90,94}Zr$, ^{96}Mo, and ^{104}Ru and $^{90}Zr + ^{90,94}Zr$ over a broad range of energies from far below to well above the Coulomb barrier. We observe pronounced variations among the excitation functions for these cold heavy symmetric and nearly symmetric systems at all energies. At the lowest energies the variations appear to be single particle in character. At near- and above-barrier energies a new feature appears—the increases in evaporation residue formation are less rapid than expected. This may not be due to fission competition, but instead may be a consequence of dynamic processes which remove flux from the fusion channel. Further study, both theoretical and experimental, is needed to understand the relative importance of strong and weak contact processes, and their consequences, when heavy nuclei come together.

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[30]In Ref. 18 the fission barrier for $^{90}Zr + ^{90}Zr$ was lowered to 8.0 MeV, ~80% of the finite-range value of 9.9 MeV. (It is 74% of the rotating liquid drop value.)

[31]In Ref. 16 an extra-push energy for the $^{90}Zr + ^{90}Zr$ system of 10.5 ± 3.0 MeV was deduced. This large value is not required to describe the revised $^{90}Zr + ^{90}Zr$ data.

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