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Author
Mathews, G.J.

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Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA, BERKELEY, CA

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G. J. Mathews and L. G. Moretto

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G. J. Mathews and L. G. Moretto

Nuclear Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

ABSTRACT

We show that the width for thermal barrier penetration (Γ_{out}) of a classically trapped (complete-fusion) trajectory can be important and that this decay mode may explain the enchanced fusion-fission yield observed in some systems.

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Among the reaction channels available during the collision of relatively light projectiles ($A \lesssim 40$) with nuclei, one of the most widely studied has been the so called complete-fusion process [1,2] whereby for low partial waves the projectile can be completely absorbed and subsequent reaction products appear either as evaporation residues or an equilibrium binary fission-like mass distribution.

Numerous classical theoretical models [1-4] have been proposed to account for the systematics of experimental complete-fusion cross sections. These models usually involve classical trajectory calculations on the two-nucleus potential similar to that sketched in Figure 1. This total effective potential (coulomb + nuclear + rotational energy) as a function of internuclear distance can have a minimum or a pocket. If dissipative forces act between the two ions, the classical trajectory may become trapped within the pocket. Generally it is considered that these trapped trajectories have no probability of penetrating back over the barrier and instead rapidly relax into the compound nucleus equilibrium configuration. We wish to emphasize a warning in this letter that neither is the width for the system to cross back over the barrier vanishingly small nor is the width for the system to relax into the compound-nucleus overwhelming. The formation of the compound nucleus involves a complicated shape evolution of the system. This shape evolution may be hindered if the viscosity of the system is large (as the current popular view of one-body dissipation seems to imply [5]), or may not happen because of potential energy considerations. For example, the evolution along the mass-asymmetry coordinate may in fact drive the system towards symmetry rather than compound nucleus.

If this happens, an initially trapped system may become unbound since the Coulomb repulsion increases for more symmetric configurations. Another important consideration is that even though the classical trajectory may be trapped, the dissipated energy remains within the system. This means that sufficient energy is available for the system to overcome the barrier and reemit fragments (see Figure 1). The only reason that this binary decay appears hindered is that the fraction of phase space occupied by those states of the system which would lead to the emission of fragments may be small.

In this letter we show, however, that this fraction of phase space may not be neligible. In particular, we derive here an expression for the thermal penetration width (Γ_{out}) of a trapped system of two overlapping spherical heavy nuclei and show that this width can be quite large. Furthermore we argue that this binary decay from the pocket in the potential may be responsible for observed enhanced fusion-fission yields [6-8].

The width for the thermal barrier penetration of a trapped partial wave can be written in complete analogy with the fission width as

$$\Gamma_{out} = \left[\frac{1}{\frac{2\pi}{h} \iint \rho_M (E - \frac{p^2}{2\mu} - \frac{1}{2} ax^2) dx dp} \right] \int_0^{E-B} \rho_B(E-\varepsilon) d\varepsilon \quad . \tag{1}$$

The level density, ρ_M, is calculated at the minimum of the potential pocket. The phase space associated with collective vibrational motion of the system against the barrier is considered explicitly in the integration over dxdp. ρ_B is the level density at the top of the barrier. The integration over ε accounts for the phase space associated with the decay coordinate. The fairly minor correction due to quantum barrier penetration has been neglected.

Expanding the level densities so that

$$\rho(E-\varepsilon) = \rho(E)\exp\left(-\varepsilon/T\right), \tag{2}$$

then Eq. (1) simplifies to,

$$\Gamma_{out} = \frac{T\rho_B(E-B)}{\frac{2\pi}{\hbar}\sqrt{\frac{\mu}{a}}\,T\,\rho_M(E)} \cong \hbar\omega\exp(-B/T), \tag{3}$$

where $\hbar\omega$ is the vibrational phonon energy and T is the statistical temperature.

From Eq. (3) we see that when the barrier vanishes the width is just $\hbar\omega$ and corresponds to the lifetime of the system to oscillate in and out against the potential. Furthermore, this width remains large up to barrier heights on the order of the statistical temperature. Therefore certainly in the neighborhood of the highest trapped ℓ-wave this decay width should be important, and depending upon the timescale for the evolution of the system toward compound nucleus, may continue to be important for lower ℓ-waves.

In summary, we have argued that for a variety of reasons fusion-fission events may arise from a configuration more closely represented by the ion-ion effective potential than the rotating compound-nucleus potential. This is significant because the former decay mode competes much more favorably with neutron emission and would therefore cause an enhancement of the apparent fusion-fission yield. A possible illustration of this effect may already exist in the data.

It has been realized [6-8] that for some systems the observed fusion-fission yield is too high to be accounted for in terms of ordinary compound-nucleus fission in competition with neutron emission. For example it was noted in ref. [6] that in order to reproduce the observed cross section for the symmetric fission-like component in the mass distribution from the ^{40}Ar + Ag reaction it was surprisingly necessary to decrease the liquid-drop fission barrier by 40%. We would argue that the reason for requiring such a reduction is not due to a failure of the liquid-drop model but rather that the system may be decaying from a configuration other than the compound nucleus. The yield will still appear as a symmetric fission-like distribution if the lifetime for this decay is longer than the time scale for mass equilibration of the system. Nevertheless the lifetime for decay may still be short compared to the neutron emission lifetime if the barrier is low enough. In Figure 2 the rotating liquid-drop fission barriers [6,9] are compared with the barrier heights for the dinuclear system computed with a nuclear interaction given by the proximity potential [10]. Figure 2 shows that at all angular momenta the barrier associated with the potential pocket is smaller than the corresponding compound nucleus barrier, thus allowing for a larger decay width.

We can place the above discussion on somewhat more quantitative ground by calculating the charge distribution for this system. To do this we employ the framework of the diffusion model of Moretto and

Sventek [11,12] whereby the time evolution of the population, Φ_z, at a given asymmetry, z, is given by the solution to the master equation,

$$\dot{\Phi}_z(t) = \sum_{z' = z\pm 1} \left[\Lambda_{zz'} \Phi_{z'}(t) - \Lambda_{zz'} \Phi_z(t) \right] . \qquad (4)$$

The transition probabilities, $\Lambda_{zz'}$ we write as

$$\Lambda_{zz'} = \frac{\kappa f \; \rho_{z'}(E_{z'})}{\rho_z(E_z) + \rho_{z'}(E_{z'})} . \qquad (5)$$

The average transition flux, κ, and the form factor, f, we take from the proximity formulation [11,13]. Theoretical justification for this form for $\Lambda_{zz'}$ is found in ref.[14]. The charge distribution is given by,

$$\sigma_z = \pi \lambda\!\!\!^{-2} \sum_{\ell} (2\ell+1) \int \Phi_z(t) \, \Pi(t) dt, \qquad (6)$$

where $\Pi(t)$ is a lifetime distribution which we take [12] as a gaussian centered about a mean lifetime τ_ℓ and with a width $\sigma^2 = 2T$. The mean lifetime we compute by solving the equations of motion for the entrance-channel asymmetry under the influence of the proximity potential [10] and proximity friction [13]. If this classical trajectory is trapped, however, we compute the lifetime from Γ_{out} of Eq. (3). In practice these lifetimes are fairly large so that considerable computing expense is required to solve the master equation. Fortunately, however, the lifetimes of the trapped trajectories are sufficiently long compared to the mass equilibration time (although still short compared to the neutron emission time) that the equilibrium limit of Eqs. (4) and (6) can be imposed so that,

$$\sigma_z = \pi \lambda^2 \sum_{\ell} (2\ell+1) \frac{\rho_z(E_z)}{\sum_z \rho_z(E_z)} . \qquad (7)$$

The level densities, ρ_z, apply to the scission point of the two ions. We adjust the scission radius by adding a constant to the sum of the half-density radii of the two fragments. In this way deformation of the fragments in the exit channel is approximately introduced.

In Figure 3 we compare experimental results [15,16] with a calculation of the 170-Mev $^{40}Ar + ^{108}Ag$ reaction. The fit to the data is quite satisfactory and easily reproduces both the deep-inelastic peak near the projectile and the fission-like peak near symmetry. It is interesting to also note in passing that the evaporation residue cross section, σ_{ER}, is generated naturally in this calculation by treating the compound nucleus as one of the available asymmetries in Eq. (7). We obtain σ_{ER}^{calc} = 426 mb which is in good agreement with the experimental value σ_{ER}^{exp} = 435 $\pm$ 70 mb [16].

So in conclusion we have introduced here arguments that the width for thermal barrier penetration from a configuration represented by two ions trapped in a potential pocket may be important. Furthermore we have seen that introducing such an hypothesis can lead to a natural explanation for the enhanced fusion-fission yield observed in some systems.

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FIGURE CAPTIONS

Figure 1. A schematic view of a parital wave which leads to complete fusion.

Figure 2. Barrier heights for two overlapping spherical nuclei and the rotating compound nucleus [9] as a function of incident angular momentum for the 170-Mev $^{40}Ar + ^{108}Ag$ reaction.

Figure 3. Experimental and calculated charge distributions for the 170-Mev $^{40}Ar + ^{108}Ag$ reaction.

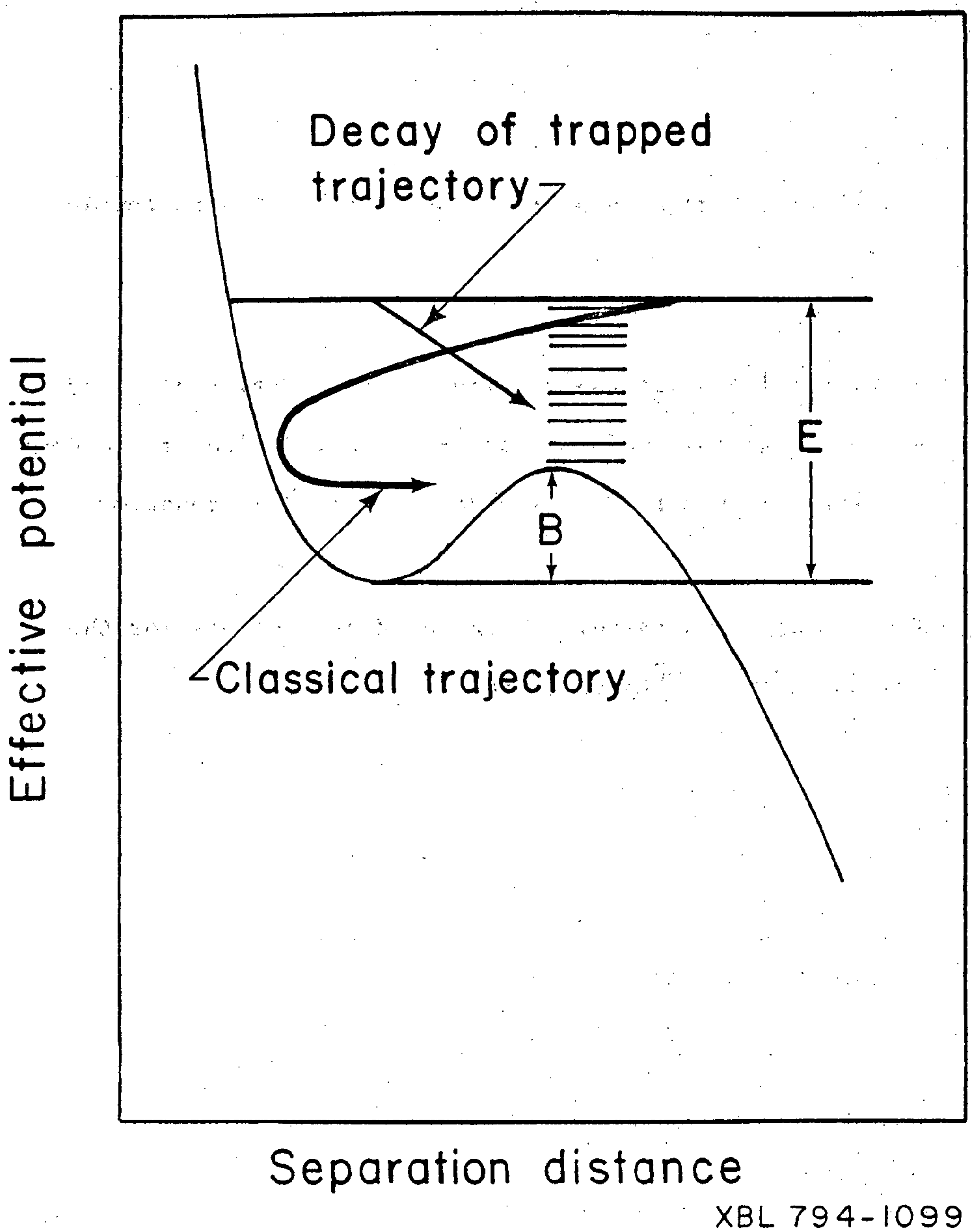

Decay of trapped trajectory
E
B
Classical trajectory
Effective potential
Separation distance
XBL 794-1099

Fig. 1

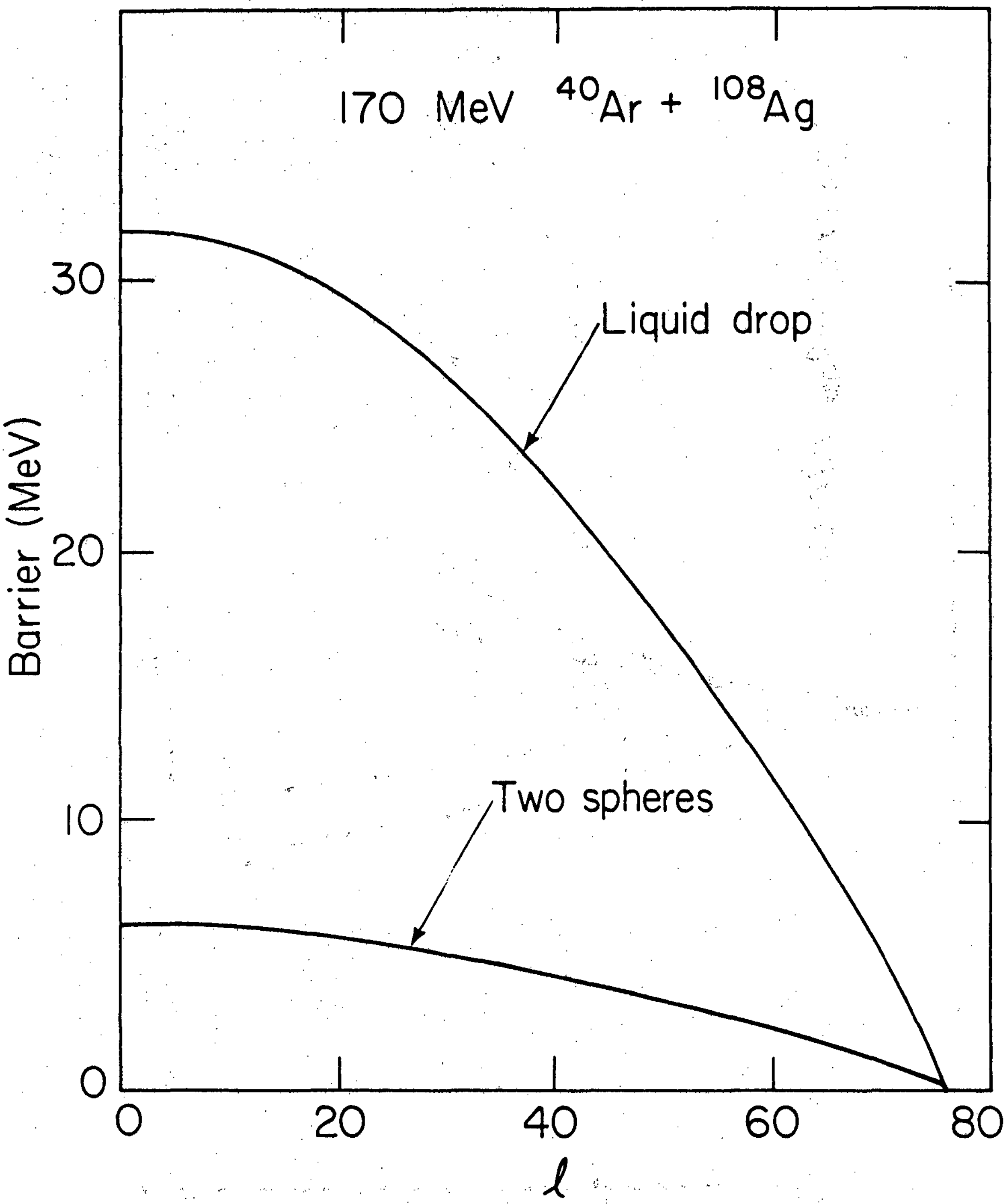
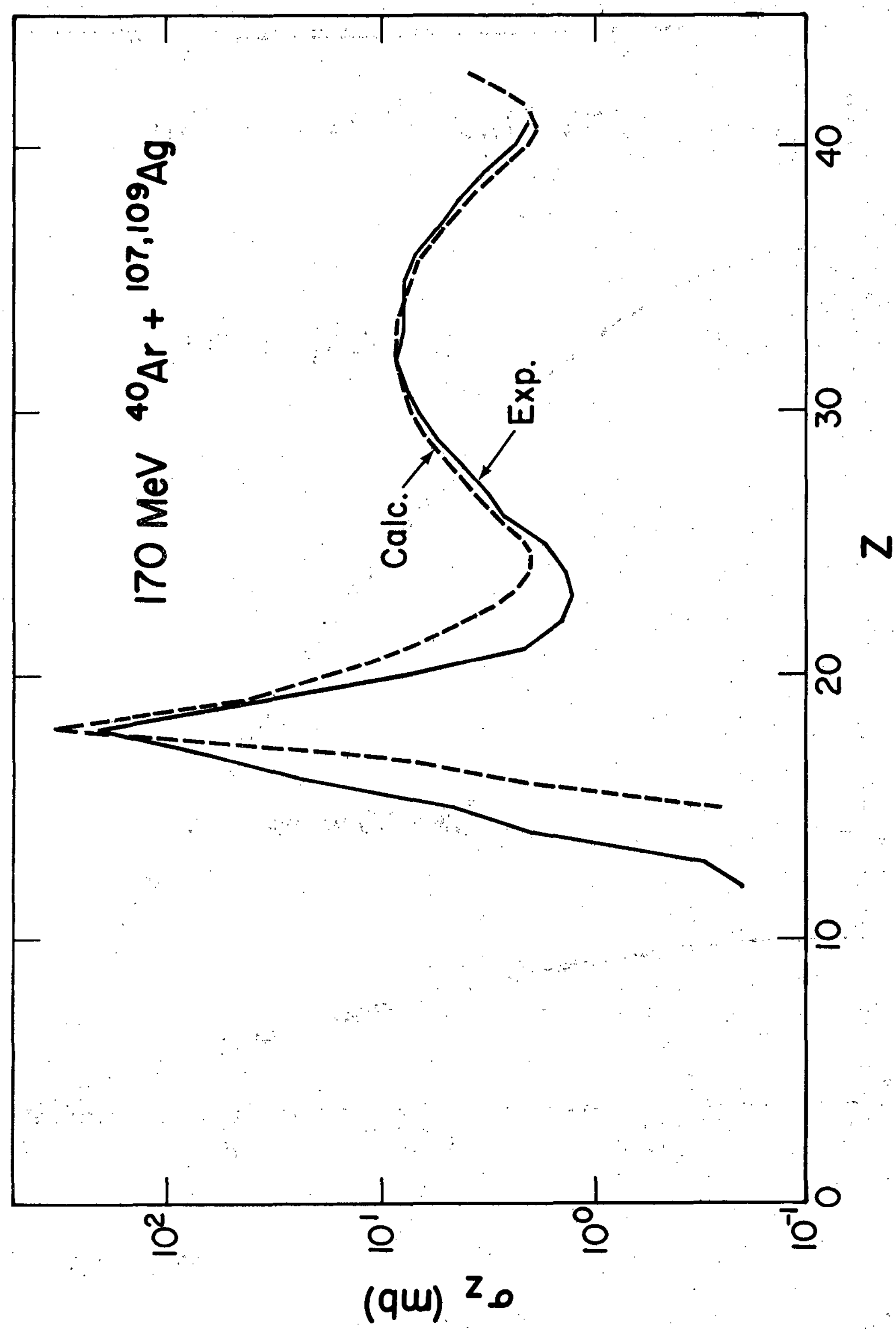

170 MeV $^{40}Ar + ^{108}Ag$
Liquid drop
Two spheres
Barrier (MeV)
30
20
10
0
0
20
40
60
80
ℓ
XBL 794-1321

Fig. 2



XBL 7612-11122 A

Fig. 3

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720