NEUTRON FLOW BETWEEN NUCLEI AS THE PRINCIPAL ENHANCEMENT MECHANISM
IN HEAVY-ION SUBBARRIER FUSION*

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CONF-880896--1

DE88 015566

— Invited Paper —

International Symposium on Heavy-Ion Reaction Dynamics
in Tandem Energy Region
Hitachi, Japan, August 1-3, 1988

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*Research supported by the U.S. Department of Energy under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

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ABSTRACT

The observed enhanced cross sections for heavy-ion fusion are interpreted with a model in which the near barrier cross sections are dominated by neck formation initiated by neutron flow between the colliding nuclei. The collective properties of the colliding nuclei are then interpreted as a modulation of the thresholds for neck formation and dominate the cross sections in the region far below the barrier.

1. Introduction

Most theories developed to account for the observed enhanced cross sections for heavy-ion fusion in the barrier region have barrier transmission and coupling to low-lying collective states as cornerstone concepts. We present a different picture based on neutron transfer which relegates enhancement caused by collective states to the region far below the barrier (<10 mb). The overlap of the projectile and target shell-model potentials indicate that the valence neutrons of the colliding nuclei can begin to flow between the nuclei at distances which are typically 1.5 fm outside of the mean barrier distance. This neutron flow may precipitate a neck between the nuclei which provides the driving force for fusion. The cross sections in the near barrier region (10 to 200 mb) are well represented by a parabolic energy dependence which follows from the integration of the simple expression $(1-B/E)$ from a threshold energy to the bombarding energy. The threshold energies for fusion correlate well with the binding energies of the valence neutrons of the colliding nuclei. The heaviest isotopes of each element, which have the smallest neutron binding energies, have the largest cross sections in the near barrier region.

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The collective properties of the colliding nuclei (mainly the low-lying quadrupole states) are then considered to modulate the thresholds for neck formation. This modulation produces cross sections in the region far below the barrier (.01 to 10 mb) which are in agreement with experiment and which correlate well with the collective properties of the colliding nuclei. We use these concepts to interpret the fusion cross sections of the following systems: (Ni-58) + (Ni-58,64); (Ni-64) + (Ni-64); (Ca-40) + (Ca-40,44,48); (Ca-44) + (Ca-44); (Mg-24) + (Zr-90,92,94,96); (Ar-40) + (Sm-154); and (Ge-74) + (Ge-74).

2. Difficulties with coupling only to low-lying collective states

We have encountered two main problems in trying to account for the observed cross sections for fusion in the barrier region by coupling only to the low-lying collective states. The first problem is that these couplings do not provide large enough cross sections. This problem becomes progressively more serious as one moves to heavier systems. To illustrate the basic problem, we show in Fig. 1 the observed fusion cross sections for the two systems O-16 + Pb-208 and O-16 + W-182.^{1,2)} The region above the barrier is fitted to the classical expression

$$\sigma = \pi R_b^2 [1 - (ME)/E] \quad (1)$$

Fig. 1. Fusion cross sections for O-16 + Pb-208, W-182. The open squares are experimental values. The curves are based on use of equations (1) and (3) with parameters listed in Table 2.

where ME is the mean barrier energy. The cross sections in the barrier region are fitted to a simple parabolic expression (see equation 3 below). We see that the subbarrier cross sections are well fitted for both systems and that the shape and magnitude of the cross sections are rather similar for both systems. Yet Pb-208 is a doubly-closed-shell nucleus with a high-lying $2+$ state of small collectivity; whereas, W-182 is a permanently deformed nucleus with a well-defined low-lying rotational band. Within the spirit of coupling to low-lying collective states, one would have expected to find a much more pronounced difference. To put it a different way, if the introduction of what should have been the dominant new coupling produces such a small difference, how can one hope to account for the subbarrier cross sections by coupling to the low-lying collective states? The result has been the assignment of extremely generous or even unrealistic amounts of collectivity to the colliding nuclei in attempts to increase the subbarrier cross sections. Tanimura, Makowka, and Mosel³⁾ have emphasized that coupling to collective states does not produce large enough cross sections in the subbarrier region.

The second problem we have encountered is that although the cross sections in the near subbarrier region have noticeable variations from system to system, these variations do not correlate well with the collective properties of the colliding nuclei. The variations in cross sections do show a good correlation with the binding energies of the valence neutrons of the colliding nuclei. Such an "isotope effect" was clearly seen in the early measurements of Scobel et al.⁴⁾ of the fusion cross sections for Cl-35 on the different isotopes of nickel. We will not consider these cases but will, instead, take systems which more strongly demonstrate this dependence on valence neutron binding energies.

3. Description of the model

We were led to a parabolic energy dependence for the fusion cross sections of heavy ions in the near barrier region by studies of the distribution of barriers required to fit experimental cross sections.⁵⁾ Although we now believe it is appropriate to replace the distribution of barriers by an averaged weight for neck formation, in this discussion we will continue to use the form of the equation previously given. We have simply replaced mean barrier, B_m , by mean energy, ME , and threshold barrier, B_t , by threshold energy, TE . We first consider collisions between nearly symmetric

systems, such as between the nickel or calcium isotopes, which may be identical (Ni-58 + Ni-58 or Ca-44 + Ca-44) and, therefore, involve nuclei with identical binding energies for the valence neutrons, or which may be quite different in the binding energies for the valence neutrons (Ca-40 + Ca-48). Since compelling evidence for the validity of the neutron flow picture comes from considering collisions between nuclei with quite different binding energies for the valence neutrons, we need to carefully discuss this case. Figure 2 shows the situation for the collision Ni-58 + Ni-64. Neutron flow from Ni-64 (low binding energy for valence neutrons) to Ni-58 begins at an energy of 89.7 MeV (distance of 12.52 fm). Taking the form of the equation previously presented,⁵⁾ we have

$$\sigma(E) = \pi R^2 \frac{1}{8[ME - (TE)_{Ni-64}]} \frac{[E - (TE)_{Ni-64}]^2}{E}, \quad (2)$$

Ni-64 → Ni-58

Fig. 2. Schematic diagram of collision between Ni-58 and Ni-64.

like nuclei since the TE value is the same for each nucleus. We then have

$$\sigma(E) = \pi R^2 \frac{1}{4(ME - TE)} \frac{(E - TE)^2}{E}. \quad (3)$$

This simplified equation is also used for the fusion of light-heavy systems since it is found empirically that the influence of the light partner's neutron binding energy is slight.

We next assume that the thresholds for neck formation are modulated by the collective motions of the colliding nuclei. One simple procedure is to take the modulation to be a gaussian:

$$G(E) = 1/\omega(2\pi)^{1/2} \exp[-(E-(TE))^2/2 \omega^2] . \quad (4)$$

When two different TE values are involved in the collision, we modulate both cross sections with gaussians having the same value for ω . In the adiabatic limit⁶⁾ we have $\omega = (\omega_1^2 + \omega_2^2)^{1/2}$, where $\omega_{1,2} = \frac{(\beta^2)_{1,2} R_{1,2}}{\sqrt{4\pi}} \times \frac{dV}{dr}$, where dV/dr is the gradient of the potential at the distance r corresponding to the energy TE. The gradient is calculated for quadrupole distortions of the nuclei. Some examples of adiabatic ω 's for symmetric systems are given in Table 1.

Table 1

System	$1.41*\omega_1$ (fm)	Gradient (MeV/fm)	ω (MeV)
Ca-44 + Ca-44	0.43	3.4	1.45
Ni-64 + Ni-64	0.34	5.6	1.9
Ge-74 + Ge-74	0.57	6.9	3.9

The nuclei Sm-154 and Mg-24 have permanent quadrupole deformations. Collisions with such nuclei result in an asymmetric modulation of the threshold energies. In these cases we show the modulation in graphical form.

4. Model fits to experimental fusion cross sections

A. The nickel nuclei

Beckerman et al.⁷⁾ have obtained an extensive set of fusion cross sections for the nickel isotopes. The fits to these cross sections in the barrier region are shown in Fig. 3. The parameters used for these fits are given in Table 2. A graphical summary of the parameters ME, TE, and the modulation shapes are shown in Fig. 4. The modulation required for the Ni-58 + Ni-64 cross sections is particularly interesting since it clearly reveals the different threshold values for the two isotopes. It is satisfying that the required modulations are similar for all three reactions. It is also interesting that the widths of the modulation are less than half of the adiabatic values. It should be borne in mind that the modulation

also contains the contribution from the experimental energy spread, which is not negligible compared to these narrow modulations. A general trend that we have observed is that the required modulation is about equal to the adiabatic value for low-lying $2+$ states and falls significantly below the adiabatic value for nuclei with $2+$ states as high as those for the nickel isotopes.

The potential barriers for the nickel isotopes are shown in the left-hand part of Fig. 5. Examples of merged neutron potentials are shown in the right-hand part of the figure. We show Ni-58 + Ni-58 at a distance of 11.9 fm and Ni-64 + Ni-64 at a distance of 12.5 fm.

B. The calcium isotopes

The fusion cross sections for collisions between the different calcium isotopes have been measured by Aljuwair et al.^{8,9)} We have found these cross sections to be quite instructive. Both Ca-40 and Ca-48 are doubly-closed-shell nuclei with high-lying $2+$ states of small collectivity. On the other hand, Ca-44 has a $2+$ state at 1.15 MeV with a β_2 value of 0.25 (somewhat more collective than the $2+$ states of the nickel isotopes). From the viewpoint that subbarrier enhancement is caused solely by coupling to low-lying collective states, we would expect small enhancements for

Fig. 3. Fusion cross sections for the nickel isotopes. Experimental values are shown as open squares. The curves are based on formulas 1, 2, 3, and 4 with parameters given in Table 2.

Table 2

System	ME (MeV)	TE (MeV)	π^*R^2 (mb)	Modulation ω (MeV)
O-16 + Pb-208	74.9	70.9	3700	
O-16 + W-182	69.1	64.4	3470	
Ni-58 + Ni-58	101.2	93.9	3400	0.75
Ni-64 + Ni-64	97.3	89.55	3600	0.6
Ni-58 + Ni-64	99.1	Ni-58 93.7 Ni-64 89.8	3200	0.85
Ca-40 + Ca-48	51.7	Ca-40 49.7 Ca-48 48.05	2100	0.6
Ca-44 + Ca-44	51.7	48.9	2140	1.1
Ca-40 + Ca-44	52.2	Ca-40 49.9 Ca-44 48.6	2400	0.8
Ca-40 + Ca-40	52.4	51.5	2540	1
Mg-24 + Zr-90	62.7	58.6	3040	a
Mg-24 + Zr-92	62.4	57.1	2920	a
Mg-24 + Zr-94	62.2	56	2800	a
Mg-24 + Zr-96	62	54.7	3040	a
Ar-40 + Sm-154	126.9	117.6	3700	b
Ge-74 + Ge-74	124	113.9	2440	3.2

a) Permanently deformed Mg-24.

b) Permanently deformed Sm-154.

Fig. 4. Plots of ME, $\overline{TE}$, and modulations of $\overline{TE}$ required to fit nickel fusion cross sections.

Fig. 5. Potential barriers for the nickel isotopes are shown in the left-hand part of the figure. Two examples of merged neutron potentials are shown in the right-hand part of the figure. We show Ni-58 + Ni-58 at a distance of 11.9 fm and Ni-64 + Ni-64 at a distance of 12.5 fm.

Ca-40 + Ca-40 and Ca-48 + Ca-40 and larger enhancements for Ca-44 + Ca-40 and Ca-44 + Ca-44. The observed cross sections and our fits to these cross sections, based on the parameters listed in Table 2, are shown in Fig. 6. While the enhancement observed for Ca-40 + Ca-40 is strikingly small ($ME - TE = 0.9$ MeV), the enhancement for Ca-40 + Ca-48 is about the same as that for Ca-44 + Ca-44. However, the model suggests that the origin of the enhancements is different. Figure 7 shows the location of the TE values and the modulations.

The cross sections at the lowest energies for Ca-40 + Ca-40 are much higher than the model predictions. A confirmation of these experimental values is needed. In fact, because the calcium isotopes contain such a nice mixture of varying collectivities and valence neutron binding energies, additional experimental cross sections would be valuable. It would be especially useful to have detailed sets of cross sections for Ca-44 + Ca-48 and even Ca-48 + Ca-48.

Fig. 6. Fusion cross sections for the calcium isotopes. Experimental values are shown as open squares. The curves are based on the formulas 1, 2, 3, and 4 with parameters given in Table 2.

C. The Mg-24 + Zr isotopes

Ecker et al.¹⁰⁾ have measured some very interesting subbarrier fusion cross sections for Mg-24 on the nuclei Zr-90, -92, -94, and -96. All the Zr nuclei have small collectivity with Zr-90 and Zr-96 being somewhat analogous to Ca-40 and Ca-48. These cross sections are plotted in Fig. 8 along with the model fits based on the parameters given in Table 2. Since Mg-24 has valence neutrons with high binding, we have assumed that the neutrons only flow from the Zr nuclei to Mg-24 and have used the simpler equation (3). The near barrier cross sections show a systematic variation with isotope which correlate with the change in the binding energy of the valence neutrons. We have also assumed that the modulation of the neutron flow

Fig. 7. Plots of ME, $\overline{TE}$, and modulations of $\overline{TE}$ required to fit the calcium fusion cross sections.

thresholds is caused by the varying angular orientation of the permanently deformed Mg-24. These modulations are shown in Fig. 9. We see that the model provides a good representation of the experimental cross sections. Additional measurements at lower energies would be quite interesting.

D. The systems Ar-40 + Sm-154 and Ge-74 + Ge-74

The subbarrier behavior of many systems has been studied. We do not have space to describe these systems. We will here only briefly mention two systems for which very extensive experimental results are available. Reisdorf et al.¹¹⁾ have provided a most impressive set of measurements for the fusion of Ar-40 + Sm-154 which extend down to the microbarn level. These cross sections, together with our fit (parameters in table 2), are shown in Fig. 10. In this case we have assumed that the modulation function is that due to the permanently deformed Sm-154. The assumption of a gaussian form for the modulation leads to degraded fits as illustrated in Fig. 11.

Fig. 8. Fusion cross sections for Mg-24 on the even zirconium isotopes. Experimental values are shown as open squares. The curves are based on formulas 1 and 3. The modulations caused by a permanently deformed Mg-24 are shown graphically in Fig. 9.

Beckerman et al.¹²⁾ have provided an extensive set of cross sections for the symmetric system Ge-74 + Ge-74, which are shown in Fig. 12 together with our fit. In this case a gaussian modulation provides a good fit all the way down to the 20 microbarn level. The width of the gaussian is about 0.8 of the adiabatic value given in Table 1.

Fig. 9. Plots of ME, $\overline{TE}$, and the modulation of $\overline{TE}$ caused by a permanently deformed Mg-24 nucleus.

Fig. 10. Fusion cross sections for Ar-40 + Sm-154. The experimental cross sections are shown by open squares. The curves are based on formulas 1 and 3. The modulation is assumed to be caused by the permanently deformed Sm-154.

Fig. 11. Attempts to fit the smallest cross section region of Ar-40 + Sm-154 by gaussian modulations compared to a modulation based on a permanent deformation.

Fig. 12. Fusion cross section for Ge-74 + Ge-74. The experimental cross sections are shown as open squares. The curves are based on formuals 1 and 3 with parameters listed in Table 2.

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