Adiabatic Quantum Tunneling in Heavy-Ion Sub-barrier Fusion

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The measured fusion barrier distributions for ^{40}Ca + ^{192}Os, ^{194}Pt show significant features due to projectile excitation, while none are seen for ^{16}O + ^{144}Sm. This conflict is reconciled using realistic coupled-channel calculations, which show that the higher excitation energy of the 3^- state in ^{16}O produces an adiabatic potential renormalization, without affecting the structure in the barrier distribution. This result indicates that adiabatic effects restrict, in a natural way, the states which influence the *shape* of a fusion barrier distribution. [S0031-9007(97)04047-7]

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Quantum tunneling plays an important role in a range of diverse phenomena in physics and chemistry. Recent attention has been focused on tunneling in systems with many degrees of freedom [1]. One of the interesting aspects of the problem is in determining which of the multitude of degrees of freedom must be explicitly included in any theoretical description, and which can be omitted. In particular, it is essential to define the role of excitation energy, or the degree of adiabaticity, in limiting the effectiveness of a specific degree of freedom.

In nuclear physics, heavy-ion fusion reactions at energies near and below the Coulomb barrier provide an ideal opportunity to address this question. In order for fusion reactions to occur, the Coulomb barrier created by the strong cancellation between the repulsive Coulomb force and the attractive nuclear interaction has to be overcome. Extensive experimental as well as theoretical studies have revealed that couplings of the relative motion to nuclear intrinsic degrees of freedom of the colliding nuclei cause enhancements of the fusion cross section at subbarrier energies, sometimes by several orders of magnitude, over the prediction of a single–barrier penetration model [2]. In a simple eigenchannel approach, such couplings result in the single fusion barrier being replaced by a distribution of potential barriers. A method of extracting barrier distributions directly from fusion excitation functions was proposed [3], and stimulated precise measurements of the fusion cross sections for several systems. These analyses of the barrier distributions have beautifully demonstrated the effects of coupling of the relative motion to various nuclear intrinsic excitations [4,5] as well as to transfer reactions between the colliding nuclei [4].

Despite these successes, there are apparent conflicts regarding the role of projectile excitation. Each barrier distribution for the reactions ^{40}Ca + ^{194}Pt, ^{192}Os shows a characteristic structure, with a higher energy peak which has been associated with the octupole excitation of ^{40}Ca [6]. Calculations of fusion cross sections for the reactions ^{16}O + ^{154}Sm, ^{A}Ge in Refs. [7,8] indicated that excitation of ^{16}O is important. In marked contrast, there are no specific features in the measured barrier distribution for the ^{16}O + ^{144}Sm reaction which can be associated with the excitation of ^{16}O [4].

All the above conclusions were based on comparison of the experimental results with simplified coupled-channel calculations. The simplification has been achieved by using one or more of the following approximations: (1) the no-Coriolis approximation [9], where the centrifugal potential is assumed to be the same for all channels and equal to that in the elastic channel; (2) the linear coupling approximation, where the nuclear coupling potential is assumed to be linear *w.r.t.* the coordinate of the nuclear vibrational excitation; (3) the constant coupling approximation, where the coupling potential is assumed to be constant over the interaction range; and (4) intrinsic excitation energies are treated approximately.

The first approximation, common to most coupled-channel calculations, including those presented in this Letter, has been shown to work well for heavy-ion fusion calculations [10]. Simplified coupled-channel calculations [4,6,8,11] use the second approximation in conjuction with either the third or fourth. Recent studies [12,13] have shown the linear coupling approximation is not valid even in systems where the coupling is weak, and that higher order couplings strongly influence the calculated barrier distributions. It is therefore probable that in reactions with nuclei like ^{16}O and ^{40}Ca, where the couplings to the octupole vibrational excitations are strong, barrier distributions calculated with simplified coupled-channel codes like CCFUS [11] do not provide a good representation of the fusion process.

In this Letter we present the results of realistic coupled-channel calculations which demonstrate the effects of nonlinear coupling and finite excitation energy of nuclear intrinsic (environmental) degrees of freedom, and resolve the apparently conflicting conclusions regarding the influence of the projectile excitation. The relevance of the "counter term" prescription of Caldeira and Leggett [1] in heavy-ion fusion reactions is also discussed, and the double counting problem of coupling effects is clarified.

The coupled-channel equations are solved by imposing the incoming wave boundary condition to simulate the strong absorption inside the fusion barrier. The real nuclear potential is assumed to have a Woods-Saxon shape, and the depth was chosen to reproduce the experimental fusion cross sections at high energies using the single-barrier penetration model. The values of deformation parameters are extracted from the reduced transition probabilities. The parameters of the calculations are listed in Table I.

In order to show the inadequacies of the often used linear coupling approximation, calculations were performed for the $^{16}O + ^{144}Sm$ reaction using the linear coupling approximation. The results of our calculations for the fusion excitation function and the barrier distribution are shown in Fig. 1. In the following discussion we concentrate on the latter since they are a more sensitive way to compare experimental data and calculations. The dotted line shows the result when the excitation of ^{16}O is not included in the calculations. This calculation reproduces well the features of the experimental barrier distribution. Calculations including the excitation of the lowest-lying octuple state of ^{16}O are shown by the solid line. Even though the experimental barrier distribution around the lower energy peak ($\sim$ 60 MeV) is reproduced, significant strength is missing around the higher energy peak near 65 MeV. A similar discrepancy between theory and experimental data was encountered in Ref. [4], where calculations, shown by the long-dashed line, were performed using a modified version of the CCFUS code. It is clear that both calculations which include the octupole excitation of ^{16}O in the linear coupling approximation fail to reproduce the experimental barrier distribution.

Realistic coupled-channel calculations were then performed, where the couplings to the octupole vibrations of both ^{16}O and ^{144}Sm are treated to all orders; i.e., the nuclear interaction is not expanded with respect to the deformation parameter [12]. It is remarkable that these calculations, shown in Fig. 2, reestablish the double-peaked structure seen in the experimental data, which was absent in the equivalent linear coupling calculations. The shape of the barrier distribution obtained by including the octupole vibration of ^{16}O using all order coupling is now very similar to that obtained by ignoring it. This similarity becomes particularly evident when the calculated barrier distribution is shifted in energy, as shown by the dashed line in the figure. This is consistent with the general conclusion that the main effect of the coupling to inelastic channels whose excitation energies are larger than the curvature of the bare fusion barrier, i.e., an adiabatic coupling, is to introduce a static potential shift as well as a mass renormalization [14], and hence, the shape of the barrier distribution does not change unless the coupling form factor itself has a strong radial dependence.

In macroscopic quantum tunneling in condensed matter physics, the so-called counter term is often introduced in order to compensate for the static potential renormalization due to the coupling to the environment [1]. In contrast, in heavy-ion reactions, one usually estimates the bare potential, for example, by fitting the fusion cross section at high energies, and discusses the effects of channel coupling without introducing the counter term. Figure 2 shows that this approach reproduces the experimental fusion cross sections and fusion barrier distributions without explicitly taking into account the excitation of the octupole vibrational state of ^{16}O. This indicates that the effects of its excitation are already included in the bare potential. If this is the case, the effect of the coupling to the 3$-$ state of ^{16}O is double counted if the coupled-channel calculations explicitly take it into account, resulting in a dramatic overestimate of the the experimental cross sections. A recipe to cure this problem is to introduce the counter term as in condensed matter physics. Since the experimental data are well reproduced when the calculated distributions are shifted to higher energies by 2 MeV, this shift evidently mimics the effects of the counter term.

In contrast to the $^{16}O + ^{144}Sm$ case, the analyses of $^{40}Ca + ^{192}Os$ and ^{194}Pt reactions, also performed using simplified coupled-channel calculations [6], suggest that the excitation of ^{40}Ca is important in determining the observed barrier distribution. An important difference between the ^{16}O and ^{40}Ca projectiles is that the excitation energy of the octupole vibration in the latter is smaller and

TABLE I. Parameters used in the coupled-channel calculations for the indicated reactions.

	Channel couplings					Potential parameters		
Reaction	Nucleus	Type	λ^{π}	E^* (MeV)	β_{λ}	V (MeV)	r_0 (fm)	a (fm)
$^{16}O + ^{144}Sm$	^{144}Sm	vib	3^-	1.81	0.205	105.1	1.1	0.75
	^{16}O	vib	3^-	6.13	0.733			
$^{40}Ca + ^{194}Pt$	^{40}Ca	vib	3^-	3.70	0.339	330.0	1.0	0.84
	^{194}Pt	rot	2^+	0.328	$\beta_2 = -0.154$			
					$\beta_4 = -0.045$			
$^{40}Ca + ^{192}Os$	^{192}Os	rot	2^+	0.206	$\beta_2 = 0.167$	148.0	1.1	0.84
					$\beta_4 = -0.043$			

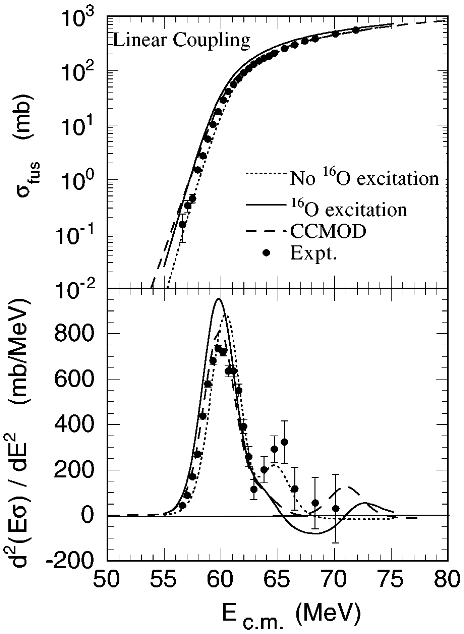

FIG. 1. Fusion excitation functions (upper panel) and the barrier distributions (lower panel) for the $^{16}O + ^{144}Sm$ reaction. The experimental data (filled circles) are taken from Ref. [4]. The linear coupling approximation is used in the coupled-channel calculations. In all calculations, the effects of the octupole vibration of ^{144}Sm are taken into account. The dotted line shows the results when ^{16}O is treated as inert. The solid line is the result of the coupled-channel calculations when the coupling to the octupole vibration of ^{16}O is also taken into account; the dashed line is the result of an equivalent CCFUS calculation.

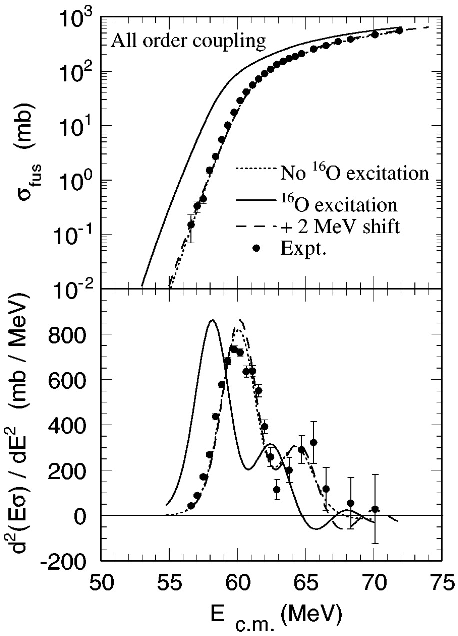

FIG. 2. Same as Fig. 1, but for the case when the coupled-channel calculations have been performed by including all order coupling. The meaning of the solid and the dotted lines is the same as in Fig. 1, while the dashed line is the same calculation as the solid line with the average barrier increased by 2 MeV.

and nearly equal to the energy scale of the curvature of the fusion barrier; hence the coupling is intermediate between adiabatic and sudden. It is therefore interesting to investigate the degree of adiabaticity of the octupole excitation of the ^{40}Ca projectile.

The results of the coupled-channel calculations are compared with the experimental data in Fig. 3. All order couplings to both the target and the projectile excitations have been included. Although ^{194}Pt and ^{192}Os are transitional nuclei which lie between the γ-unstable and rotational limits in the interacting boson model [15], we have assumed that they are rigid rotors with axial symmetry. The ground state rotational band of the target nucleus, with states up to the 10^+ member, has been included in the calculations. When the ^{40}Ca excitation is ignored, barrier distributions are obtained which are similar to those expected for a classically deformed nucleus, and these are inconsistent with the experimental data. When the octupole excitation of ^{40}Ca is included in the calculations, a higher energy peak is introduced which agrees well with that observed in each reaction. The mutual excitation channels up to $4^+ \otimes 3^-$, the former and the latter refering to the targets and the projectile respectively, are also included in the calculations. It is apparent that the projectile excitation significantly affects the shape of the barrier distribution in this case, as suggested in the simplified coupled channel calculations in Ref. [6].

As has been shown in the discussions for $^{16}O + ^{144}Sm$ reactions, the correct treatment of the coupling, without making the linear coupling approximation, significantly reduces the effect of projectile excitation on the shape of the barrier distribution. Calculations of the CCFUS type, which fail in these regards, would therefore be expected to predict larger coupling effects than observed experimentally. The apparent success of the CCFUS calculations reported in Ref. [6] was probably due to the compensation for this overestimate by the use of a smaller deformation parameter than that obtained from the octupole transition strength.

The theoretical calculations for the reactions with the ^{40}Ca projectile still significantly underestimate the fusion cross section at low energies, even after the excitation of the projectile is taken into account. As suggested in Ref. [6], coupling to transfer channels, which have been ignored in the present calculations, might enhance the fusion cross section at low energies.

In summary, we have performed coupled-channel calculations for the fusion reactions $^{16}O + ^{144}Sm$ and $^{40}Ca + ^{194}Pt$, ^{192}Os. The calculations with full order coupling show that the dominant effect of the excitation of the ^{16}O octupole state at 6.1 MeV is to renormalize the static potential without significantly changing the

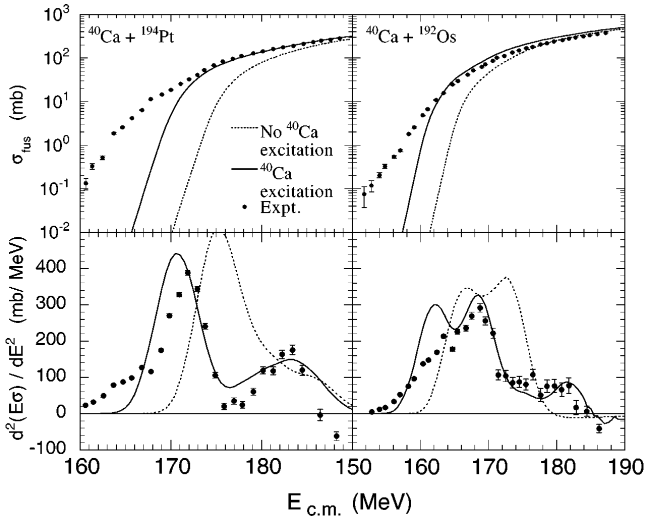

FIG. 3. The comparison of the experimental fusion cross sections (upper panels) and fusion barrier distributions (lower panels) for the ^{40}Ca + ^{194}Pt, ^{192}Os reactions with the coupled-channel calculations. In all calculations, the effects of the excitation of the target nuclei are treated in the rotational model and couplings to all orders are included. The dotted lines are the results when ^{40}Ca is treated as inert. The solid lines include the coupling to the octupole vibrational state in ^{40}Ca.

shape of the barrier distribution. On the other hand, the excitation of the 3^- state at 3.7 MeV in ^{40}Ca introduces well-defined peaks in the barrier distribution. These results suggest a natural limit to the energy of states which need to be considered explicitly in coupled-channel calculations. The myriad of weak, high energy excitations which might be possible contribute only to a potential renormalization without affecting the shape of the barrier distribution. The effects of these excitations can then be included in the bare potential in coupled-channel calculations. If these channels are explicitly included in the coupled-channel calculations without introducing the counter term, they could be double counted, depending on the choice of the bare potential.

It has been shown that in order to interpret the high precision fusion excitation functions that have recently become available, it is vital to perform exact coupled-channel calculations which treat the excitation energy and the radial dependence of the coupling form factor correctly. While CCFUS-based calculations have apparently been very successful in reproducing observed barrier distributions, it is clear from our results that care must be taken in their interpretation; the approximations used are unreliable even for relatively weak coupling strengths. Exact coupled-channel calculation is the only reliable means of quantitatively understanding the fusion excitation function.

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