Simultaneous Description of Quasielastic and Fusion Reactions in Low-Energy Heavy-Ion Collisions

M. J. Rhoades-Brown and M. Prakash
Physics Department, State University of New York at Stony Brook, Stony Brook, New York 11794
(Received 19 March 1984)

A unified approach is used to describe quasielastic and fusion processes in heavy-ion reactions at near barrier energies. The spin distributions for fusion are used in conjunction with transition-state theory to calculate fission fragment angular distributions. Results for the reaction $^{16}O+^{208}Pb$ show that when transfer contributions are small, satisfactory agreement with data is obtained. The role of fragment anisotropy as a useful probe of entrance channel effects at energies close to the barrier is pointed out.

PACS numbers: 25.70.$-$z

In heavy-ion collisions surface degrees of freedom play a central role in models that describe quasielastic processes[1] (for a survey, see Satchler[2]). Recently the influence of these degrees of freedom on fusion reactions has attracted much interest.[3-6] We wish to consider a single reaction model aimed at a unified description of quasielastic and fusion processes at near barrier energies. Predictions of the spin distribution for fusion are then used to probe the fission decay of the compound nucleus (CN). To focus on the influence of inelastic excitations on fusion, we have neglected the more complex transfer reactions. Results of calculations are presented for the reaction $^{16}O+^{208}Pb$ at laboratory energies of 80–102 MeV. For our purpose, the data from Videbaek[7] are the most complete set available.

To describe fusion in the presence of inelastic excitations, we follow the method introduced by Rhoades-Brown and Braun-Munzinger[4] to calculate multidimensional barrier penetrabilities. The "bare" potential is taken to be the real part of a full optical potential[8] plus a short-range absorptive potential. The absorptive potential was constructed to reproduce WKB results for barrier penetration in one-dimension.[4] This ensures that CN formation is calculated with an appropriate normalization. By expressing the total wave function as a linear combination of channel eigenstates, we obtain the following coupled-channel (CC) equations,

$$[d^2/dr^2 - l_\alpha(l_\alpha+1)/r^2 - U_\alpha^{\rm OPT} + K_\alpha^2]R_\alpha^{J\pi} = \sum_\beta V_{\alpha\beta} R_\beta^{J\pi}(r), \qquad (1)$$

in the usual notation.[9] The complex transition potential $V_{\alpha\beta}$ was calculated by use of vibrational eigenstates and a second-order expansion in the deformation length. Both nuclear and Coulomb excitation were included with equal deformation lengths for each transition. Specifically, the 3^-(6.73 MeV) state in ^{16}O and the 2^+(4.07 MeV), 3^-(2.61 MeV), and 5^-(3.2 MeV) states in ^{208}Pb were included. Transition strengths were taken from experiment.[10,11] At sub-barrier energies, only the low-lying excited states were found to contribute to fusion since coupling to high-lying states reduces the energy of relative motion. At energies well above the barrier this feature may not prevail; however, we have included all channels strongly coupled to the ground state. Equation (1) was solved by use of the CC version of Ptolemy.[9] Assuming that all inelastic channels can be handled in this way the fusion cross section is given by

$$\sigma_F(E) = \sum_l \sigma_F^{\rm cc}(l) = \sum_l (\pi/k^2)(2l+1)(1-\sum_\beta |S_l^\beta|^2),$$

where k is the asymptotic wave number, β refers to final states, l is the entrance-channel orbital angular momentum, and S_l^β is the S matrix in channel β. The above argument holds if contributions from deep-inelastic and prequilibrium processes may be neglected.

For the energies considered the decay modes of the CN consist mainly of neutron emission and fission. The partial widths of both these modes depend on $\sigma_F(l)$. We study the influence of $\sigma_F^{\rm cc}(l)$ on the fission-fragment angular distribution, $W(\theta)$, which is calculated by use of the transition state (TS) theory.[12] For an axially symmetric TS configuration characterized by a total spin I and projections M and K on the space-fixed and body-fixed axes, respectively, $W(\theta)$ is given by

$$W(\theta) = \sum_I \sigma_F(I) \sum_K \rho_t(I,K) \tfrac{1}{2}(2I+1) \times |D_{MK}^I(\theta)|^2, \qquad (2)$$

where θ is the angle with respect to the space-fixed axis. For fusion-fission reactions with spin-zero target and projectile, $M=0$. One may write $I=l$ when spin fractionation via competing decay modes is negligible. The distribution of K values, $\rho_t(I,K)$,

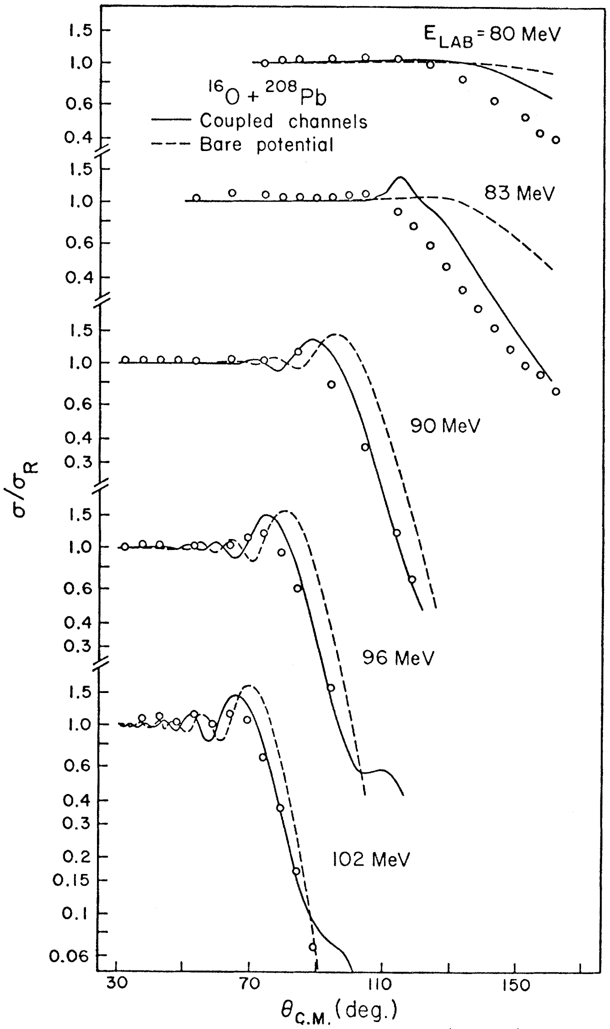

FIG. 1. Calculated and experimental (circles) elastic cross sections. The parameters of the nuclear "bare" potential are, for the real part: $V_0 = 60.5$ MeV, $a = 0.658$ fm, and $R = 9.956$ fm in a Woods-Saxon form, and for the imaginary part: $V_0 = 10$ MeV, $a = 0.4$ fm, and $R = 8.445$ fm, in a Woods-Saxon squared form.

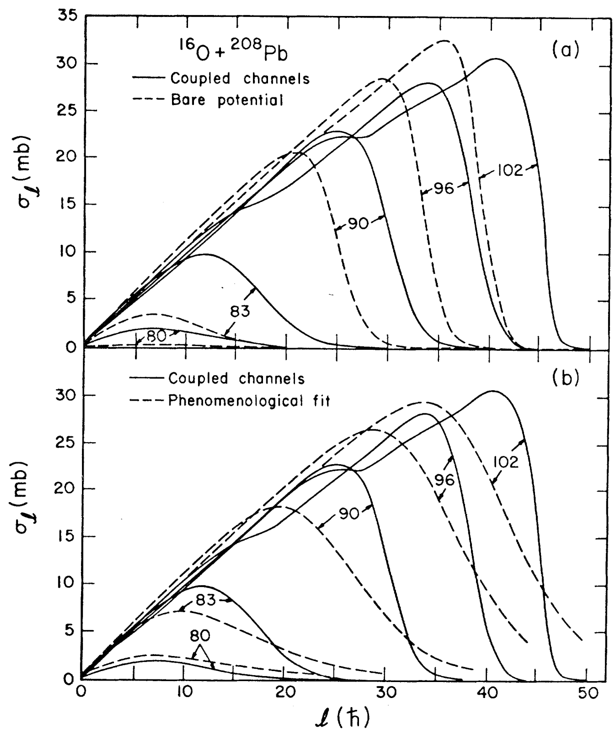

FIG. 2. Spin-dependent cross sections for fusion.

is calculated at the TS[13] and K is assumed to be conserved from the TS shape onwards. The TS properties are calculated from the rotating liquid drop model with use of the constants from Cohen.[14] The shape parametrization was taken from Brack.[15] Nucleonic shell and pairing effects diminish appreciably for a temperature $T \sim 7A^{-1/3}$ MeV and were neglected.

In Fig. 1, results are shown for the "bare" potential and CC calculations for elastic scattering. The surface absorption introduced by coupling to inelastic channels gives reasonable agreement with the data at 90, 96, and 102 MeV. However, at 80 and 83 MeV, more absorption is required to account for the data at backward angles. At these energies, the contribution from transfer is large and may account for a part of the required loss in flux.

In Table I, σ_F is shown for both the "bare" potential and CC calcualtions. At 80 MeV, the coupling produces an enhancement factor of 18 but at 102 MeV there is only a small enhancement. At 80 MeV, the data are underpredicted by a factor of 2. The percentage contributions of the different reaction channels are also shown. For $E_{\rm lab} = 90$, 96, and 102 MeV, transfer has been observed to contribute $\sim 20\%$ of $\sigma_{\rm tot}$ and yet elastic, inelastic, and fusion calculations are reasonably consistent with the data. At these energies, the "bare" potential itself does a reasonable job of predicting elastic cross sections. Possibly the real potential is simulating some effects of included or excluded channels as this was determined from an optical-model analysis.[8] Therefore caution must be used in the interpretation of the effect of both inelastic and transfer degrees of freedom on sub-barrier fusion reactions.[4-6] To make definitive statements the problem of double counting needs to be addressed.

In Fig. 2(a), $\sigma_F^{\rm cc}(l)$ are compared with $\sigma_F^{\rm bare}(l)$. The contributions from inelastic excitations clearly show the role of surface degrees of freedom. The shoulder in $\sigma_F^{\rm cc}(l)$ for $E_{\rm lab} > 90$ MeV may be understood in terms of penetration through a spectrum of energy- and l-dependent potential barriers

TABLE I. $^{16}O + ^{208}Pb$ reaction channel cross sections.

Channel	Inelastic		Fusion-fission			Transfer
E_{lab} (MeV)	$\sigma_{inel}^{(expt)}$ (mb)	$\sigma_{inel}^{(theory)}$ (mb)	$\sigma_F^{(expt)}$ (mb)	σ_F^{bare} (mb)	σ_F^{cc} (mb)	$\sigma_{trans}^{(expt)}$ (mb)
80	24 ± 4 (24%)	11.3	36 ± 4 (36%)	1.1	20.9	40 (40%)
83	60 ± 12 (25%)	21.6	108 ± 10 (45%)	35	131.1	69 (30%)
90	92 ± 12 (16%)	71.2	377 ± 50 (65%)	332.7	423.1	108 (19%)
96	· · ·	107.5	685 ± 70 (· · ·)	564.9	641	· · ·
102	157 ± 20 (14%)	134	844 ± 90 (73%)	728.8	837.7	154 (13%)

induced by the coupling. This structure occurs for $l \sim \langle l \rangle_{rms}$, in contrast to the structure shown at larger l for the $^{58}Ni + ^{58}Ni$ reaction in Landowne and Pieper.[6] In Fig. 2(b), we compare $\sigma_F^{cc}(l)$ with the $\sigma_F(l)$ given by Videbaek[7] that were fitted to the fission data alone. For all energies, the surface widths of $\sigma_F^{cc}(l)$ are much smaller than those of Videbaek.[7] For $E_{lab} > 90$ MeV, the two approaches lead to similar root-mean-square spins. However, at 80 MeV, the CC root-mean-square spin is much smaller than that of Videbaek.[7]

In Fig. 3, we compare calculated fission-fragment anisotropies $W(\theta)/W(90°)$ to those measured. For 90 and 102 MeV, agreement with data is acceptable. However, for 80 MeV, the anisotropies are underpredicted. The calculated anisotropy results from the combined effects of: (a) the spin distribution for fusion, $\sigma_F(l)$, (b) the effective moment of inertia, $\mathscr{I}_{eff}$, and (c) the temperature, T, at the saddle point.

(a) To account for the fission data at 80 MeV, a long tail in $\sigma_F(l)$ was required by Videbaek.[7] To

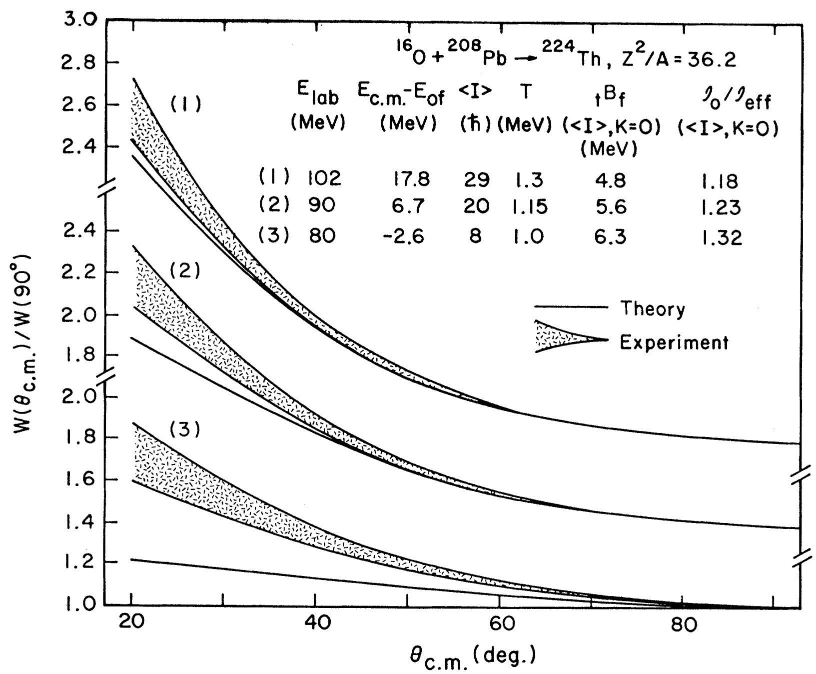

FIG. 3. Calculated and experimental (consistent with the data in Ref. 7) fission angular distributions. The inset shows the lab energy, energy with respect to barrier, and the mean spin for fusion. The calculated temperature, fission barrier height, and the ratio of spherical to effective moments of inertia of the TS shape are also shown.

explore the sensitivity to the "bare" potential, we increased the depth of the real potential from 60.5 to 70 MeV. This change reduced the barrier height, E_{0F}, from 76.9 to 76.3 MeV; without affecting the tail region appreciably and hence the elastic scattering results. The results for fusion became $\sigma_F^{\text{bare}} = 2.8$ (805.8) mb and $\sigma_F^{\text{cc}} = 40.2$ (891.2) mb for $E_{\text{lab}} = 80$ (102) MeV. This shows that enhancements are due to the dynamical coupling while the uncertainties in E_{0F} control the magnitude of σ_F^{bare}. However, the fission anisotropies were not altered significantly, since the root-mean-square spin did not change appreciably. At near barrier energies corrections due to evaporation residues, unobserved by Videbaek,[7] are largest. With the assumption that the evaporation-residue contributions arise from the low angular momenta, we obtained $l_{\text{ER}} \sim (4\text{–}5)\hbar$ for estimates of $\sigma_{\text{ER}} \sim 5\text{–}10$ mb. The subsequent enhancement in anisotropies was found to be small ($< 1\%$). Considering the contribution from transfer ($\sim 40\%$ at 80 MeV), it is important to ascertain whether the introduction of transfer can extend the tail in $\sigma_F(l)$.

(b) A significantly smaller I_{eff} for the TS shape, which leads to larger anisotropies, could not be obtained even with improved constants in the rotating liquid drop model.

(c) Prefission neutron evaporation could reduce T sufficiently to produce larger anisotropies. A study of this effect requires the inclusion of shell and pairing effects and is a subject for future study.

In conclusion, we have used a single reaction model to describe quasielastic and fusion processes for the reaction $^{16}O + ^{208}Pb$ at near barrier energies. At those energies where $\sigma_{\text{tran}} << \sigma_{\text{tot}}$, the calculated results are in satisfactory agreement with the data. The insensitivity of the fission anisotropy to variations in the bare potential could make this a useful probe in highlighting entrance-channel effects at energies close to the barrier.

We thank P. Braun-Munzinger, J. M. Alexander, and J. Schiffer for critical comments. This work was supported by the U.S. Department of Energy under Contract No. DE-AC02-76ER13001 with the State Univeristy of New York at Stony Brook.

[1]A. Winther, Nucl. Phys. **A409**, 21 (1983).

[2]G. R. Satchler, *Direct Nuclear Reactions* (Oxford Univ. Press, New York, 1983).

[3]D. Pelte and U. Smilansky, Phys. Rev. C **19**, 2196 (1979).

[4]M. J. Rhoades-Brown and P. Braun-Munzinger, Phys. Lett. **B136**, 19 (1984).

[5]R. A. Broglia *et al.*, Phys. Lett **B133**, 34 (1983).

[6]S. Landowne and S. C. Pieper, Phys. Rev. C **29**, 1352 (1984).

[7]F. Videbaek *et al.*, Phys. Rev. C **15**, 954 (1979).

[8]O. Akyuz and A. Winther, in *Proceedings of the Enrico Fermi School of Physics, 1979,* edited by R. A. Broglia *et al.* (North-Holland, Amsterdam, 1982), p. 492.

[9]M. J. Rhoades-Brown *et al.*, Phys. Rev. C **21**, 2436 (1980).

[10]F. Ajzenberg-Selov, Nucl. Phys. **A375**, 1 (1982).

[11]J. F. Ziegler and G. A. Peterson, Phys. Rev. **165**, 1337 (1968).

[12]A. Bohr and B. Mottelson, *Nuclear Structure* (Benjamin, New York, 1975).

[13]M. Prakash *et al.*, Phys. Rev. Lett. **52**, 990 (1984).

[14]S. Cohen *et al.*, Ann. Phys. (N.Y.) **82**, 557 (1974).

[15]M. Brack *et al.*, Rev. Mod. Phys. **44**, 320 (1972).