Energy Dependence of the Fusion Cross Section for Ca+Ca and the Dynamical Inhibition of Fusion at Low Impact Parameters

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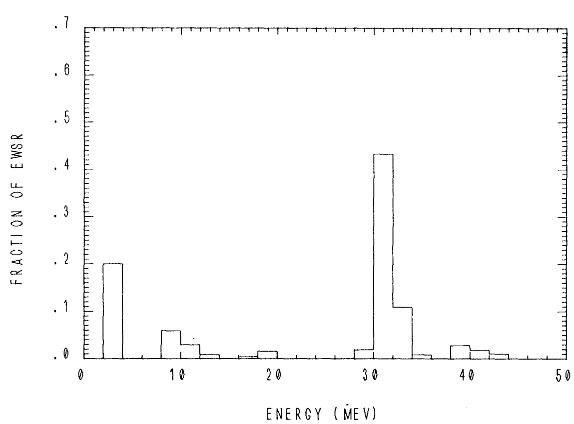
The model of heavy-ion collisions based on the excitation of damped surface modes has been used to study the fusion reactions of Ca + Ca. The calculated fusion cross section is in good agreement with recent data, and gives support to the conclusion that the decrease in the cross section below the geometrical limit for higher energies is due to dynamical difficulties in forming a compound nucleus at intermediate or small impact parameters.

The treatment of heavy-ion collisions in terms of the excitation of damped surface modes has been rather successful in describing the reaction of Kr + Pb (cf. Broglia *et al.*[1]). For such heavy systems the main objective was to give an adequate description of the deep inelastic events which build up almost all of the observed reaction cross section. On the other hand, reactions involving lighter nuclei are dominated by the formation of a compound nucleus. Thus, the accurate description of the variation of the fusion cross section with energy becomes an important test of the ability of the model to cover the whole range of heavy-ion reactions.

The main effort in applying the model lies in the determination of the response function of target and projectile. The strength distributions for ^{40}Ca [exemplified in Fig. 1(a)] were calculated in the framework of the random-phase approximation, using the experimental evidence to adjust the strength of the isoscalar and isovector coupling constants (for more details see Ref. 1). The results of these calculations are summarized in Fig. 1(b).

We have used this information to evaluate the reaction and fusion cross sections for Ca + Ca for a number of bombarding energies. Besides the response function, this calculation only depends on the ion-ion potential, for which we have used the proximity potential of Blocki *et al.*[3] This potential determines not only the elastic scattering, which is in good agreement with experimental data, but also the form factors for the excitation of the surface modes. The accuracy of the approximation which is involved in considering the inelastic modes represented in Fig. 1 as surface vibrations has recently been investigated[4] for isoscalar collective as well as noncollective excita-



(a)

L	E(MEV)	% EWSR
2	3.9	25.0
2	17.0	50.0
3	3.8	20.0
3	31.0	58.0
4	5.3	5.0
4	21.0	25.0
5	4.5	5.0
5	23.0	45.0

(b)

FIG. 1. Oscillator-strength distribution for isoscalar excitations in ^{40}Ca. In (a) we show the octupole strength distribution in percent of the classical sum rule per 2-MeV interval. It is the result of a random-phase approximation, diagonalizing a separable interaction in a harmonic-oscillator basis including particle-hole excitations up to 50 MeV (cf. Ref. 2). On the basis of this and similar diagrams for other multipolarities the spectrum shown in (b) was constructed. It collects the strength for each multipolarity, L, into a low- and a high-lying collective state with the energies E and transition probability which is given in terms of the percentage of the energy-weighted sum rule (% EWSR). The width assigned to each of the high-lying levels was 4 MeV while the low-lying levels were ascribed a nonlinear damping with $s_\lambda = \frac{1}{3}$ (cf. Ref. 1).

tions.

The results of the calculation are given in Figs. 2(a)–2(c). In order to obtain a qualitative understanding of these results, one must consider that several competing effects influence the relative motion of the two ions. Thus, since the interaction between the ions is a surface-surface interaction, the effective potential energy for the radial motion is strongly affected by the deformations. When the two ions separate, the surfaces tend to keep in contact, but the attractive force between them is lowered as compared to the force between spherical nuclei, because the radii of curvature at the point of contact become smaller. Secondly, the effective potential is lowered as compared to the situation in the entrance channel by the loss of angular momentum to the surface vibrations and intrinsic rotation.

For impact parameters below the one corresponding to grazing, the radial motion passes over the Coulomb barrier in the effective potential for the entrance channel. The inner turning point in the radial motion is (except for very small impact parameters) rather insensitive to the repulsive part of the proximity potential. During the inward motion as well as during the outward motion after the turning point, energy is dissipated from the radial motion to vibrational and intrinsic energy in the two nuclei. The question of whether the outward motion is stopped, and the two nuclei are caught in the attractive field (eventually to fuse) is decided by the competition between the rate of energy dissipation and the rate at which the barrier dwindles due to the deformation and the angular-momentum transfer.

Fusion is most likely to happen close to the orbiting angular momentum where a small energy loss is sufficient to give rise to a turning point in the outward motion. This conclusion is valid insofar as the angular-momentum loss is not too rapid.

For smaller impact parameters and above a certain threshold in energy, the lower value of angular momentum combined with the change in curvature of the nuclear surfaces may eventually allow the ions to separate. That big deformations are associated with these processes is clearly reflected by the final energy of relative motion which, as shown in Fig. 2(b), is typically below the Coulomb barrier in the entrance channel. The angular distribution of these strongly damped reaction products is peaked at an angle close to the grazing peak. Experimental evidence at higher bombarding energies[6] seems to indicate that the

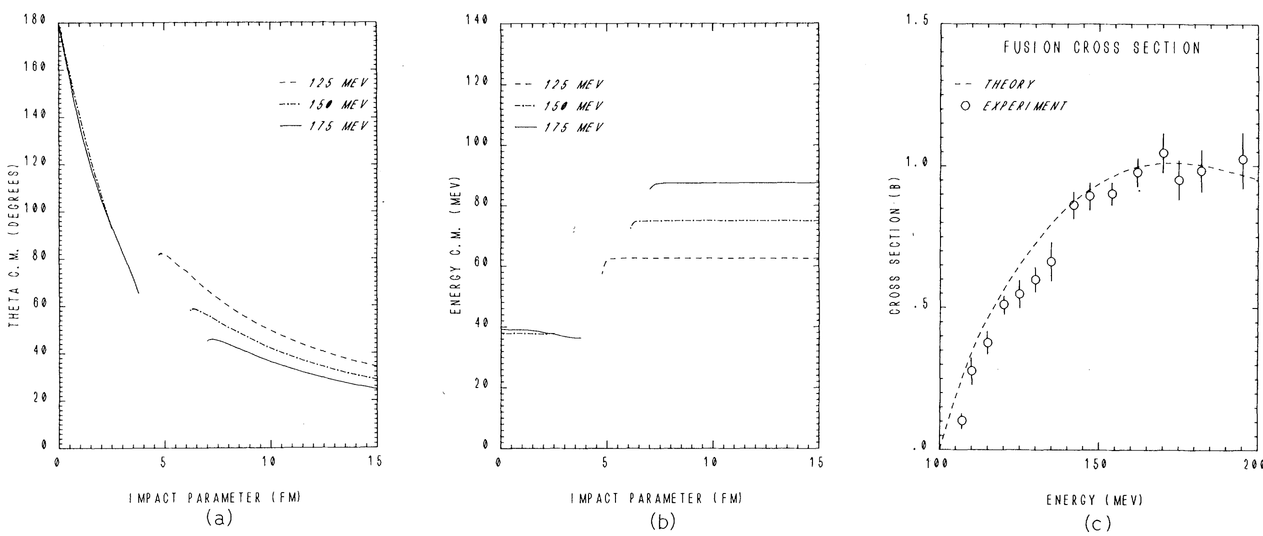


FIG. 2. The reaction $^{40}Ca + {}^{40}Ca$ at three different bombarding energies. The theoretical average deflection function, i.e., deflection angle θ as a function of the impact parameter and the associated energy loss for three cases (125, 150, and 175 MeV) are displayed in (a) and (b), respectively. Both the deflection functions and the energy-loss curves are discontinued for the range of impact parameters where the relative motion displays a second turning point, i.e., a turning point in the outward motion. In this situation the two nuclei remain within the interaction region for a very long time and the collision leads to fusion. The cross section associated with the corresponding range of impact parameters (fusion cross section) is plotted in (c) as a function of the bombarding energy in the laboratory system in comparison with experimental data (Ref. 5).

deep inelastic reaction products are actually found at somewhat smaller angles.

The fusion cross sections derived from these calculations are shown in Fig. 2(c) together with the experimental data. The good agreement may indicate that we have somewhat overestimated the effect of the surface degrees of freedom, since we have not included the additional damping due to particle transfer. We have also made a number of preliminary calculations including this damping through prescriptions of the type of Moretto and Schmitt[7] and of Blocki *et al.*[8] These results confirm that the reduction in the fusion cross section below the geometrical limit is due to the fact that at higher bombarding energies fusion at small impact parameters is dynamically inhibited (cf. also Broglia, Dasso, and Winther[9]). The calculations including transfer also indicate that the deflection function for the deep inelastic reaction products is shifted somewhat towards forward angles.

It is interesting that the tendency of the ions to "bounce off" for small impact parameters has been found also in time-dependent Hartree-Fock calculations.[10]

In order to obtain a unique signal of the predicted "bouncing off" of the projectile for low impact parameters, one might utilize the kinematics of heavy-ion reactions. If one assumes that the final total kinetic energy in the center of mass is approximately equal to the height of the Coulomb barrier E_B one finds that the projectile after a head-on collision is at rest in the laboratory system if the bombarding energy is

$$E_p = (1+r)r^{-2}E_B,$$

where r is the mass ratio of projectile to target nucleus. The small Doppler shift of the γ quanta from the de-excitation of the scattered projectile at this bombarding energy might be an interesting effect to look for.

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New Evidence for a Direct Process in the (e, α) Reaction

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Alpha-particle energy and angular distributions have been measured for the reaction ^{60}Ni$(e,\alpha)e'X$ using electrons of energies 33, 60, and 120 MeV. Statistical-model calculations give good quantitative agreement in the region of the peak of the α energy spectra. Higher-energy α particles exhibit a forward-peaked angular distribution and a cross section several orders of magnitude above the statistical-model predictions, indicating the presence of a direct-reaction component.

Alpha particles emitted by medium-weight nuclei which have been excited by real or virtual photons originate mainly from the statistical decay of the excited nucleus.[1-4] In heavy nuclei there is some evidence of a direct-reaction process,[2,5] but such a process has not been observed