COULOMB DISTORTION IN HEAVY-ION REACTIONS*

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(Received 31 October 1966; revised manuscript received 13 March 1967)

The distortion of a nucleus by the Coulomb field of a second nucleus has been discussed[1] in static approximation using the liquid-drop model. Geilikman[1] finds that the equilibrium shapes are oblate along the axis of centers if the centers of mass are fixed and that the Coulomb barrier is raised appreciably over the undistorted value. If, instead, the contact condition is fixed it is easily shown that the equilibrium shapes are prolate and that the barrier is lowered. The prolate case corresponds to the scission of a heavy nucleus.

The recent interest[2] in producing very heavy transuranic nuclei by heavy-ion reactions promted a further study of these Coulomb distortion effects. It is believed that a transuranic nucleus with a stable ground state can be formed if the excitation energy of the compound nucleus is low enough to allow neutron evaporation to compete with excited-state fission, and it is proposed[3] to achieve this condition by judicious use of the mass defects of the reacting nuclei, which, in favorable cases, can absorb the entire excitation energy. Based on the dynamics of Coulomb distortion, we believe this idea is unsound.

We have studied the classical dynamics of head-on collisions of two liquid-drop nuclei using a Lagrangian formed from the Geilikman[1] interaction potential and the Bohr[4] hydrodynamic collective energies. In the Lagrangian, only quadrupole terms up to second order in the distortions were retained. The three coupled Lagrange equations were solved by a Runge-Kutta integration starting at large separations. In all cases it was found that the incoming nuclei have oblate distortions that increase smoothly up to and beyond the turning point of the centers of mass and that the closest separation of surfaces occurs before the turning point. For collisions below the barrier the distortions progress into strong free oscillations of the recoiling nuclei. For a collision at the barrier the distortion energy at contact is mostly potential, and although the distortion is somewhat smaller than Geilikman's the barrier increase is somewhat greater. However, for a wide variety of nuclei the adiabatic estimate of the barrier is fairly good. Representative results are given in Fig. 1 where Z and A are chosen from Green's[5] line of beta stability. Green's nuclear radius and fission parameter $Z^2/50A$ are adopted. ω_1 and ω_2 are the hydrodynamic values of the free oscillation frequencies. E_B and $E_B{}^0$ are, respectively, the calculated barrier height and its undistorted value.

From these results it is clear that a heavy compound nucleus formed at the barrier has a very large collective energy and, in particular, much more energy than is required to fission through a prolate shape. For example, for the nuclei $A_1=A_2=108$, a collision at the barrier yields a spherical compound nucleus of 122-MeV excitation, and a "quadrupole" scission shape with 96-MeV excitation remaining. These energies can be lowered by assuming a larger radius constant or by a more careful choice of the mass defects. However, so long as one admits the validity of the liquid-drop model the collective vibration will exceed

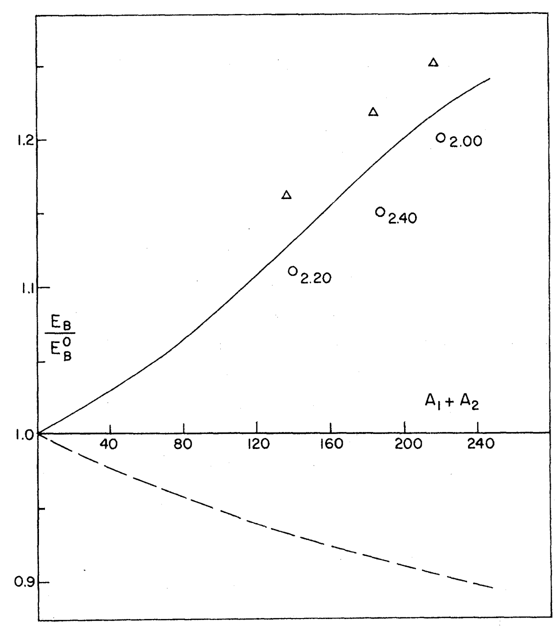

FIG. 1. Effect of Coulomb distortion on the Coulomb barrier for liquid-drop nuclei. The solid line is for the oblate static shapes of Geilikman and the dashed line for the prolate static shapes, both for $A_1=A_2$. The three triangles are dynamically calculated values for $A_1=A_2$. The circles are also dynamically calculated but for $A_1\neq A_2$ and the numbers labeling them are the ratios ω_1/ω_2.

the static prolate minimum by several tens of MeV and immediate fission should result.

For collisions below the barrier these distortion effects are closely related to Coulomb excitation theory, but we have not developed the correspondence. It should be mentioned in this connection that the Geilikman interaction includes moderately large terms which are neglected in the usual multipole expansion of the trajectory and that the large classical oscillation amplitudes which we find imply that high-order perturbation theory is needed. In any case, it is indicated that strong vibrational excitation will be observed in collisions of heavy ions.

I wish to thank G. Breit, G. T. Garvey, and J. Weneser for conversations on this work and J. Vitale for programming the integrations.

*Work supported in part by the U. S. Atomic Energy Commission.

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TWO-PROTON FINAL-STATE INTERACTIONS IN THE REACTIONS $D(^3He, t)2p$ AND $^3He(d, t)2p$ AT A CENTER-OF-MASS ENERGY OF 21 MeV*

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(Received 6 April 1967)

Triton spectra were measured at 0 and 3° for the reaction $D(^3He,t)2p$ and at 5° for the reaction $^3He(d,t)2p$ at the same c.m. energy (21 MeV). The results were compared with predictions of the Watson-Migdal final-state interaction theory, and the proton-proton scattering length a_p was determined for each reaction. Although the overall fit for the first reaction is poor, the best fit to the high-energy region of the data is obtained for $a_p = -12.6 \pm 0.6$ F. For the second reaction, $a_p = -7.3 \pm 0.6$ F gives a reasonably good overall fit.

Final-state interactions of two nucleons continue to be of interest, particularly from the point of view of determining the $^1S_0$ scattering length for two neutrons, a_n. Recently[1] the ^3He spectra at 6 and 8° (lab) from the reaction $T(d, {}^3He)2n$ were analyzed using the final-state interaction theory of Watson[2] and Migdal[3] and gave a value of $a_n = -16.1 \pm 1.0$ F. Application of the simple Watson-Migdal theory was justified by analysis of the triton spectrum at 8° (lab) from the reaction $^3He(d,t)2p$ for the same c.m. energy. Using the same theory a value of $a_p = -7.41^{+0.39}_{-0.49}$ F was found,[1] which agrees with the results of low energy free p-p scattering. The scattering length a_n from this experiment agrees with the result of the $D(\pi^-, \gamma)2n$ experiment[4] where $a_n = -16.4 \pm 1.3$ F, and also agrees with the theoretical prediction of Heller, Signell, and Yoder[5] based on charge symmetry of nuclear forces and the experimental value for a_p. In disagreement with the above results, similar analyses[6,7] of the proton spectra from the reaction $D(n,p)2n$ for an incident neutron energy of 14 MeV gave $a_n = -21 \pm 2$ F, and $-23.6^{+2.0}_{-1.6}$ F. The final-state interaction of two protons has also been observed[8] in the reaction $^3He(p,d)2p$ for 12-MeV incident protons. However, the high-energy peak was found to be much narrower than the prediction of the Watson-Migdal theory.

The final-state interaction theory as formulated by Watson and Migdal does not include the details of the reaction mechanism other than that the interaction be of short range. As a test of the applicability of this theory we report here results for the reactions $D(^3He, t)2p$ and $^3He(d, t)2p$ involving two protons in the final state. Experimental conditions were chosen so that the tritons correspond to 0 and ~180° emission from the same initial reaction: $^3He + d$ at 21 MeV c.m. energy. The two final states presumably result from different reaction mech-