Canada.

---

[1] H. G. Pugh, P. G. Roos, A. A. Cowley, V. K. C. Chang, and R. Woody, Phys. Lett. 46B, 192 (1973).

[2] R. Frascaria, P. G. Roos, M. Morlet, N. Marty, A. Willis, V. Comparat, and N. Fujiwara, Phys. Rev. C 12, 243 (1975).

[3] H. Tyrén, S. Kullander, O. Sundberg, R. Ramachandran, P. Isacsson, and T. Berggren, Nucl. Phys. 79, 321 (1966).

[4] C. F. Perdrisat, L. W. Swenson, P. C. Gugelot, E. T. Boschitz, W. K. Roberts, J. C. Vincent, and J. R. Priest, Phys. Rev. 187, 1201 (1969).

[5] P. G. Roos, Phys. Rev. C 9, 2437 (1974).

[6] C. A. Goulding, B. T. Murdoch, M. S. deJong, W. T. H. van Oers, and R. H. McCamis, Nucl. Instrum. Methods 148, 11 (1978).

[7] N. Chant, private communication.

[8] S. W.-L. Leung and H. S. Sherif, Can. J. Phys. 56, 1116 (1978).

[9] B. S. Podmore and H. S. Sherif, in *Few Body Problems in Nuclear and Particle Physics*, edited by R. J. Slobodrian *et al.* (Les Presses de l'Université Laval, Laval, 1975), p. 517.

[10] N. S. Chant, P. Kitching, P. G. Roos, and L. Antonuk, Phys. Rev. Lett. 43, 495 (1979).

[11] R. D. Haracz and T. K. Lim. Phys. Rev. C 9, 569 (1974).

Time-Dependent Hartree-Fock Fusion Calculations for ^{86}Kr + ^{139}La and ^{84}Kr + ^{209}Bi Collisions

K. T. R. Davies
Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

and

K. R. Sandhya Devi
Department of Theoretical Physics, University of Manchester, Manchester M13 9PL, United Kingdom

and

M. R. Strayer
Department of Physics, Yale University, New Haven, Connecticut 06520

(Received 18 October 1979)

Time-dependent Hartree-Fock fusion calculations are presented for head-on collisions of ^{86}Kr + ^{139}La and ^{84}Kr + ^{209}Bi. A large fusion region is found for moderately high energies above the Coulomb barrier, and a lower limit for the fusion cross section of ^{84}Kr + ^{209}Bi $\rightarrow {}^{293}_{119}X^*$ is estimated from non–head-on collisions. Also, fusionlike behavior is found for a narrow range of energies near the barrier.

It is important to understand deep-inelastic scattering and fusion in time-dependent Hartree-Fock (TDHF) calculations of heavy-ion collisions in which the composite mass is greater than 200.[1,2] This concern is motivated in part by experimental studies[3] of reactions such as ^{84}Kr + ^{209}Bi, which exhibits considerable strong damping but has very small fusion cross sections.[4] Another fundamentally important reason for such TDHF studies is to determine whether fusion can be found for reactions which could conceivably lead to the formation of superheavy nuclei.[5] The most significant result reported in this paper is the discovery of a large fusion region beginning at $E_{\rm lab} \approx 850$ MeV for the reaction ^{84}Kr + ^{209}Bi $\rightarrow {}^{293}_{119}X^*$. This is the heaviest composite system for which fusion has been found in a TDHF calculation.

In studies[2] of the ^{86}Kr + ^{139}La system, we have observed new dynamical features, foremost among which is the existence of a fusion energy threshold (i.e., an energy above the Coulomb barrier below which fusion does not occur). For heavy nuclear systems such thresholds have been seen in macroscopic fluid-dynamic calculations.[6] Even though TDHF studies are quite different from such macroscopic approaches, this threshold effect might qualitatively be explained as follows. The energy above the Coulomb barrier must be sufficiently high so that the two ions *strongly* interpenetrate one another, and if enough energy is dissipated the system may fuse. In this paper we study the fusion behavior for collisions of ^{86}Kr + ^{139}La and ^{84}Kr + ^{209}Bi, and we find a threshold behavior that is more complicated than that observed in previous calculations.[2,6]

We specialize our TDHF computations to mainly head-on collisions. The advantage of treating central collisions is that we can use an axially symmetric, two-dimensional code[1,2,7] which reproduces exactly three-dimensional results[8] for the head-on case. Other details of the calculation are identical to those given in Refs. 1, 2, and 7.

In our calculations the system is assumed to be fused if the rms radius of the total system and the fragment separation coordinate[7] R both undergo several complete oscillations.[8,9] For cases that fused it is found that the systems remain coalesced for times greater than 4.5×10^{-21} sec, which is greater than the collision time but much less than the decay time of the compound nucleus.

$^{86}Kr+{}^{139}La$.—We previously made preliminary axially symmetric calculations[2] of this system at $E_{\rm lab}=505$, 610, and 710 MeV, at which energies there are experimental data.[10] Improved TDHF studies[11] are presently being done using the separable, two-dimensional model.[12,13] Also, analysis is in progress to determine the experimental fusion cross sections.[14]

In Table I we list results for head-on collisions. For cases in which fusion does not occur, it is seen that the final c.m. energy of the separated fragments is very nearly constant over the complete range of energies studied and is well below the entrance-channel Coulomb barrier.[1,2] There are two distinct regimes where fusionlike behavior is observed: a narrow energy region just above the Coulomb barrier at about $E_{\rm lab}=410$ MeV, and also for a broad band of energies from $E_{\rm lab}\approx 650$ to 850 MeV. The fusion behavior exhibited near the barrier is significantly different from that seen at the higher energies. At $E_{\rm lab}=410$ MeV the coalesced shape resembles an asymmetric dumbbell, with rms radii of 6.1 and 6.8 fm for the end sections joined by a large neck whose radius is 4.5 fm. In the higher-energy regime we observe much more compact shapes. Strictly speaking, the long-lived configuration at 410 MeV does not satisfy our criterion for fusion since the rms radius has not undergone several oscillations even though it remains coalesced for times greater than 5.0×10^{-21} sec. Finally, for cases when the fragments separate, the Kr-like fragment is always "reflected from" the target for all energies below $E_{\rm lab}\approx 660$ MeV, whereas for $E_{\rm lab}\gtrsim 860$ MeV it "passes through" the target, exhibiting the transparency behavior always seen in studies of lighter heavy ions.[8,9]

$^{84}Kr+{}^{209}Bi$.—In exploring the energy region above the Coulomb barrier, we observed at $E_{\rm lab}=510$ and 525 MeV very long-lived configurations in which the fragments separate with $\tau_{\rm int}=4.2$ and 4.1×10^{-21} sec, respectively. Thus, the type

TABLE I. TDHF results for head-on collisions of ^{86}Kr$+{}^{139}$La. $E_{\rm c.m.}$ and $E_{\rm c.m.}{}^f$ are the initial and final c.m. energies in MeV. $\tau_{\rm int}$ is the interaction time (Ref. 1) in units of 10^{-21} sec.

$E_{\rm lab}$	$E_{\rm c.m.}$	$E_{\rm c.m.}{}^f$	$\tau_{\rm int}$
310.0	191.5	189.6	0
360.0	222.4	195.0	0.95
410.0	253.3	...	>5.0
460.0	284.2	196.3	3.50
505.0	312.0	193.4	2.28
610.0	376.8	192.3	2.60
660.0	407.7	Fusion	
710.0	438.6	Fusion	
810.0	500.4	Fusion	
840.0	518.9	Fusion	
860.0	531.3	195.4	3.65
910.0	562.2	193.3	1.55

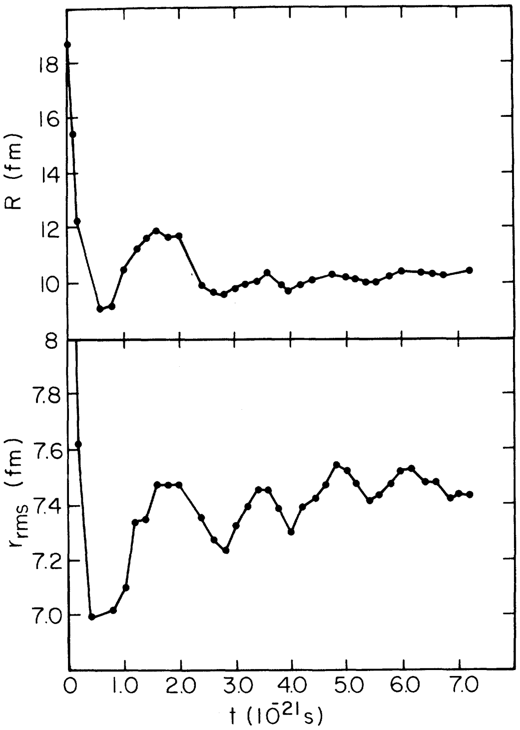

FIG. 1. The fragment separation coordinate (Ref. 7) R and the rms radius as functions of time for a head-on collision of ^{84}Kr$+{}^{209}$Bi at $E_{\rm lab}=850$ MeV. For comparison, the rms radius of the fused *spherical* system (Ref. 15) is 6.30 fm.

of dynamical resonance seen near the barrier in $^{86}\mathrm{Kr}+{}^{139}\mathrm{La}$ persists in this reaction. We also find a high-energy fusion region, which extends from $E_{\mathrm{lab}}=850$ to 1100 MeV. The upper and lower limits have been approximately determined; fusion does *not* occur for $E_{\mathrm{lab}}=800$ MeV or for $E_{\mathrm{lab}}=1200$ MeV (for which case the Kr-like ion "passes through" the target). In Fig. 1 we show the behavior of the rms radius and the fragment separation coordinate[7] as functions of time for $E_{\mathrm{lab}}=850$ MeV. It is seen that these quantities undergo many oscillations. For this case we followed the dynamical evolution up to a time of 7.5×10^{-21} sec, at which point the system still remained fused. In Fig. 2 we display density contour plots for $E_{\mathrm{lab}}=850$ MeV. The basic shape remains essentially unchanged after about 3.0×10^{-21} sec.

We have made an estimate of the fusion cross section for $^{84}\mathrm{Kr}+{}^{209}\mathrm{Bi}$ using the sharp-cutoff approximation,[8,9] for which we must consider non-head-on collisions. We find at $E_{\mathrm{lab}}=875$ MeV that the system fuses for an angular momentum of $l=75\hbar$ but not for $l=100\hbar$, which implies that $99<\sigma_{\mathrm{fusion}}<176$ mb, which is about 5% of the total reaction cross section. The method employed in our calculations is the axially symmetric model[1,2,7] which is unreliable at the energies being considered. However, this model has previously underestimated the amount of fusion[9] and thus the above result is a *lower limit* for the fusion cross section. This should be compared with very rough estimates of *upper limits* for the experimental fusion cross sections at lower energies,[4] which are 177 mb at $E_{\mathrm{lab}}=598$ MeV and 240 mb at $E_{\mathrm{lab}}=714$ MeV.

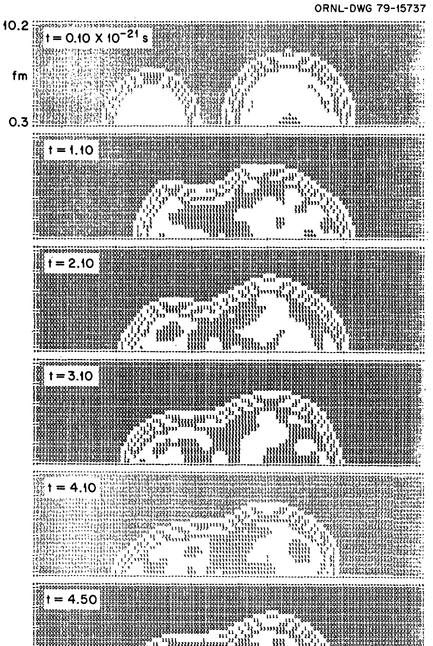

FIG. 2. Equidensity contours for various times during the head-on collision of $^{84}\mathrm{Kr}+{}^{209}\mathrm{Bi}$ at $E_{\mathrm{lab}}=850$ MeV.

Our results suggest that it would be interesting to investigate experimentally the behavior of $^{84}\mathrm{Kr}+{}^{209}\mathrm{Bi}$ for $E_{\mathrm{lab}}\gtrsim 800$ MeV. However, despite the fusion observed in our calculations, it is unlikely that a stable superheavy formation will be found.[16] First, our fused composite system may not survive long enough to form a compound nucleus. In particular, the neglect of pairing in our calculations might inhibit preequilibrium fission.[5] Even if the compound nucleus $^{293}119$ were formed, its excitation energy would be very high[17] ($\approx$ 300 MeV for $E_{\mathrm{lab}}=850$ MeV) and its fission barrier[17] would be small ($\approx$ 3 MeV). Thus, the system would probably fission at some point during the deexcitation process.[16,18]

This research was supported by the Division of Basic Energy Sciences, U. S. Department of Energy, under Contract No. EY-76-C-02-3074, and under Contract No. W-7405-eng-26 with the Union Carbide Corporation; by the National Science Foundation Grant No. Phy 78-11577; and by the Science Research Council Daresbury Laboratory. We would like to acknowledge useful discussions with D. M. Brink, S. E. Koonin, J. B. McGrory, and F. Plasil.

---

[1] K. T. R. Davies, V. Maruhn-Rezwani, S. E. Koonin, and J. W. Negele, Phys. Rev. Lett. 41, 632 (1978).

[2] K. T. R. Davies, K. R. Sandhya Devi, and M. R. Strayer, Phys. Rev. C 20, 1372 (1979).

[3] W. U. Schröder and J. R. Huizenga, Annu. Rev. Nucl. Sci. 27, 465 (1977).

[4] J. R. Huizenga, unpublished data.

[5] R. Y. Cusson, J. Maruhn, and W. Greiner, to be published. At the 1979 TDHF Workshop (at Orsay, France), R. Y. Cusson reported TDHF fusion for $^{48}\mathrm{Ca}+{}^{238}\mathrm{U}$.

[6] J. R. Nix and A. J. Sierk, Phys. Rev. C 15, 2072 (1977).

[7] K. T. R. Davies and S. E. Koonin, to be published.

[8] H. Flocard, S. E. Koonin, and M. S. Weiss, Phys. Rev. C 17, 1682 (1978); P. Bonche, B. Grammaticos, and S. E. Koonin, Phys. Rev. C 17, 1700 (1978).

[9] S. J. Krieger and K. T. R. Davies, Phys. Rev. C 18, 2567 (1978), and 20, 167 (1979).

[10] R. Vandenbosch, M. P. Webb, P. Dyer, R. J. Pugh,

R. Weisfield, T. D. Thomas, and M. S. Zisman, Phys. Rev. C 17, 1672 (1978).

[11] B. Flanders, P. Bonche, S. E. Koonin, and M. S. Weiss, unpublished.

[12] K. R. Sandhya Devi and M. R. Strayer, J. Phys. G 4, L97 (1978), and Phys. Lett. 77B, 135 (1978).

[13] S. E. Koonin, B. Flanders, H. Flocard, and M. S. Weiss, Phys. Lett. 77B, 13 (1978).

[14] R. Vandenbosch, private communication.

[15] D. Vautherin and D. M. Brink, Phys. Rev. C 5, 626 (1972).

[16] J. R. Nix, Annu. Rev. Nucl. Sci. 22, 65 (1972).

[17] William D. Myers, *Droplet Model of Atomic Nuclei* (Plenum, New York, 1977).

[18] R. Vandenbosch and J. R. Huizenga, *Nuclear Fission* (Academic, New York, 1973).

Fusion Doorway States in the $^{12}C + ^{12}C$ System

R. H. Lemmer
Department of Physics and Nuclear Physics Research Unit, University of the Witwatersrand, Johannesburg, South Africa

and

C. Toepffer(a)
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

(Received 2 October 1979)

The role of isoscalar giant quadrupole excitations in ^{24}Mg as doorway states for symmetric fission and intermediate structure resonances in $^{12}C + ^{12}C$ elastic scattering is investigated by means of model calculations using particle-hole excitations over two major shells. The fission mode is treated as a shape degree of freedom that couples the giant quadrupole resonances in ^{24}Mg to the ground state. The associated intermediate-structure resonances have calculated widths for symmetric fission and γ decay that are in qualitative agreement with experiment.

In earlier attempts to explain the resonance structure observed in various reaction channels at energies in the vicinity of the Coulomb barrier in the ^{12}C-^{12}C system, the emphasis has been on the role played by quasibound states, shape resonances, and inelastic excitations[1-3] of the fragment nuclei leading to a double-resonance mechanism.[4] Such models, however, are not able to describe the narrow widths of the resonances found at higher energies in ^{12}C-^{12}C reactions. These resonances form a higher-lying rotational band[5] and can be interpreted in terms of an intermediate-structure mechanism in which elementary excitations in the rotating ^{24}Mg compound nucleus serve as doorway states.[6,7] Extrapolating downwards, one expects the head of the high-lying band at energies near the Coulomb barrier, and the question arises whether resonances there are the low-spin members of that band and what the nature of the elementary excitation modes is. The Coulomb barrier in the ^{12}C-^{12}C system lies at about 6 MeV, corresponding to $E_x = 20$ MeV excitation energy in ^{24}Mg. The dominant symmetric excitation mode in this energy region is the isoscalar giant quadrupole resonance (GQR) which exhausts $(65 \pm 25)\%$ of the energy-weighted sum rule (EWSR) for 15 MeV $\leq E_x \leq 24$ MeV.[8] A GQR has indeed been recently identified as a doorway in the symmetric, electron-induced photofission[9] of ^{24}Mg and in the time-reversed reaction, the radiative capture[10] of one ^{12}C by another ^{12}C. Both reactions show a narrow $I^{\pi} = 2^+$ resonance of total width $\Gamma = 260 \pm 70$ keV near $E_x = 22$ MeV with γ-ray and fission widths[10,11] $\Gamma_\gamma(\mathrm{eV})\, \Gamma_f(\mathrm{keV}) = 35 \pm 10$.

In order to describe such processes we consider the coupling of the elastic $^{12}C + ^{12}C$ channel to elementary excitation modes of the *compound system* that act as doorway states during fission or fusion. We identify these modes with the isoscalar GQR excitations in ^{24}Mg and describe them as interacting particle-hole excitations in a rotating two-center shell-model (TCSM) potential.[12] The distance R between the two potential minima serves as a single shape parameter, $R \to \infty$ corresponding to the fission mode. A typical doorway state of angular momentum I with projection M thus has the structure $D_{MK}{}^{I} | \alpha, K\rangle$, where $|\alpha, K\rangle$ refers to all intrinsic excitations having a common projection $I_3 = K$ along $\vec{R}$. A schematic random-phase-approximation (RPA) calculation[12] leads to a set of model excitation energies $E_{\alpha K}$