Doc Saclay

Seminar on heavy ion physics
Alushta, USSR
14-21 April 1983
CEA-CONF- 6700

FAST FISSION PHENOMENA

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We review the conditions under which two heavy ions can fuse together. Then we discuss fast fission mechanism which is an intermediate mechanism between inelastic and compound nucleus reactions.

The existence of heavy ion accelerators has permitted to investigate the interaction between two pieces of nuclear matter. A large amount of studies have been devoted to the possibility of merging two heavy ions in a single system. At the begining of these investigations the main goal was to try to synthetize new nuclei. Very soon it has also appeared that the fusion mechanism was very passionating in itself. Therefore many systematic studies have been undertaken to understand under which conditions two heavy ions can fuse together.

When light heavy ions are used (typically ^{12}C, ^{14}N, ^{16}O...) the fusion cross section is a large part of the total reaction cross section. For bombarding energies smaller than about $\sim$ 10 MeV/A, the fusion of two heavy ions corresponds to the formation of an excited compound nucleus. Therefore the fusion cross section can be identified with the compound nucleus cross section. With the advent of heavier ion beams, like ^{40}Ar or ^{84}Kr for instance, it was very tempting to extrapolate our knowledge of lighter systems. In particular we could think that the fusion cross section was still a large part of the total reaction cross section and that in any case a compound nucleus was formed. It happened that all these extrapolations were all wrong for very heavy systems and the experimentalists were faced with unexpected observations. The most surprising one was that two very heavy ions cannot fuse together /1/. To be more specific, this happens when the product Z_1Z_2 of the two atomic numbers of the projectile and of the target is larger than about 2500-3000. This finding turned out to be very dramatic for all the attempts to synthetize the superheavy element by the fusion of two very heavy ions.

Problems have also appeared in the understanding of the fusion of medium systems (typically with Ar ions and medium, heavy targets). Indeed it is convenient to parametrize the fusion cross section in terms of a critical angular momentum ℓ_{cr}. This quantity is the largest orbital angular momentum value ℓ, leading to fusion. It is deduced from the experimental fusion cross section under the two following assumptions : 1. that the lowest ℓ values contribute only to fusion, 2. that the sharp cut off approximation is good. This mean that all ℓ values between 0 and ℓ_{cr} lead to fusion. Now if we consider a compound nucleus, we know that its fission barrier decreases when the angular momentum increases /2/. This barrier vanishes for a value of the angular momentum equal to ℓ_{Bf}. Consequently a compound nucleus cannot be formed with an angular momentum larger than ℓ_{Bf}. If fusion would be identical to compound nucleus formation we should always have $\ell_{cr} \leqslant \ell_{Bf}$. For these medium systems, this turned out not to be the case and many examples can be found in the litterature /3/ where $\ell_{cr} > \ell_{Bf}$. The large differences between ℓ_{cr} and ℓ_{Bf} which can be observed cannot be ascribed to a wrong calculation of ℓ_{Bf} which is of course model dependent. Consequently fusion cannot always be identified with compound nucleus formation. For these medium systems it has been proposed that the extra fusion cross section which has been observed comes from a new mechanism intermediate between deep inelastic and compound nucleus reactions : fast fission /4-7/.

In this lecture, we will present our actual understanding of the fusion process. We will in particular discuss what is fast fission and under which conditions it can be observed. The discussion will be schematic with a special emphasis on the physical ideas. Nevertheless this schematic description is based on the results of a dynamical model which has been developed for dissipative heavy ion collisions /3,6,7/. This model allows to treat deep inelastic reactions as well as fusion. For technical details and more complete results, we refer the reader to refs.3,6,7.

1. Limits for fusion

The interaction potential between to heavy ions plays a dominant role in heavy ion collisions. It is one of the basic input in dynamical models for dissipative reactions and some of its feature are of special importance for the fusion process.

Two kinds of interaction potentials can be defined wich correspond to two limiting situations : 1) the sudden potential which is calculated assuming that the densities of the two incident ions remain frozen during the collision. 2) the adiabatic potential where the energy of the system is minimized at each step of the process. The sudden potential is more realistic at the very beginning of the collision. The adiabatic potential is more appropriate to describe the fission process. In strong interactions there is a continuous evolution between the entrance potential, which is well described by the sudden potential, and the exit potential which is, in many cases, close to the adiabatic one. The dynamical model of ref. /6/ makes this transition between the sudden and the adiabatic potential in a phenomenlogical way. Of course not all the impact parameters will have an adiabatic potential in the exit channel : the overlap between the two ions should be large enough during the collision.

The fact that we have fusion or not seems to be entirely determined by the entrance channel, and, consequently, by the sudden potential. We will get fusion if the system can be trapped into the pocket of the interaction potential. Therefore we should first examine the conditions under which we have a pocket in the interaction potential of two heavy ions. We shall use for that the energy density potential developped in ref. 8. which has proved to be quite successful when it is used to describe heavy ion collisions.

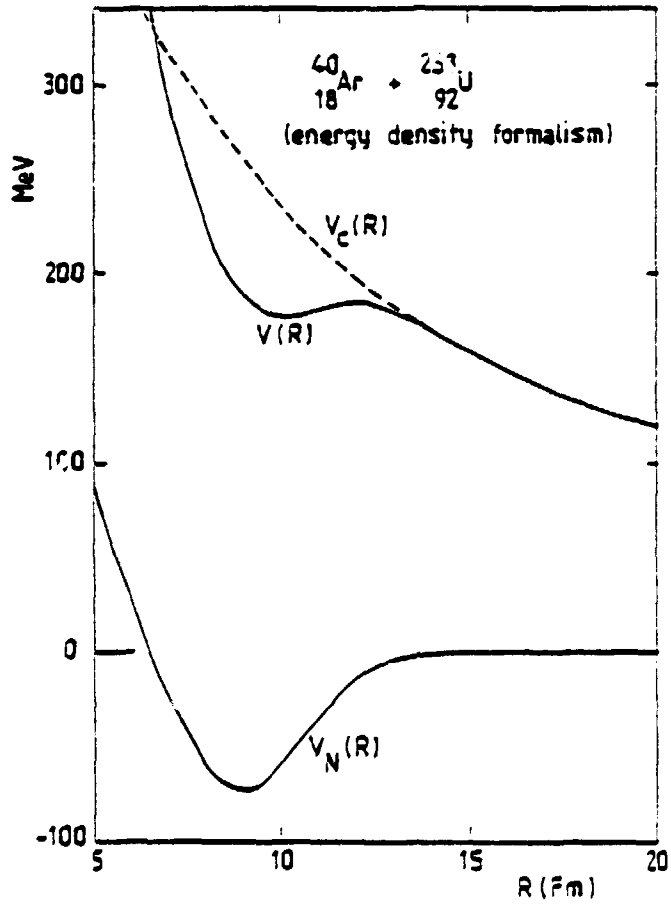

Fig. 1. Total interaction potential V(R), for a head on collision, as a function of R, the distance separating the center of mass of the two ions. V_N is the nuclear part and V_C the Coulomb one. This calculation has been done using the energy density formalism and the sudden approximation of ref. 8 for the $^{40}Ar + ^{238}U$ system.

In fig. 1 is shown, as an example, the interaction potential for the $^{40}Ar + ^{238}U$ system calculated in ref. 8 for a head on collision. The total interaction potential, $V_c(R)$, is the sum of two terms : the nuclear potential $V_N(R)$, and the

Coulomb potential, $V_C(R)$. R is the distance separating the center of mass of the two ions. We see that V(R) has a pocket which will allow the system to be trapped. Consequently we can have fusion for this system.

The pocket can disappear because of two reasons : 1. due to the orbital angular momentum ℓ, 2. due to the Coulomb field.

For a given system, if we increase the orbital angular momentum, the depth of the pocket will decrease because the centrifugal force is repulsive. For large ℓ values this pocket will disappear. This is illustrated in fig. 2. for the Ar + U system where V(R) is plotted for different ℓ values. If ℓ_{sup} is the ℓ value for which the pocket just disappears, it should nevertheless be noted that we can have fusion for ℓ values just above ℓ_{sup}. The reason is that tangential friction reduces the initial orbital angular momentum. However this indicates that the critical angular momentum is bounded at high bombarding energy. As a consequence the fusion cr-ss section will decrease like $1/E_{CM}$.

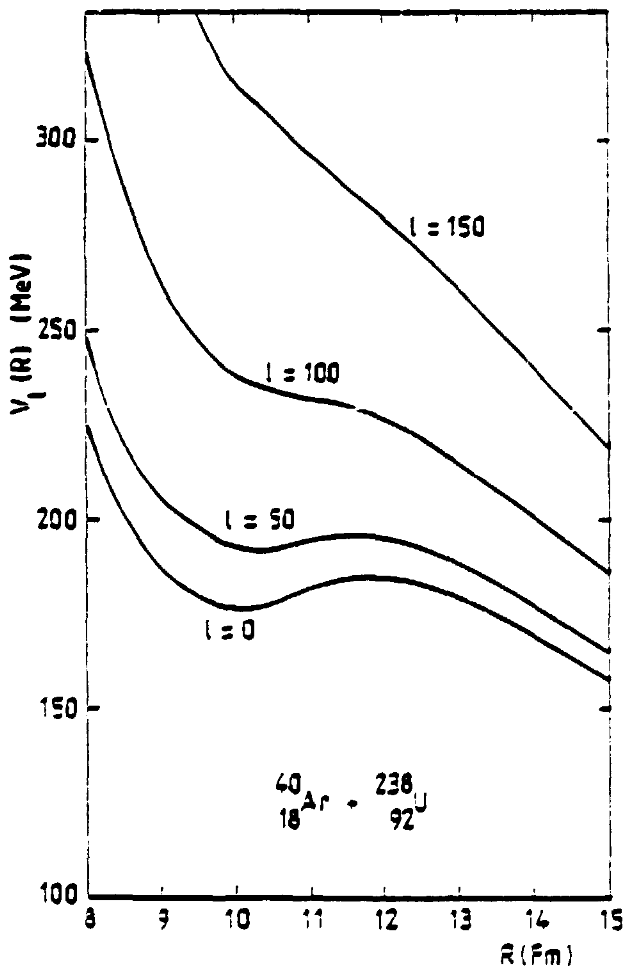

Fig. 2. Total interaction potential V(R) for the $^{40}Ar + ^{238}U$ system calculated for different values of the orbital angular momentum ℓ. (Calculation according to ref. 8).

The second reason for a disappearance of the pocket comes from the Coulomb field between the two incident ions which becomes very large for two very heavy nuclei. The Coulomb force increases like Z_1Z_2 whereas the nuclear force increases only like $(A_1^{1/3}A_2^{1/3})/(A_1^{1/3}+A_2^{1/3})$ /9/. For very heavy systems the Coulomb force cannot be counteracted anymore by the nuclear force and the pocket disappears. In fig. 3 is shown an example of such a situation for the $^{208}Pb + ^{238}U$ system.

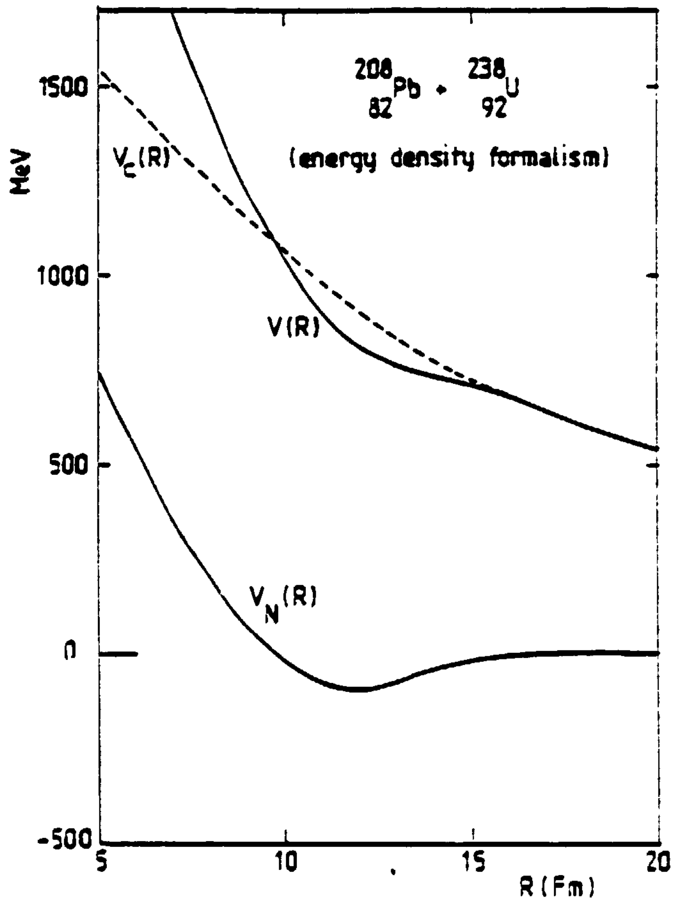

Fig. 3. Same as fig. 1 for the $^{208}Pb + ^{238}U$ system (calculation according to ref. 8).

Using the energy density potential we can show that the pocket disappears when $Z_1Z_2 \geqslant 2500$-3000 and this is about the limits where fusion cannot be anymore observed experimentally. Using the simple parametrization of the energy density potential proposed in ref. 9 we can draw, in the Z_1-Z_2 plane, the line where fusion just disappears. This is shown in fig. 4 (the calculation has been performed for nuclei located along the beta stability line). This line separates the plane in two regions corresponding to fusion and no fusion. We can also express the limitation for fusion due to the Coulomb field using the effective fissility parameter ξ introduced by Swiatecki /10/ :

$$\xi = \frac{4Z_1Z_2}{A_1^{1/3}A_2^{1/3}(A_1^{1/3}+A_2^{1/3})} \qquad (1)$$

According to the energy density potential, fusion should occur only if $\xi \leqslant 47$. For values of $\xi \geqslant 47$ fusion is not possible.

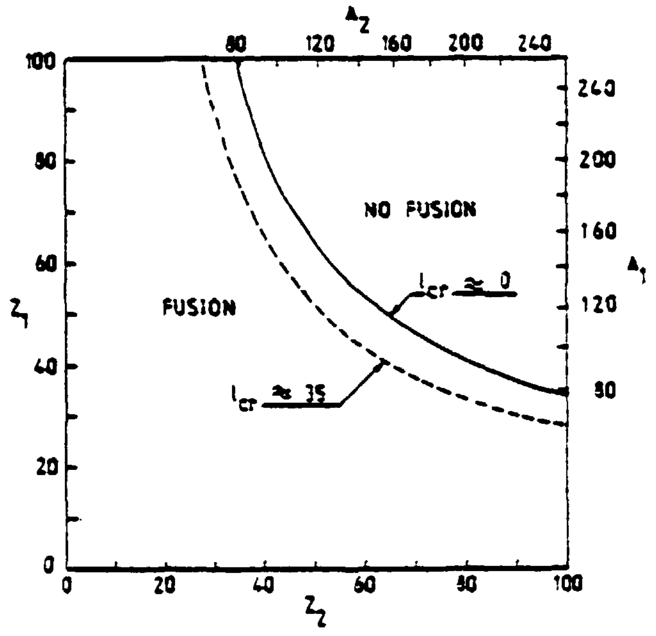

Fig. 4. Limits for the fusion of two heavy ions of atomic number Z_1 and Z_2 belonging to the beta stability line. The full curve corresponds to $\ell_{cr} \simeq 0$ and the dashed one to $\ell_{cr} \simeq 35$ (from ref. 7).

2. Fast fission phenomenon

According to the model of ref. 6, we can observe fast fission only if there is fusion. Consequently the effective fissility parameter should be smaller than about 47. Fast fission can occur in two cases : 1) if the fission barrier of the compound nucleus vanishes due to angular momentum. 2) when the saddle configuration of the compound nucleus is too compact. In this case fast fission has been called quasi-fission.

a - Fast fission due to angular momentum

When the system is trapped into the pocket of the entrance potential (sudden potential) there is fusion. Then, as proposed in ref. 6, there will be a transition from the sudden to the adiabatic potential. At the same time a lot of mass is exchanged between the two parts of the composite system. If the system is not too asymmetric ($x = (A_2-A_1)/(A_2+A_1) \leqslant 0.7$) a symmetric two center configuration will be reached. At variance, if it is too asymmetric ($x \gtrsim 0.7$) a one center system will be formed. If the saddle configuration of the adiabatic potential is less compact than the pocket configuration, two situations can happen : 1) when $l<l_{B_f}$ the system which was trapped into the pocket will remain trapped when the adiabatic landscape will be reached. Consequently there will be an evolution towards the formation of a real

compound nucleus. This compound nucleus can undergo subsequently fission. 2) If $\ell \geq \ell_{B_f}$ the compound nucleus has no more a fission barrier and cannot be formed. The composite system will therefore decay in two fragments. In the case where a two center system is formed this is what is called fast fission. It corresponds to a situation where the system remains trapped for a while before it decays by fission after the mass asymmetry degree of freedom has equilibrated or almost equilibrated.

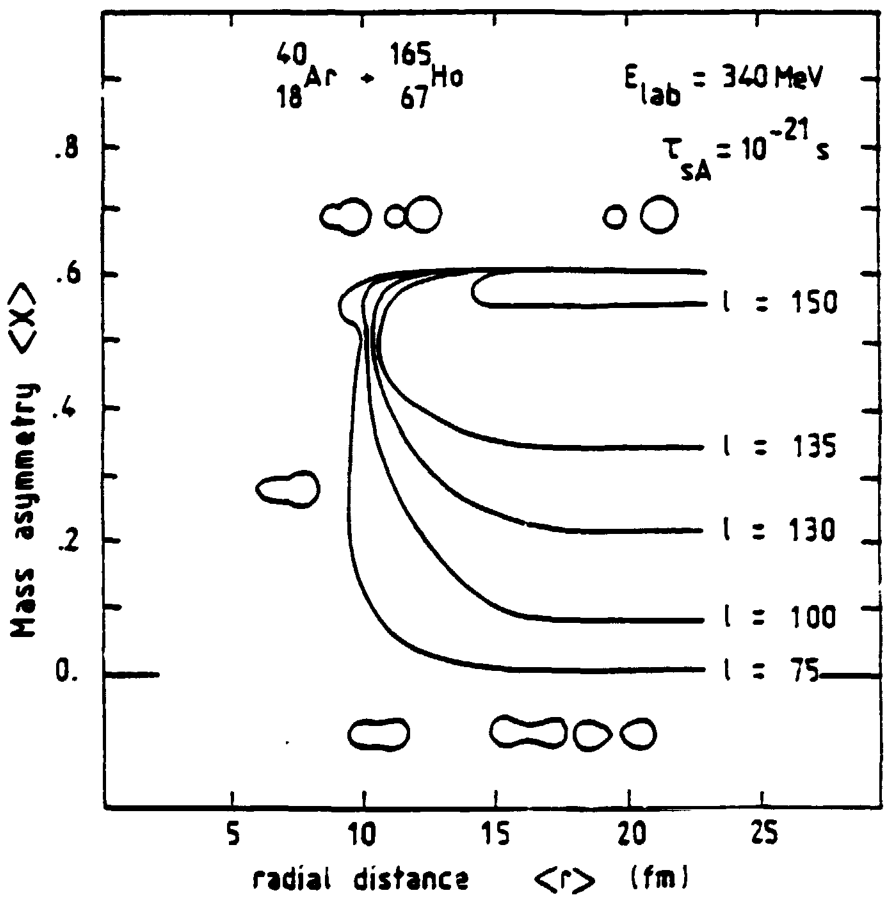

Fig. 5. Typical trajectories in the r,x plane for the 340 MeV $^{40}Ar + ^{165}Ho$ system. r is the distance separating the center of mass of the two ions and x the mass asymmetry coordinate ($x = \frac{A_1 - A_2}{A_2 + A_1}$). From ref. 3.

The above description is illustrated in fig. 5 for the 340 MeV $^{40}Ar + ^{165}Ho$ system. In this figure are shown some mean trajectories followed by the system for different values of the initial orbital angular momentum. For this particular system $\ell_{B_f} = 72$, calculated according to ref. 6.

For $\ell = 150$ there is a strong interaction between the two heavy ions but the system is not trapped and the final masses remain close to the initial ones. This trajectory is a typical deep inelastic reaction.

For $\ell = 75$, 100, 130 and 135, the system is trapped into the pocket of the entrance potential. A lot of mass is transferred from the big fragment to the small one and for $\ell = 75$ the mass asymmetry degree of freedom has time to reach equilibrium (x=0). However, these ℓ values are larger than ℓ_{B_f}. Consequently when the adiabatic potential is reached there is no barrier to retain the system and it fissions. These trajectories correspond to fast fission. The interaction time of such a process ranges from 10^{-21}s to 10^{-20}s. It is larger than the interaction time for deep inelastic collisions (10^{-22} - 10^{-21}s) but smaller than the time necessary to form a compound nucleus.

For $\ell < 72$ the system is trapped in the pocket of the entrance potential but it remains trapped when the adiabatic potential is reached because of the fission barrier. Consequently we will get a compound nucleus.

The mass distributions of the fission and fast fission products will be similar. However, for $^{40}Ar + {}^{165}Ho$, the model of ref. 6 predicts that larger widths should be observed for the fast fission products than those for the fission products following compound nucleus formation. This prediction seems to be confirmed by the experiment which shows a large increase of the width of the fission like products when ℓ becomes larger than ℓ_{B_f} /11/.

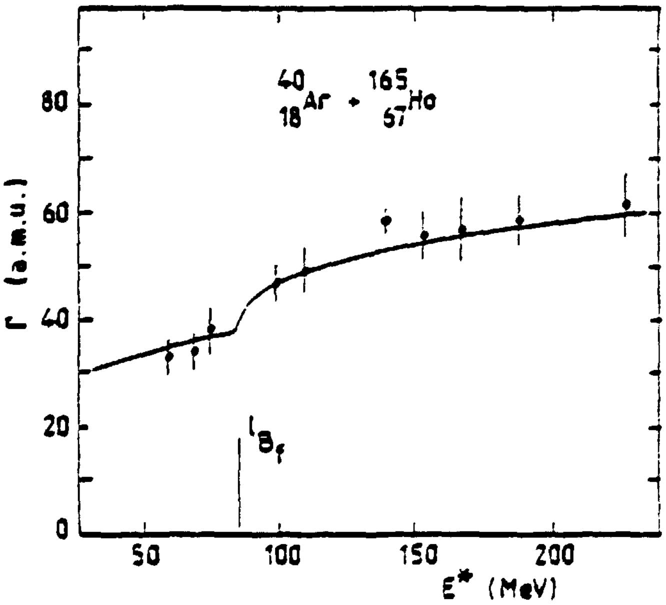

Fig. 6. FWHM of the fission like mass distribution Γ as a function of the excitation energy. The dots are the experimental points of ref. 4. The full curve is the result of the calculation of ref. 7.

In fig. 6 is shown the experimental FWHM of the mass distribution of the fission like products detected in the Ar + Ho reaction at different bombarding energies as a function of the compound nucleus. The dots are the experimental data of refs 4,11

eas the full curve is the calculation of ref. 7. Fast fission starts to con-
ute for excitation energies larger than the one corresponding to the case where
ℓ_{Bf} (indicated in the figure). This is better shown in fig. 7 where the fusion
s section is shown as a function of the inverse center of mass bombarding energy
M. The full curve is the result of the calculation and it rather well reproduces
experimental points (dots). The total fusion cross section can be separated in
contributions which are given by the model calculation : compound nucleus cross
ion (long dashed line) and fast fission cross section (short dashed line). It
ld be noted that the threshold for fast fission is larger than the one for
ound nucleus formation. Indeed fast fission occurs when $\ell > \ell_{Bf}$, consequently
should be larger than ℓ_{Bf}.

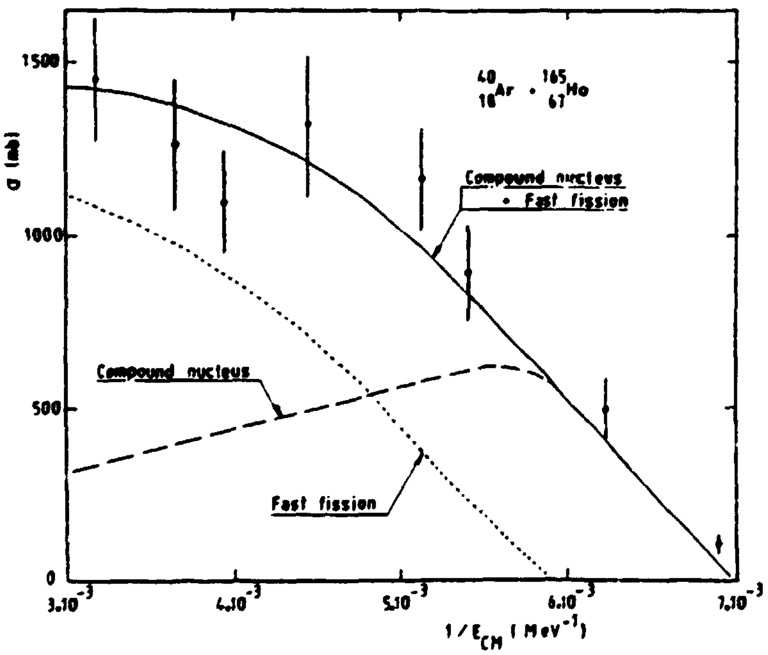

Fig. 7. Experimental fusion cross section (dots) from ref. 4, as a function of $1/E_{CM}$ the inverse of the center of mass energy compared with the theoretical calculation of ref. 6. The full line is the fusion cross section which is the sum of the compound nucleus cross section (long dashed line) and of the fast fission cross section (short dashed line).

- Quasifission

This mechanism has been pointed out by Swiatecki /10/ in the case of heavy
ems and it appears also naturally in our model. It should also be noted that
ifission was also obtained in the model of ref. 12.

We have seen above that for system like Ar+Ho, fast fission occurs when $\ell > \ell_{B_f}$. When $\ell < \ell_{B_f}$ a compound nucleus is formed. When the mass of the compound nucleus increases, the saddle configuration becomes more compact and it can become more compact than the pocket configuration does. This occurs when the fissility parameter $\eta = \frac{Z^2}{A}$ is larger than about 40. As a consequence when the adiabatic potential is reached, the system can nevertheless escape even if the fission barrier is non zero just because it is located on the wrong side of the saddle configuration. Therefore for systems with $\eta \geqslant 40$ we can have fast fission (or quasifission) even if $\ell < \ell_{B_f}$.

Conclusion

Let us now summarize the basic results of the model of ref. 6 concerning fusion (see fig. 8) :

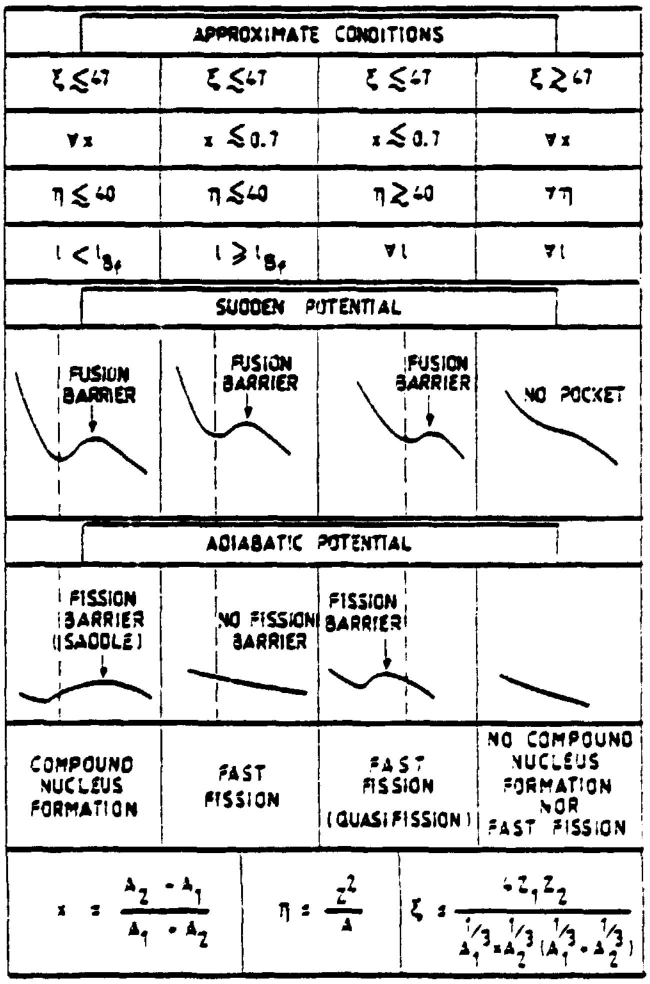

Fig. 8. Schematic description of different mechanisms following fusion. The limiting values of the parameters x,η and ξ should only be taken as orders of magnitude.

Fusion occurs if the effective fissility parameter ξ is smaller than about 47.

When $\xi \lesssim 47$ there is fusion. A compound nucleus can be formed if the saddle configuration is not too compact ($\eta \lesssim 40$) and if $\ell < \ell_{Bf}$. If the two preceding situations are not fulfilled we can have either fast fission ($\eta \lesssim 40$ and $\ell \gtrsim \ell_{Bf}$) or quasifission ($\eta \gtrsim 40$) provided that the system is not too asymmetric ($x \lesssim 0.7$). In the case where the system is very asymmetric ($x \gtrsim 0.7$) the model cannot make any prediction but we will probably be in a situation close to compound nucleus formation although a real compound nucleus will not be formed. It should also be noted that the above numbers are to be considered as order of magnitude.

The introduction of fast fission and quasifission, which appear naturally in dynamical models taking into account of the exit channel, has not changed our old understanding of dissipative heavy ion collisions. However they allow to understand a lot of experimental data which were difficult to understand before. The results of the models appear simple and in some way quite obvious. Although no direct experimental evidence of this mechanisms has been available up to now, there are strong experimental indications that they exist. Therefore more experimental studies should be devoted to this subject.

We were faced with the problem of medium system fusion more than 10 years ago. The present understanding of fusion has been reached after a lot of discussions and I would like to especially thank Christian GREGOIRE, Marc LEFORT, Jean PETER, Bernard REMAUD and Bernard TAMAIN.

I would like also to thank Mrs. F. LEPAGE and T. LECUYER for the material preparation of this manuscript and J. MATUSZEK for drawing the figures.

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