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THE ROLE OF DYNAMICS IN THE FUSION PROCESS

Christian Ngô

Service de Physique Nucléaire - Métrologie Fondamentale
91191 Gif-sur-Yvette Cedex, France

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Service de Physique Nucléaire - Métrologie Fondamentale
91191 Gif-sur-Yvette Cedex, France

Abstract

We review a recent theoretical approach to heavy ion fusion above the Coulomb barrier. We present a simple dynamical model which allow to well reproduce a lot of experimental data. It is shown that the fusion cross section is governed by a dynamical barrier which is, in some cases, different from the static one. Then we investigate what happens to the fused system. It is shown that some of the unexplained experimental data can be understood by the occurence of a new mechanism : fast fission. Its properties are discussed and we give the conditions of occurence for such a mechanism.

Fusion is a process which has a great importance in heavy ion reactions at low bombarding energies. In most of the cases it occurs with a cross section, σ_F, which is a large part of the total reaction cross section. During the collision of two heavy ions which fuse together, all the kinetic energy and orbital angular momentum which are in the entrance channel, are transformed respectively in excitation energy and spin of the fused system. For this reason, fusion can be viewed as the most dissipative phenomena which can be observed in heavy ion collisions. Many models have been developed to explain the fusion process. During the recent years this field has known a renewed interest because of new experimental data [1]. This has pushed the introduction of original ideas and this conference occurs at the right time to make a synthesis of them. In this talk I would like to describe our present understanding of fusion [2,4]. Our main aim will be to try to answer the two following questions :

1. Under which conditions can two heavy ion fuse together and what is the probability of such a process?

2. What happens to the fused system? Do we always form a compound nucleus?

Our aim is to try to get a single picture where all the fusion data can be understood as quantitatively as possible. We will restrict ourselves to the fusion process which occurs above the threshold and up to 10-15 MeV/u.

I. FUSION

1. Some definitions

When two heavy ions fuse they form a system with some excitation energy and angular momentum. It will de-excite by emitting light particles and γ-ray leading to residual nuclei. If the fission barrier is small, or reduced sufficiently by angular momentum, it will fission. The experimental fusion cross section, σ_F, is experimentally defined as the sum of two terms : the evaporation residue cross section, σ_{ER}, and the fission-like cross section, σ_{FL}, which in many cases, is assumed to come from the fission of the compound nucleus :

$$\sigma_F = \sigma_{ER} + \sigma_{FL} \qquad (1)$$

The fusion cross section is very often expressed in terms of a critical angular momentum, ℓ_{CR}, whose definition is displayed in Fig. 1. It is assumed that the lowest ℓ values contribute to fusion and that the sharp cut off approximation is valid. Therefore ℓ_{CR} is the largest ℓ value which fuses. It depends on the system and on the bombarding energy.

From the theoretical point of view, a dissipative heavy ion reaction can be viewed as two colliding nuclei moving on classical trajectories which are governed by potential, inertial and dissipative terms. Fusion will take place if the system is trapped in the interaction region (see Fig. 2). For this to occur the total interaction potential, as a function of the distance R separating the center of mass of the two fragments, should have a pocket. The system can be trapped in this pocket if dissipation is large enough, otherwise we get a deep inelastic reaction.

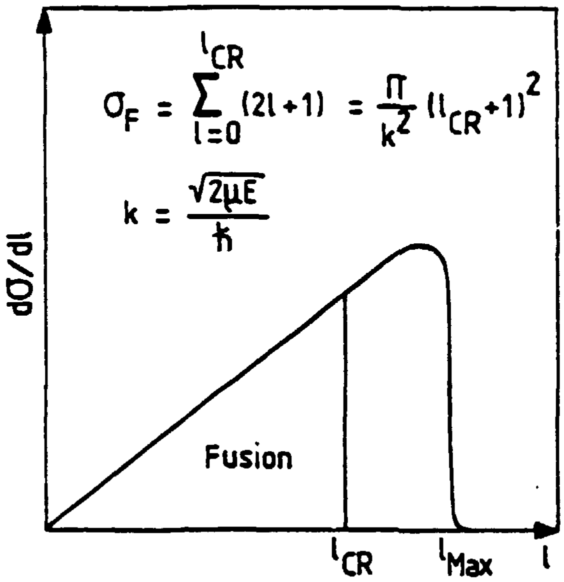


Fig. 1 - Definition of the critical angular momentum for fusion.

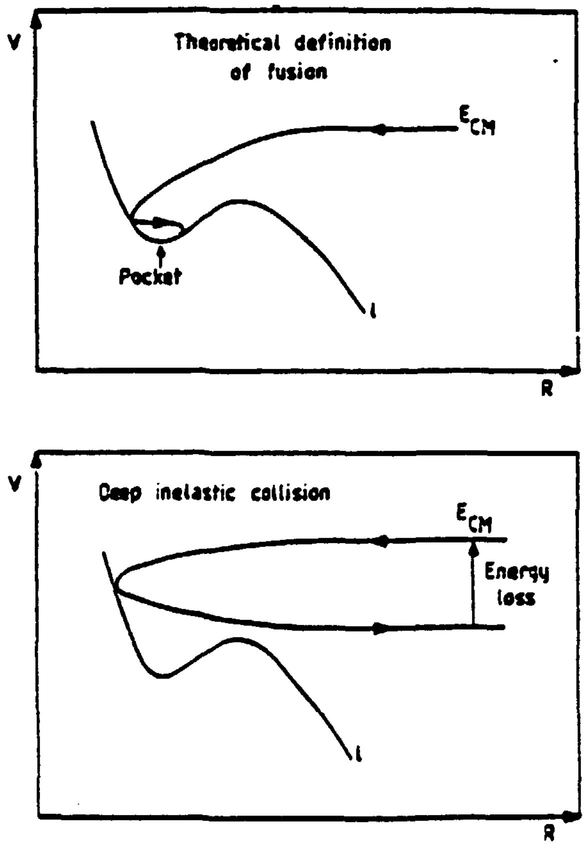


Fig. 2 - Schematic description of fusion and deep inelastic reactions. The total interaction potential V including the centrifugal energy (the orbital angular momentum is ℓ) is plotted as a function of R, the distance separating the center of mass of the two ions. E_{CM} is the initial bombarding energy. A part of it is lost in the interaction region and the system could be trapped (top figure) leading to fusion or escape (bottom part of the figure) giving deep inelastic fragments.

2. Basic features of the fusion cross section

We shall now present, in a schematic way, the principal characteristics of the experimental fusion cross section [1].

1. Fusion can only be observed if the two colliding nuclei are not too heavy [5]. Practically, the product Z_1Z_2 of the atomic numbers of the two ions should not exceed ~ 2500-3000. This means that, even if the superheavy element would exist, it could not be possible to synthesize it by the fusion of two heavy nuclei.

2. - For a given system, where fusion is possible, one observes, for bombarding energies not too far above the Coulomb barrier, that the fusion

cross section goes almost linearly as a function of the inverse of the bombarding energy (see Fig. 3).

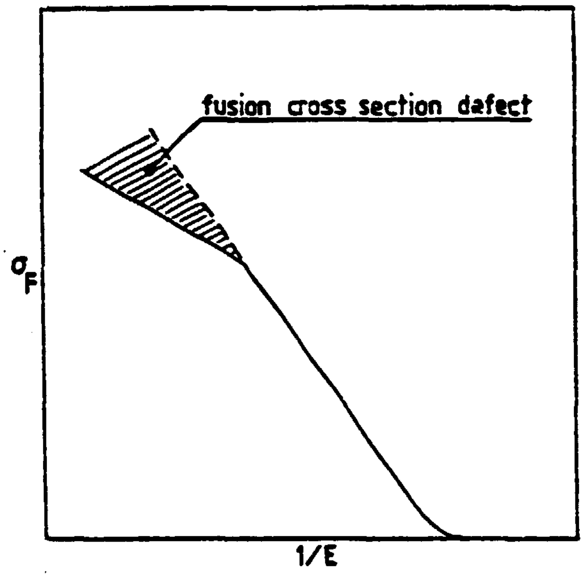


Fig. 3 - Schematic presentation of the fusion excitation function as a function of 1/E. At high bombarding energy we observe a fusion cross section defect compared to an extrapolation of the low energy domain.

3 - For the preceding systems at higher bombarding energies, larger values of the orbital angular, ℓ, are involved. The measured fusion cross section becomes smaller than what can be expected by an extrapolation of the preceding straight line (see Fig. 3). In other words, we observe a fusion cross section defect compared to the extrapolation of the low energy data.

4 - A fusion cross section defect is also observed for systems belonging to the region where fusion just disappears [6] (heavy systems) and this is due to an increase of the fusion threshold which is schematically illustrated in Fig. 4.

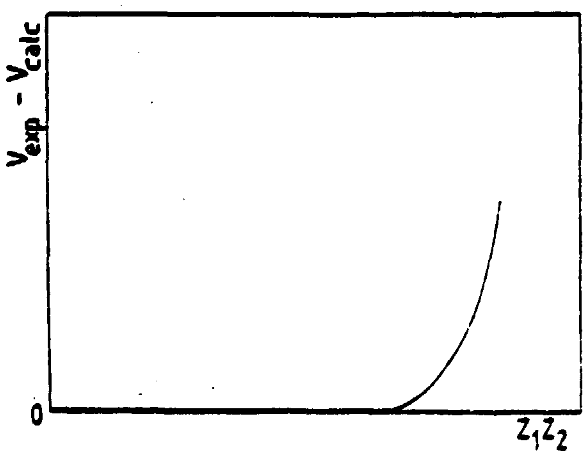


Fig. 4 - Schematic illustration of the difference between the experimental and the theoretical fusion threshold as a function of the product Z_1Z_2 of the atomic number of the two ions.

3. Static considerations

The simplest description of fusion is to use a static approach. It means that we hope to understand the phenomenon by only potential energy considerations. Let us briefly examine the solution of the different points quoted in section 2.

1. The non fusion of very heavy system can be explained by the Coulomb repulsion between the two ions which becomes so strong that the nuclear attraction cannot counteract it any more [7]. Consequently the pocket in the total interaction potential for a head-on collision disappears, and the system cannot fuse. When the following condition is fulfilled [2] :

$$\frac{Z_1 Z_2}{C_1 C_2 (C_1 + C_2)} > 8.7 \tag{2}$$

fusion is no longer possible. In eq.(2) C_1 and C_2 are the central radii of the nuclei ($C_i = R_i - 1/R_i$ and $R_i = 1.16\ A_i^{1/3}$).

2. The region which is just above the Coulomb barrier can be understood by looking if it is possible for the system to overcome the fusion barrier associated to a given initial ℓ. There are now in the literature many interaction potentials which are able to well reproduce the fusion data [8,9] . This is the case for instance of the energy density potential [2,8] which will be used through along this paper.

3. In order to explain the third point it was necessary to introduce a more restrictive condition for fusion. In ref.[10] it was assumed that the necessary condition for the fusion of two nuclei was not only to overcome the barrier, but to reach a certain distance called critical distance for fusion. However there is no deep theoretical justification for this notion.

4. The last point is hard to understand in a static picture, even using the notion of critical distance.

Up to now there is no simple static picture, based on entrance properties of the system, which is able to describe the fusion cross section for all heavy ion combinations, and for all bombarding energies in the range going from the Coulomb barrier up to about 10-15 MeV/u . The reason for that might be found in the fact that the dynamics plays an important role in heavy ion collisions, or that one has to consider also the properties of the compound nucleus (see the talk of S.M. Lee). We shall now show that the dynamics is able to give an overall understanding of the fusion process.

4. New concepts introduced by the dynamics

We know that in heavy ion collisions, where a strong overlap between the two nuclei occurs, dissipation plays a very important role. In a pure static picture, fusion is obtained, for a given ℓ value, if the bombarding energy is larger than the corresponding static fusion barrier associated to this particular collision. However, friction may act before the system reaches the static barrier and some energy loss in the relative motion will result. This is illustrated in Fig. 5 for a head-on and for a non-central collision. We see that, for the system to reach a barrier it will be necessary to provide it with a certain amount of extra energy above the static threshold. This supplement of kinetic energy is necessary to compensate the friction forces which are acting before the system reaches the barrier.

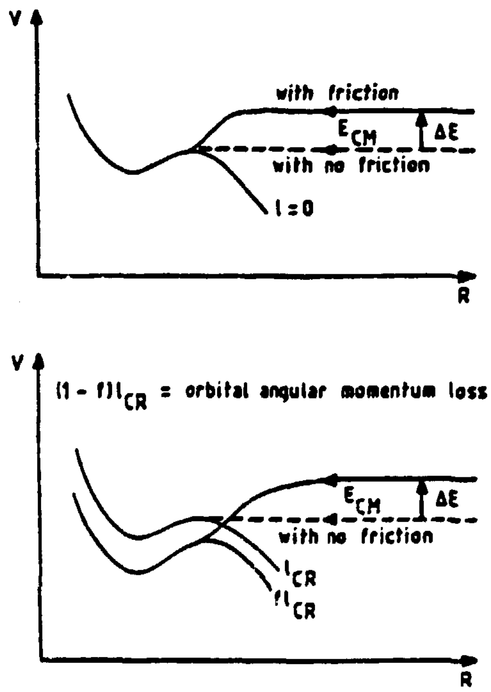


Fig. 5 - Schematic illustration of the fact that some extra kinetic energy is needed to overcome the fusion barrier : on top is the case of a head-on collision. In the bottom when the orbital angular momentum is equal to ℓ_{CR}. In this later case the total interaction potential, including centrifugal energy, changes due to angular momentum loss.

For the largest ℓ value leading to fusion, ℓ_{CR}, we can show that the condition for fusion can be written in the following way :

$$E = V(R_{f\ell_{CR}}) + \frac{\ell_{CR}^2 \hbar^2}{2\mu \; R^2_{f\ell_{CR}}} + \Delta E \qquad (3)$$

The derivation of eq.(3) can be found in ref.[2,3]. It is based on the fact that the energy loss in the tangential motion is, to a good approximation, equal to the change of the rotational energy. V is the total interaction potential (nuclear + Coulomb) for a head-on collision, f the fraction of orbital angular momentum which remains in the relative motion after tangential friction has acted, and μ the reduced mass. ΔE is the dynamical energy surplus and represents the extra energy which we have to provide the system with in order to compensate for friction forces. For a given ℓ value the minimum bombarding energy necessary for fusion will be called the dynamical fusion barrier. The dynamical energy surplus is then defined in the following way :

dynamical energy surplus = dynamical fusion barrier - static fusion barrier

5. Dynamical description of fusion

In ref.[3] we have developed a simple dynamical model based on the preceding ideas. We describe the collision of the two heavy ions by means of two macroscopic variables : the distance separating the center of mass of the two nuclei and the corresponding polar angle. The dynamical evolution of the system is followed by classical equations of motion with friction forces proportional to the velocities [11] (see ref.[3] for more details). According to the one-body picture [12] the tangential friction coefficient is half the value of the radial one. The main difference with other calculations based on the same type of approach is the friction form factor, g(R), for which we took the following expression :

$$g(R) = \frac{1}{1 + \exp(\frac{s-0.75}{0.2})} \qquad (4)$$

where s represents the distance separating the two surfaces of the two nuclei at half density. With the above expression for g(R), and with the same value for the friction coefficient, we were able to reproduce the fusion excitation functions of a very large number of systems [3]. In fig. 6 we illustrate, on a few examples, the results obtained with such a simple model. We want to stress that this simple model allows to explain all the four points discussed in section 2.

From this dynamical calculation it is interesting to plot ΔE as a function of $s_{f\ell_{CR}}$, the position of the fusion barrier corresponding to $\ell = f\ell_{CR}$. It turns out that there is a strong correlation between these two quantities.

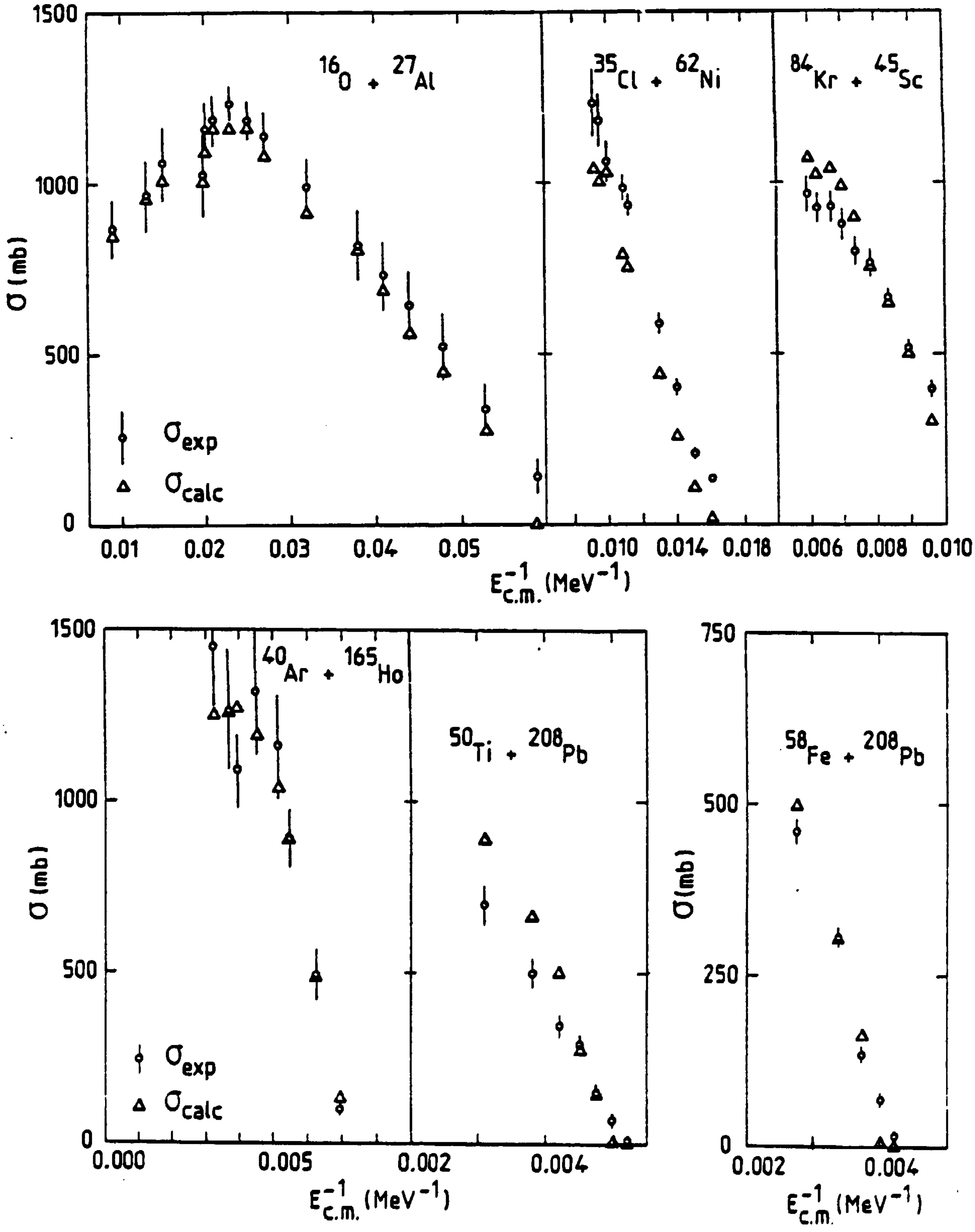


Fig. 6 - Comparison of the experimental fusion cross sections with those computed using the dynamical model of ref.[3] for the references corresponding to the experimental points see ref.[24]. Extracted from ref.[24].

This is shown is Fig. 7. The mean behaviour followed by ΔE can be parametrized by the following expression [3] :

$$\Delta E = 1100\,(1.57 - s_{f\ell_{CR}})^2 \quad \text{for} \quad s_{f\ell_{CR}} < 1.57 \text{ fm}$$

and (5)

$$\Delta E = 0 \quad \text{for} \quad s_{f\ell_{CR}} > 1.57 \text{ fm}$$

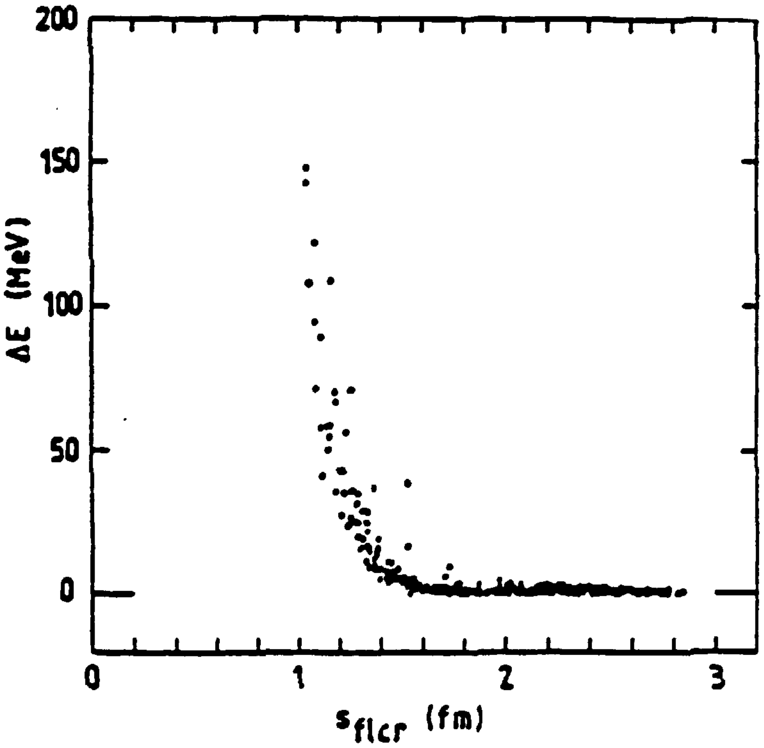


Fig. 7 - Dynamical energy surplus needed to pass the fusion barrier as a function of $s_{f\ell_{CR}}$ the position of the fusion barrier for $\ell = f\ell_{CR}$. From ref.[3].

As we can see from Fig. 7, ΔE increases a lot when $s_{f\ell_{CR}}$ becomes smaller than ~ 1 fm. This means that if it is necessary for the system to reach a distance smaller than 1 fm in order to fuse, ΔE will become so large that fusion will no longer be possible in practice. This shows the existence of a saturation distance beyond which fusion is not possible.

The fusion cross section defect which was observed in points 3 and 4 of section 2 arises from the existence of a dynamical energy surplus. This can be more clearly seen in the expression of the fusion cross section :

$$\sigma_F = \pi R^2_{f\ell_{CR}} \left(1 - \frac{V(R_{f\ell_{CR}}) + \Delta E}{E}\right) \quad (6)$$

where we see that it now enters the dynamical fusion barrier $V(R_{f\ell_{CR}}) + \Delta E$ instead of the static one $V(R_{f\ell_{CR}})$. The dynamical and the static fusion barriers are in most of the cases equal ($\Delta E=0$) except at high bombarding energies (large ℓ values) and for very heavy systems.

In conclusion we see that a very simple model, based on entrance channel properties, is able to well reproduce the experimental fusion cross sections. It gives us an overall understanding of the fusion process and more precise experiments are now needed to check this approach.

2. FAST FISSION

We shall now investigate what happens to the fused system.

1. Compound nucleus formation and fast fission

A compound nucleus is a system which has completely forgotten its formation except for some macroscopic parameter like the excitation energy, or the angular momentum, which have to obey conservation laws. When we form a compound nucleus by heavy ion collisions, it has some excitation energy and angular momentum. We know that the effective barrier against fission decreases when the compound nucleus has more and more angular momentum [13]. For some particular ℓ value, which we shall call ℓ_{B_f}, the fission barrier vanishes. Consequently it is not possible to form a compound nucleus with an angular momentum larger than ℓ_{B_f}. If fusion would be identified with compound nucleus formation, then $\ell_{CR} < \ell_{B_f}$. However many experiments have shown that this is not the case and ℓ_{CR} can exceed ℓ_{B_f} by a large amount [14]. Therefore, after a careful analysis of the situation, one is led to conclude that fusion cannot be identified with compound nucleus formation. The new question we have to answer, in case where $\ell_{CR} > \ell_{B_f}$, is the following : what do we form when $\ell_{B_f} < \ell < \ell_{CR}$?

Experiments looking at the fission like mass distribution of the Ar + Ho system at different bombarding energies have observed a strange behaviour is the evolution of the FWHM of this distribution with the excitation energy of the compound system [15] (see Fig. 8) : when ℓ values larger than ℓ_{B_f} start to contribute to fusion (as indicated in Fig. 8) one observes an increase of the FWHM which cannot be understood by the thermal fluctuations associated to an increase of the temperature of the fused system. This led the authors of ref.[15] to propose, when $\ell > \ell_{B_f}$, the existence of a new mechanism which would correspond to the fission of the composite system after mass asymmetry has relaxed to equilibrium. The observed mass distribution of the fission-like products would consist of the sum of fission products following compound nucleus formation, and of this new mechanism (called fast fission [16]). The first mechanism has to have a smaller FWHM of the mass distribution than the second. This hypothesis might be confirmed by more recent experiments, dealing with similar projectiles but with heavier targets, for which fast fission contributes more and more to the fusion cross section.

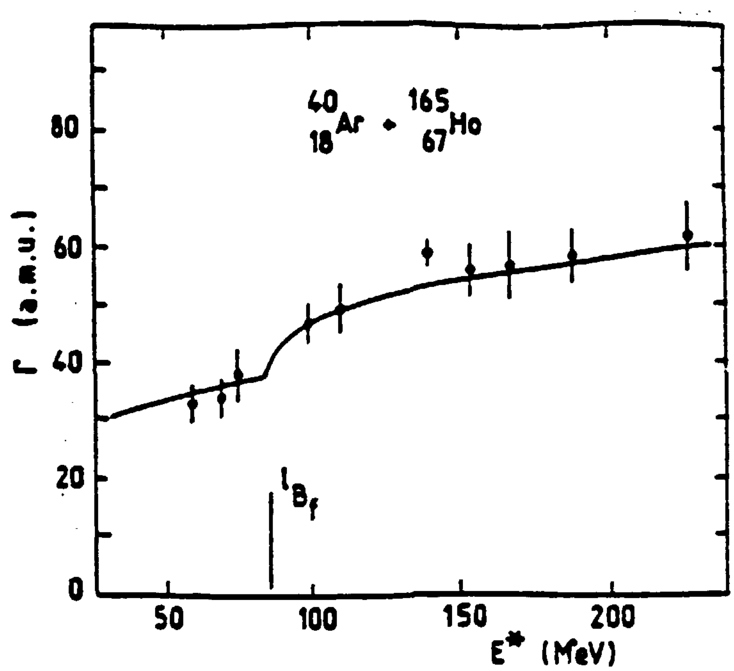


Fig. 8 - Full width half maximum, Γ, of the fission like-mass distribution, as a function of the excitation energy of the fused system, for Ar + Ho. The dots are the experimental points in ref.[15]. The full curve is the results of the calculation of ref.[14].

The existence of fast fission is difficult to infere from the experiment and it is just a convenient hypothesis to explain the data. We shall now see that there exists theoretical calculations which predict this mechanism in a natural way [4,14].

2. Dynamical model for fast fission

When two heavy ions strongly overlap, new shape degrees of freedom are excited. For instance a neck appears between the two heavy ions, creating in this way a single composite system with two centers. If we want to follow the future evolution of the fused system, we need to have a good description of these changes of shape. The main effect of these excitations is to transform a potential landscape where the two nuclei are spherical (sudden potential), in one where some of the shape degrees of freedom have relaxed to equilibrium (adiabatic potential). If our aim is also to describe the statistical (or quantum) fluctuations associated to the macroscopic variables, it is an enormous work to take into account explicitly, and in a realistic way, of the deformation degrees of freedom. One way to surmount this difficulty is to simulate the deformations by a transition between a sudden and an adiabatic potential. This has been done in ref.[4] where a dynamical transition between a sudden potential [17] in the entrance channel, and an adiabatic [18] one in the exit channel was performed. The completeness of the transition depends on the overlap between th two nuclei. The sudden potential describes the entrance channel (fusion valley) and is the relevant one to know whether the system will fuse or not. After fusion has taken place, the future evolution of the system will be mostly determined by the adiabatic potential which describes the fission valley.

The model of ref.[4] describes the collision of the two nuclei by means of four macroscopic variables ; the distance separating the two nuclei, the polar angle, the mass asymmetry of the system, and the neutron excess of one of the fragments. All the deformation degrees of freedom are simulated as it is described above. The dynamical evolution of the system is followed by means of a transport equation, derived by Hofmann and Siemens [19], which allows to describe, in a consistent way, both dissipation and fluctuations.

When some conditions are fulfilled the model reveals the existence of a mechanism which is intermediate between deep inelastic reactions and compound nucleus formation : fast fission. This is illustrated in Fig. 9 where typical mean trajectories are shown as a function of the mean mass asymmetry, and of the mean radial distance, for the 320 MeV Ar + Ho system.

The fast fission trajectory corresponds to $\ell=75$. In this case the system is trapped in the pocket of the entrance potential. Mass asymmetry relaxes to equilibrium and, at the same time, the sudden potential switches to the adiabatic one. However, since $\ell > \ell_{B_f} = 72$, the compound nucleus has no fission barrier. Therefore no pocket in the adiabatic potential will prevent the system to divide into two almost equal fragments.Such a mechanism procedure faster than ordinary fission (in about $\sim 10^{-20}$ s), does not go through a one-center configuration, but always remains a two-center system.

When $\ell < \ell_{B_f} = 72$, we form a real compound nucleus because when the system is trapped in the sudden potential, it remains trapped in the adiabatic one.

Therefore, for a system like Ar + Ho, with $\ell_{CR} > \ell_{B_f}$, we have compound nucleus formation for all ℓ values smaller than ℓ_{B_f} and fast fission when

$\ell_{B_f} < \ell < \ell_{CR}$. When the size of the fused system increases, the saddle configuration becomes more and more compact. For big compound nuclei it can be less elongated than the pocket configuration. This occurs for instance in the case of a symmetric system, when [2] :

$$\frac{Z^2}{A} > 38.5 \tag{7}$$

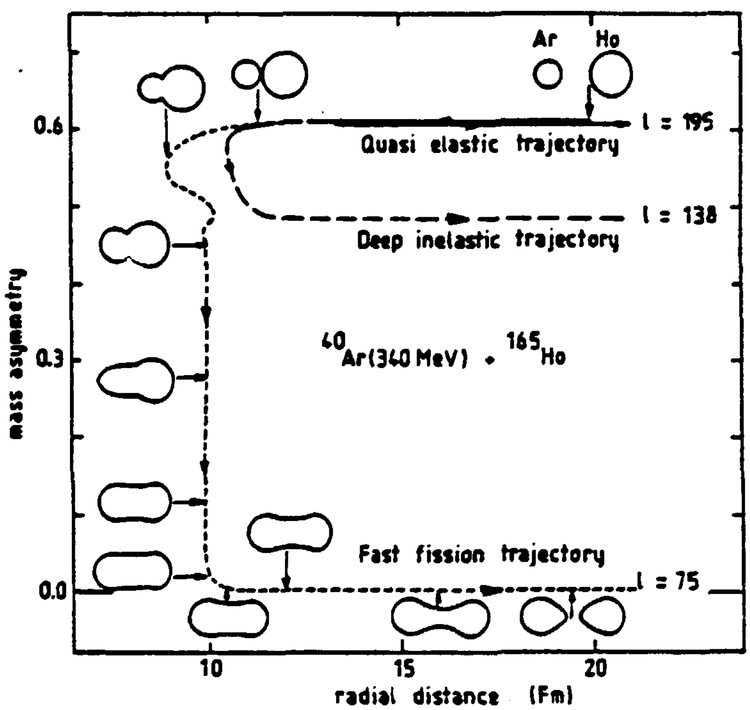


Fig. 9 - Few mean trajectories for various initial values of the orbital angular momentum, ℓ, plotted in the plane : radial distance-mass asymmetry. Three kinds of mechanisms are illustrated in this plot : 1) for ℓ=195 we have a quasi elastic collision : little mass and energy transfer. 2) for ℓ=138 we have a deep inelastic reaction : the total kinetic energy is completely relaxed and some mass transfer occurs. 3) for ℓ=75 we have fast fission : see text. Extracted from ref.[4].

Then, even if $\ell < \ell_{B_f}$ the system cannot lead to a compound nucleus. Indeed the configuration of the trapped system is more elongated than the one associated to the saddle configuration. Consequently, even if the system is trapped in the entrance channel, since it is located outside the fission barrier it will produce fast fission instead of forming a compound nucleus.

Since the dynamical model used in ref.[4] is based on a transport equation, we are able to calculate the statistical fluctuations associated to the macroscopic variables which are treated explicitly. This is for instance the case as far as the FWHM of the fast fission mass distribution is concerned. Adding to this calculation the FWHM corresponding to true fission (from ref. [20]) we can directly compare the FWHM of the fission-like mass distribution with the experimental one, at different bombarding energies. This is shown (full line) in Fig. 8 and we can see a rather good agreement between the calculation and the experimental data.

3. Summary

With the dynamical model of ref.[4] we can predict the existence of 4 types of dissipative heavy ion collisions. They are schematically illustrated in Fig. 10 where the sudden and the adiabatic potentials are represented as a function of R, the distance separating the two nuclei. This one dimensional representation is just to get a feeling of what is going on during the collision but, in the real calculation, the dynamical evolution of the system occurs in multidimensional space. In addition to the two usual dissipative heavy ion collisions (deep inelastic reactions and compound nucleus formation) we see that an extra one appears : fast fission. This new mechanism is intermediate between the two preceding ones. It occurs when the system fuses but when the conditions are such that it cannot remain trapped long enough to reach a compound nucleus. This happens either when the fission barrier has vanished due to angular momentum, or when the saddle configuration is too compact.

In Fig. 11 we summarize the conditions under which fusion and fast fission occur.

The above picture allows to understand the experimental facts which could not be understood in the usual scheme of heavy ion reaction. This is done without changing anything in our all knowledge concerning deep inelastic and compound nucleus reactions. However, from the experimental side clever experiments are needed in order to show definitely a clear evidence of fast fission.

III. <u>CONCLUSION</u>

During the recent years a great progress has been done in understanding fusion. In this talk we have shown that it is possible to describe the fusion excitation function by only considerations on the entrance channel. We have seen that the dynamics plays a very important role in determining if fusion occurs or not. This leads us to the introduction of dynamical fusion barriers and of a dynamical energy surplus which is an extra energy above the static barrier that we have to provide the system to compensate the dissipation.

As far as the subsequent evolution of fusion is concerned, we have described a dynamical model which proposes a new mechanism which is intermediate between compound nucleus and deep inelastic reactions. It occurs either, because of an instability of the compound nucleus with respect to rotation, or because we cannot reach a configuration compact enough for compound nucleus formation.

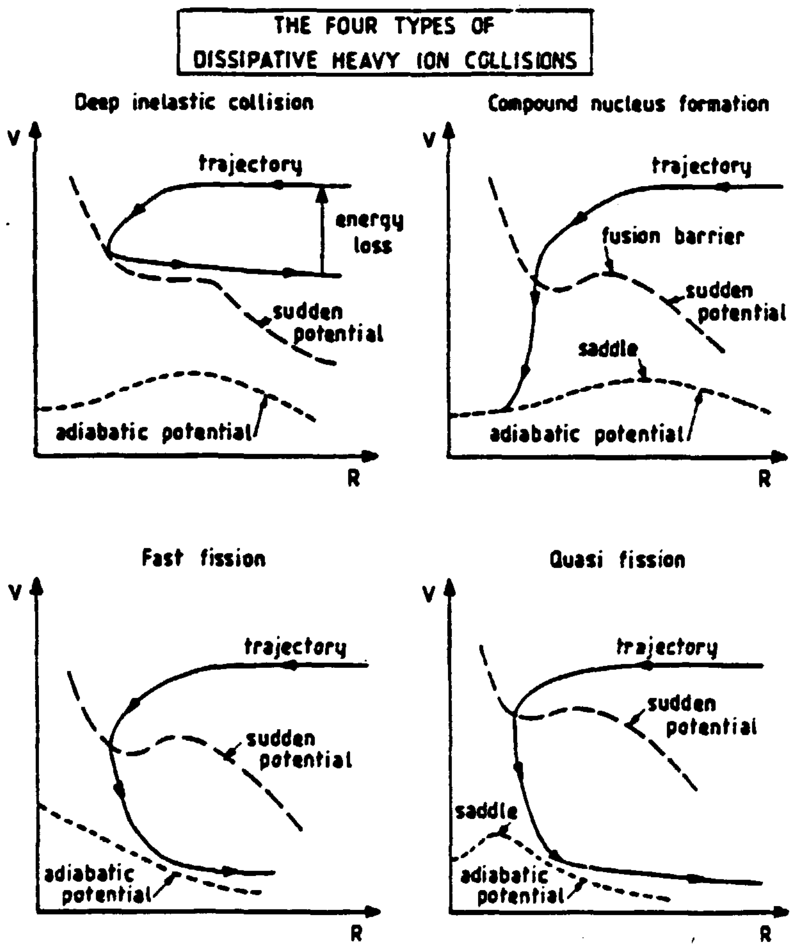
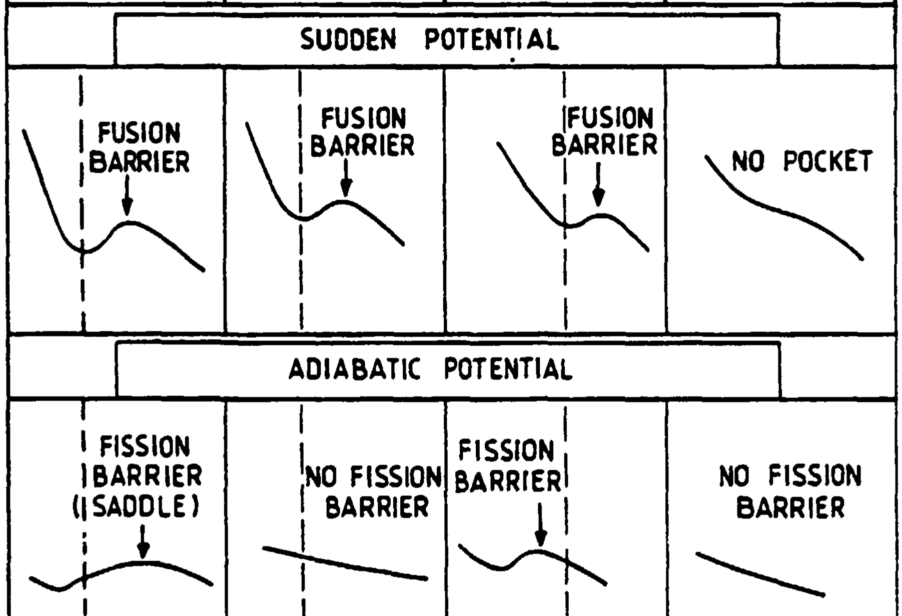


Fig. 10 - Typical illustration of the four dissipative mechanisms occuring in a heavy ion reaction : **Top left** : the system is not trapped but it looses a lot of kinetic energy in the relative motion : we have a deep inelastic collision. **Top right** : the system is trapped in the entrance channel. The sudden potential goes to the adiabatic one but the saddle configuration is elongated enough to keep the system trapped : we have compound nucleus formation. **Bottom left** : the system is trapped but the fission barrier of the compound nucleus has vanished due to angular momentum. Therefore it disintegrates in two almost equal fragments because mass asymmetry has time to reach equilibrium : we have fast fission. **Bottom right** : the compound nucleus has a fission barrier but the saddle configuration is too compact to keep the trapped system : we have also fast fission (or quasi-fission [22]).

For the moment we feel that the theories [2-4,21-23] are in advance compared to the experiments and the near future should be devoted to high resolution systematic measurements to confirm or infirm all the details predicted by the different models which are available.

APPROXIMATE CONDITIONS			
$\xi \lesssim 48$	$\xi \lesssim 48$	$\xi \lesssim 48$	$\xi \gtrsim 48$
$\forall x$	$x \lesssim 0.7$ very roughly	$x \lesssim 0.7$ very roughly	$\forall x$
$\eta \lesssim 38.5$	$\eta \lesssim 38.5$	$\eta \gtrsim 38.5$	$\forall \eta$
$l < l_{B_f}$	$l \geqslant l_{B_f}$	$\forall l$	$\forall l$



COMPOUND NUCLEUS FORMATION	FAST FISSION	FAST FISSION	NO COMPOUND NUCLEUS FORMATION NOR FAST FISSION

$$x = \frac{A_2 - A_1}{A_1 + A_2} \qquad \eta = \frac{Z^2}{A} \qquad \xi = \frac{4 Z_1 Z_2}{A_1^{1/3} \times A_2^{1/3} (A_1^{1/3} + A_2^{1/3})}$$

Fig. 11 - Summary of the different mechanisms following fusion, and of their domain of occurence.

It is a pleasure for me to thank Christian Grégoire, Renée Lucas, Bernard Remaud, Tiina Suomijärvi and E. Tomasi for their collaboration in some of the results presented in this talk. I would also like to thank Mrs. Eliane Thureau for typing the manuscript and J. Matuszek for drawing the figures.

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