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Abstract

We review recent experimental data on fusion which call for a better understanding. A macroscopic dynamical model allowing to understand these data is described. In this approach a phenomenon intermediate between deep inelastic reactions and compound nucleus formation appear : fast fission. The conditions under which fast fission can be observed, as well as its properties are discussed. We make a comparison with another approach of the same problems : the extrapush model. Finally we review a simple dynamical model of fusion which reproduces pretty well a large number of experimental fusion excitation functions.

Fast fission is a mechanism which has been proposed[1-3]) to explain experimental results which were hard to understand in the standard description of dissipative heavy ion collisions. Although there is, up to now, no direct evidence of this mechanism, we have got a consistent picture of dissipative heavy ion reactions. Most of the unexplained experimental observations are now understood without changing our old understanding of more classical experimental observations in heavy ion collisions.

In these lectures I would like to review this subject and make the connection with other new ideas related to the comprehension of the fusion process. We will treat the following items :

We will first briefly recall the experimental problems which have called for new concepts. Then we shall describe the properties of the fast fission mechanism as it appears in a dynamical approach to heavy ion reactions. In particular we shall investigate under which conditions it can be observed. We shall discuss the extension of such a dynamical approach to heavier systems and see how the fast fission process is modified. At this stage a connection with the extrapush model of Swiatecki[4]) will be done. Finally we shall describe the notion of dynamical fusion barrier which plays the same role as the extrapush in understanding fusion.

This paper is somehow a synthetic summary of the oral presentation which uses other materials from ref.[5]). For a complete survey of the question we refer the reader to refs.[5-9]) where much more details can be found.

I. EXPERIMENTAL DATA CALLING FOR NEW CONCEPTS

I.1 Critical angular momentum

The fusion cross section, σ_F, is experimentally defined as the evaporation residues plus the fission-like cross sections. This quantity is often parametrized by a critical angular momentum, ℓ_{cr}, related to σ_F by :

$$\sigma_F = \frac{\pi}{k^2} (\ell_{cr} + 1)^2 \tag{1}$$

where k is the wave number. Equation (1) has been obtained assuming that the lowest impact parameters give fusion and that the sharp cut off approximation is valid. With these assumptions the critical angular momentum is the largest ℓ value giving fusion.

One of the basic question we have to address concerns the identity between fusion and compound nucleus formation. It is closely related to how much angular momentum a compound nucleus can carry. Liquid drop studies[10]) show, for instance, that the effective barrier against fission decreases when the angular momentum of the compound nucleus increases. For a value, denoted here by ℓ_{B_f}, this fission barrier disappears. Since some amount of time is necessary to form a compound nucleus in the real sense, it is reasonable to think that it is not possible to form a compound nucleus when $\ell \geq \ell_{B_f}$. In the case where fusion would be identical to compound nucleus formation, ℓ_{cr} should always be smaller than ℓ_{B_f}. Compilation of the existing data[7]) shows that this is not true and several measurements do show that ℓ_{cr} can notably exceed ℓ_{B_f}. One possibility would be to say that σ_F not only contains complete fusion but that there is also a contribution of incomplete fusion. However, measurements of light fast particles[11]), which are usually associated with this last process, show a too small multiplicity and cannot account for the difference between ℓ_{cr} and ℓ_{B_f}. Therefore, we have to conclude that fusion cannot be identified with compound nucleus formation. Then what happens when $\ell_{B_f} \leq \ell \leq \ell_{cr}$ for which there is fusion but not compound nucleus formation?

I.2 Widths of fission-like mass distributions of the Ar + Ho system at high bombarding energies

The starting point of fast fission was a series of experiments[1]) on the Ar + Ho system done at different bombarding energies. In fig. 1 are shown (dots) the full width half maximum (FWHM) of the mass distribution of the fission-like products as a function of the excitation energy of the "compound nucleus". The FWHM increases with the excitation energy E*. Because the temperature, T, rises with increasing E*, we expect the mass distribution to broaden when T increases due to statistical fluctuations. An estimation of this effect[1]) gives however a too small increase compared to the experimental observation. The results of these experiments might tell us that the stiffness of the potential energy surface along the mass asymmetry coordinate could be strongly angular momentum dependent. Another possibility would be that the fission-like products associated to the largest partial waves are coming from another mechanism different from fission following compound nucleus formation. This mechanism would only contribute when $\ell_{Bf} \leq \ell \leq \ell_{cr}$. In fig. 1, the excitation energy corresponding to ℓ_{cr} larger than ℓ_{Bf} is at about 80 MeV and is indicated in the figure. It is precisely in this region that one might guess a particularly large increase of the FWHM. This last preliminary conclusion is supported by investigations of heavier systems (Cl + Au in ref.[11]) and Cl + U in ref.[12])). Indeed, as the system becomes heavier ℓ_{Bf} decreases and for the Cl + U system, for instance, we have mainly to deal with ℓ values larger than ℓ_{Bf}. In this case the FWHM turns out to be almost constant over the investigated bombarding energy range (240-350 MeV) whereas it varies for the Cl + Au system (204-317 MeV) but to a smaller extend than for the Ar + Ho combination. These observations suggest that when $\ell_{Bf} \leq \ell \leq \ell_{cr}$ there could be a contribution of a mechanism different

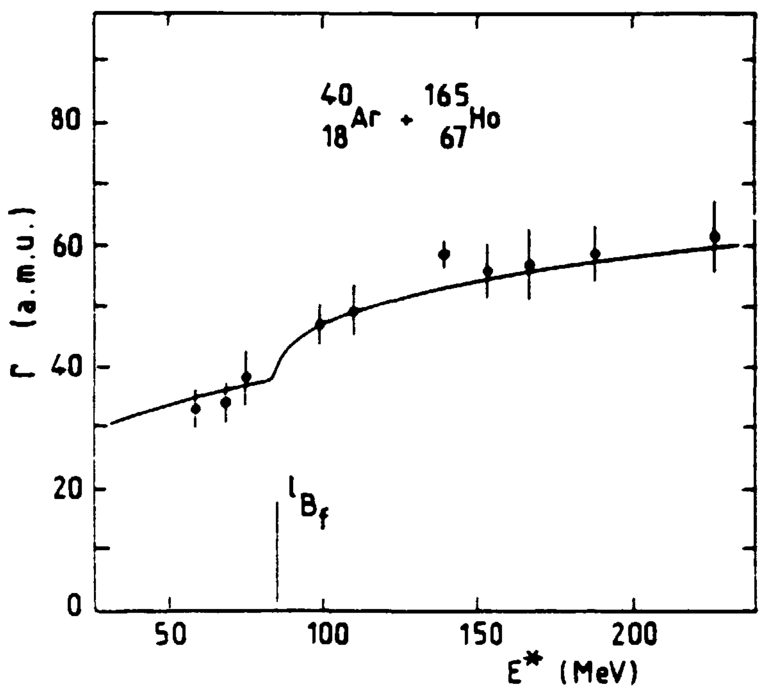

Fig. 1 - Full width half maximum, Γ, of the fission like mass distribution, as a function of the excitation energy of the fused system, for Ar + Ho. The dots are the experimental points in ref.[1]). The full curve is the result of the calculation of ref.[7]).

from ordinary fission. This process would give larger fission-like mass distributions.

I.3 Disappearance of fusion for very heavy systems

When the projectile and the target become very heavy it becomes no longer possible to make them fuse together[13]. This occurs when the product, Z_1Z_2, of the atomic numbers of the two ions becomes larger than about 2500-3000. The disappearance of this important phenomenon has been correlated with the vanishing of the pocket of the total interaction potential between two heavy nuclei[14]. It is so because the Coulomb repulsion becomes, for all overlaps, much stronger than the nuclear attraction.

Systems close to the limit where fusion disappears have been investigated in great details by Bock et al.[15]. They have observed that the difference between the measured fusion threshold and the one calculated using prescriptions working very well for lighter systems, increases as one goes towards the limit where fusion vanishes. This rise of the fusion threshold leads, of course, to a reduction in the fusion cross section compared to what can be extrapolated from our knowledge on lighter systems. The existence of such a difference has also pushed on the introduction of new concepts.

I.4 Fusion cross section defect at high bombarding energies

At bombarding energies just above the fusion threshold the fusion cross section increases almost linearly as a function of $1/E_{CM}$, the inverse of the center of mass bombarding energy. This can be explained in a simple classical picture by looking if it is possible, for a given impact parameter, to overcome the associated fusion barrier. Then σ_F is simply given by :

$$\sigma_F = \pi R_{12}^2 \left(1 - \frac{V_{12}}{E_{CM}}\right) \tag{2}$$

where R_{12} and V_{12} are respectively the location and the height of the fusion barrier for a head-on collision.

It is a well known experimental fact that at higher bombarding energies the experimental σ_F is smaller than the value calculated with eq.(2). An attractive idea proposed to understand this fusion cross section defect was the notion of critical distance proposed in refs.[16] and [17]. For medium systems this method was rather successful but could not explain why very heavy systems do not fuse. Furthermore a theoretical justification of this notion was missing.

It should be noted that this point is correlated to the preceding one since, in both cases, a fusion cross section defect is noticed.

II. THEORETICAL INVESTIGATION OF FAST FISSION

During a heavy ion collision, the two nuclei remain unchanged before they reach the interaction region. There, if the overlap is large enough, dissipative phenomena can take place. A part of the kinetic energy in the relative motion can be transformed into intrinsic excitation of the total system. This loss of energy can be such that the system remains trapped in the interaction region. In this case we say that there is fusion.

II.1 Limits of fusion

In order to fuse the total interaction potential of the system, plotted versus the interdistance separating the two nuclei, should have a pocket. Using the sudden approximation and the energy density formalism[18]) we can show[5]) that, for a head-on collision, the pocket disappears when :

$$\left(\frac{Z^2}{A}\right)_{eff} = \frac{4\ Z_1 Z_2}{A_1^{1/3} A_2^{1/3} (A_1^{1/3} + A_2^{1/3})} \lesssim 48 \qquad (3)$$

This condition expresses the fact that the nuclear force, at the distance where it is maximum, is larger than the modulus of the Coulomb force.

II.2 The dynamical fast fission model

For large overlaps, the two nuclei, initially supposed to be spherical, become deformed. Various shape degrees of freedom are excited and, for instance, a neck appears between the two ions creating in this way a single composite system with two centers. Investigation of the future evolution of the system needs a good description of these shape deformations. Since these excitations transform a potential landscape where the two nuclei are spherical (sudden potential) to one where some of the shape degrees of freedom have relaxed (adiabatic potential) it is tempting to describe this transition in a phenomenological way. This was done in ref.[3]) where a dynamical transition between a sudden potential[18]) in the entrance channel and an adiabatic one[19]) in the exit channel was done. The degree of completeness of the transition depends upon the overlap between the two ions.

The collision of the two nuclei is described by means of four collective degrees of freedom : the distance, R, separating the center of mass of the two nuclei, the corresponding polar angle, the mass asymmetry of the system and the neutron excess of one of the fragments. The dynamical evolution of the collision is followed by means of a transport equation derived by Hofmann and Siemens[20].

This model allows to describe deep inelastic properties as well as fusion. For some systems it shows new features which we shall discuss now.

II.3 The appearance of fast fission

When conditions are fulfilled, the model reveals the existence of a mechanisms intermediate between deep inelastic reactions and compound nucleus formation. This can be seen, for instance, for the 340 MeV Ar + Ho system. In fig. 2 typical mean trajectories are shown versus mass asymmetry and radial distance.

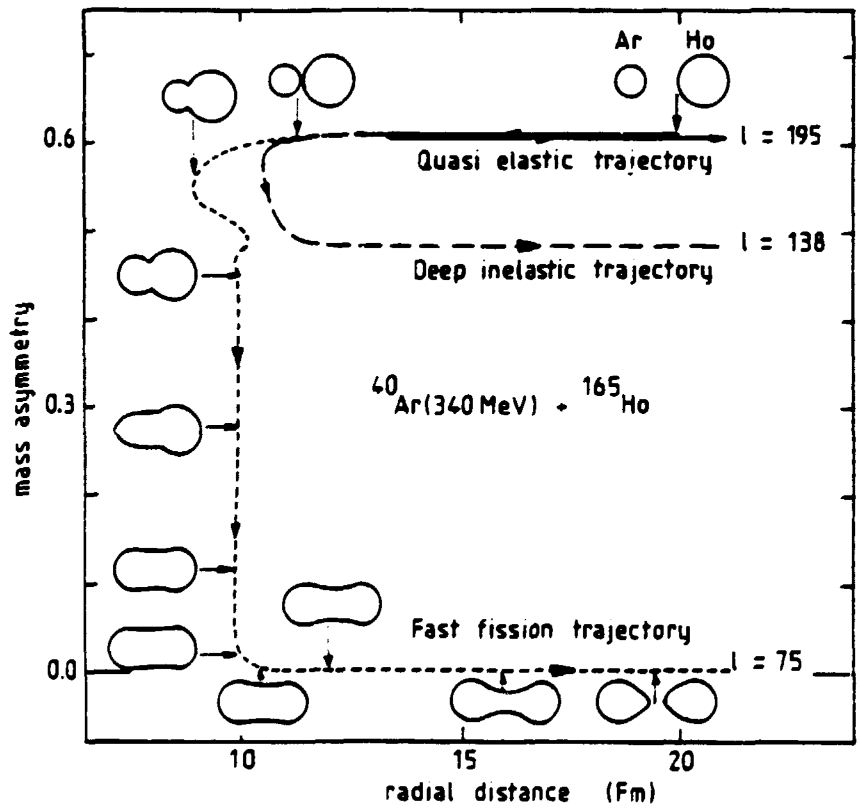

Fig. 2 - Few mean trajectories for various initial values of the orbital angular momentum, ℓ, plotted in the plane radial distance-mass asymmetry. Three kinds of mechanism are illustrated in this plot : 1) quasi-elastic process for ℓ=195, 2) deep inelastic collision for ℓ=138 and 3) fast fission phenomenon for ℓ=75. For $\ell < \ell_{B_f} = 72$, a compound nucleus is formed. This figure has been extracted from ref.[3].

-ℓ =195 corresponds to a quasi elastic reaction : we have little mass and energy exchanged during the interaction.

- ℓ=138 represents typically a deep inelastic trajectory : a lot of kinetic energy is lost in the relative motion and a non negligeable mass transfer occurs for this particular ℓ value.

- ℓ=75 shows a new kind of phenomenon. The system is trapped into the pocket of the entrance potential. Mass asymmetry relaxes to equilibrium and, simultaneously, the sudden potential changes to the adiabatic one. However, for such a large value of the angular momentum the fission barrier of the compound nucleus does not exist any more. Consequently the system cannot remain caught any longer in the interaction region and separates in two fragments. We have a phenomenon similar to fission following compound nucleus formation except that we start from a two-center system. This is schematically illustrated in fig. 3. The interaction time for such a collision is smaller than the one corresponding to compound nucleus formation followed by fission. It is of the order of 10^{-20}s which is nevertheless larger than those involved in deep inelastic reactions.

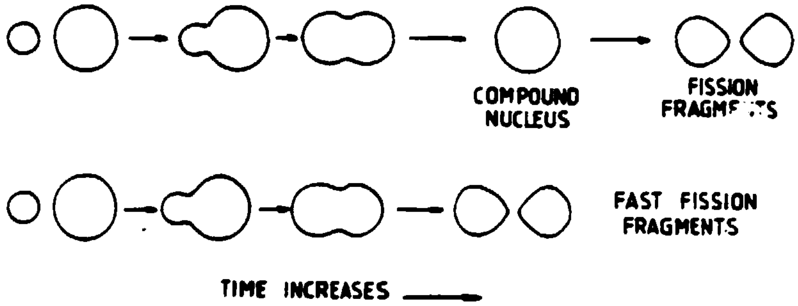

Fig. 3 – Schematic picture of compound nucleus fission and fast fission.

- For this particular system ℓ_{Bf} = 72. When ℓ < 72 the system which is trapped in the entrance channel remains trapped in the adiabatic potential because the fission barrier still exists and has a configuration less compact than the one of the pocket.

In conclusion, for a system like Ar + Ho, fast fission only occurs when $\ell_{Bf} \leq \ell \leq \ell_{cr}$.

II.4 Fast fission phenomena for heavy systems : quasifission

When the fissility parameter, $\frac{Z^2}{A}$, increases the saddle configuration becomes more and more compact. For big nuclei it can become less elongated than the pocket configuration. For a symmetric system this occurs when the following condition is fulfilled :

$$\frac{Z^2}{A} \gtrsim 38.5 \qquad (4)$$

where Z and A are the atomic and mass numbers of the compound nucleus. In this case, even if $\ell < \ell_{Bf}$, the system which is trapped into the pocket of the sudden potential cannot remain trapped when the adiabatic landscape is reached, because it has an elongation larger than the one associated to the pocket : it reseparates in two fragments. This special type of fast fission, which occurs for $0 \leq \ell \leq \ell_{cr}$, has been called quasifission by Swiatecki[4]) who was the first to point out this possibility.

II.5 Properties of fast fission

According to the macroscopic model described above, fast fission should have very similar properties to those of fission following compound nucleus formation. This makes difficult to get unambiguous proofs of its existence. At the present stage it is the simplest possibility to understand the data but that is all. The most advanced experimental proof might be found in experiments done by Ho et al.[21]) who have found evidence of light particles emitted by an equilibrated two-center system with a lifetime of the order of 10^{-20}s.

Since it is based on a transport equation, the fast fission model permits to calculate the FWHM of the fast fission mass distribution. Using the results of ref.[22]), for the fission of the compound nucleus, together with the output of the present model, it is possible to calculate the FWHM of the fission-like products. This is shown by the full line in fig. 1.

When $\frac{Z^2}{A} \lesssim 38.5$, the fast fission threshold is larger than the one corresponding to compound nucleus formation. This is illustrated in fig. 4 which shows the fusion excitation function of the Ar + Ho system. The full curve is the calculation of ref.[3]) and the dots are the experimental data of ref.[1]). The full curve can be decomposed in two terms : compound nucleus formation and fast fission.

II.6 The four classes of dissipative heavy ion collisions

We summarize schematically in fig. 5 the four classes of dissipative heavy ion collisions which can be predicted by the macroscopic dynamical model of ref.[3]). In this figure the entrance sudden and the adiabatic potentials are represented as a function of R. This one dimensional plot is just to get a feeling of the real collision which occurs in fact in multidimensional space.

In fig. 6 we show the range of ℓ values, or impact parameters, to which these dissipative phenomena are associated and fig. 7 summarizes the conditions under which fusion, fast fission and quasifission occur.

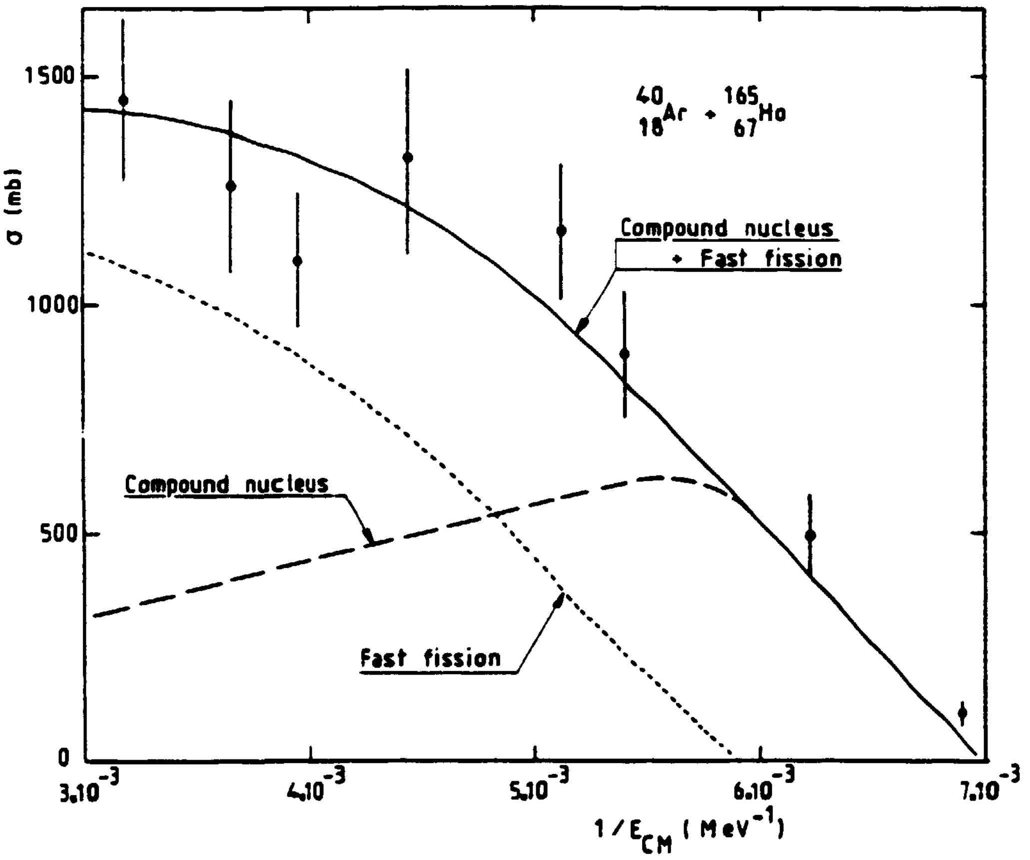

Fig. 4 - Experimental fusion cross section (dots) from ref.[1]) plotted as a function of $1/E_{CM}$, the inverse of the center of mass bombarding energy. It is compared with the calculated fusion cross section of ref.[3]) (full curve). The fusion cross section is the sum of the compound nucleus and of the fast fission cross sections. Their corresponding excitation functions are also shown in the figure. This figure is extracted from ref.[3]).

III. COMPARISON WITH THE EXTRAPUSH MODEL

III.1 The dynamical extrapush model

Swiatecki[4]) has developed a dynamical model for head-on collisions of two heavy ions. There are three macroscopic variables : one associated to the distance separating the two fragments, one connected with mass asymmetry and a last one related to the size of the neck connecting the two nuclei. The dynamical evolution of the macroscopic variables, is followed by Newton equations with friction forces proportional to the velocities and given by the one body approach[23]). Except for the interdistance of the two separated nuclei, inertial forces were neglected (overdamped motion in the sense of Kramers[24])).

Three particular configurations play an important role in this approach : 1) the contact one (it is at this point that the neck degree of freedom is unfrozen), 2) the conditional saddle (saddle point calculated under the condition that the mass asymmetry degree of freedom remains frozen to its initial value), 3) the unconditional saddle (usual saddle point). To each of

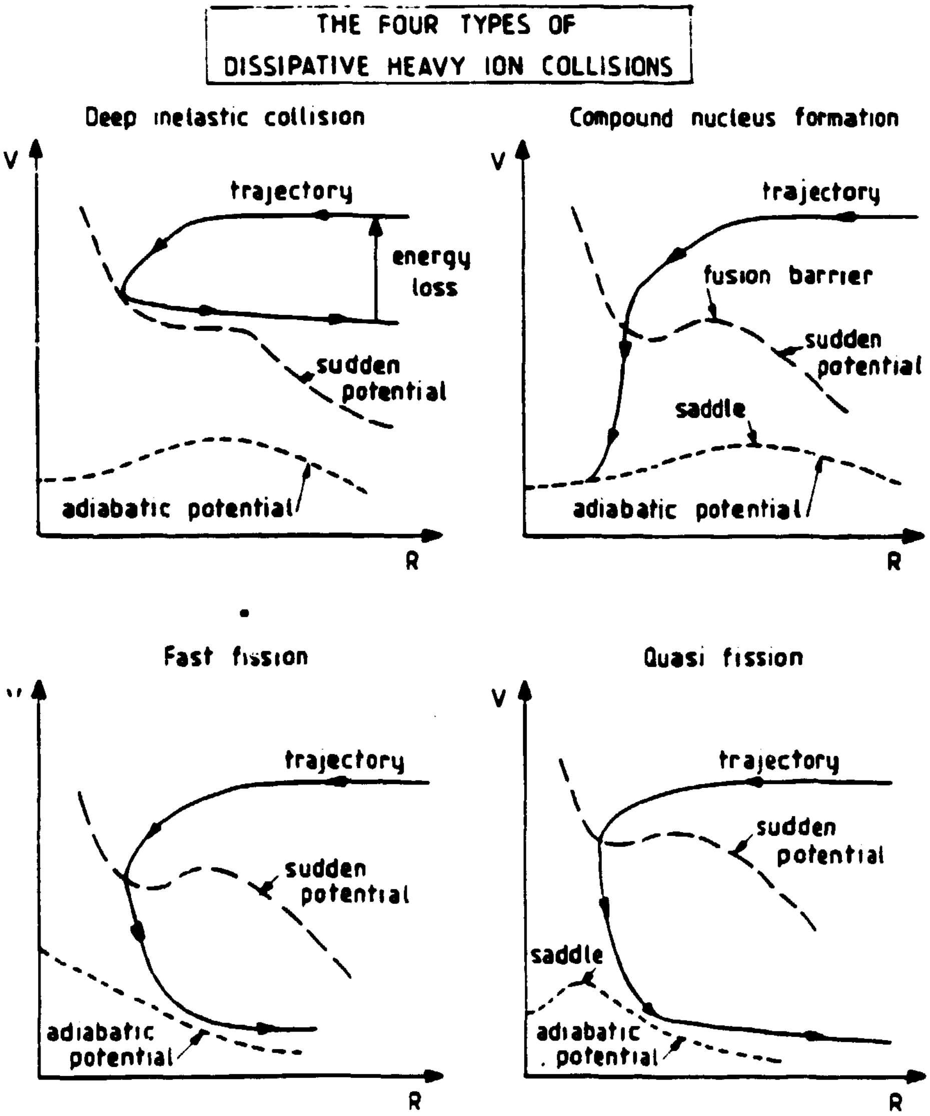

Fig. 5 – Typical illustration of the four dissipative mechanisms occuring in a heavy ion reaction : Top left *: the system is not trapped but it looses a lot of kinetic energy in the relative motion : we have a deep inelastic collision.* Top right *: the system is trapped in the entrance channel. The 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 desintegrates in two almost equal fragments because mass asymmetry had 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.*

these configurations three thresholds are associated ; they are shown in fig. 8 borrowed from ref.[25]). Fusion occurs only if the conditional saddle is reached. For heavy systems this configuration is more compact than the contact one (case of fig. 8) and some extra energy, over the contact point, is needed to reach it and to compensate the energy loss due to friction : it is the extra-push. For light systems this extrapush is zero because the contact configuration is more elongated than the conditional saddle. The above considerations explain why the fusion threshold becomes larger than expected for heavy systems[15].

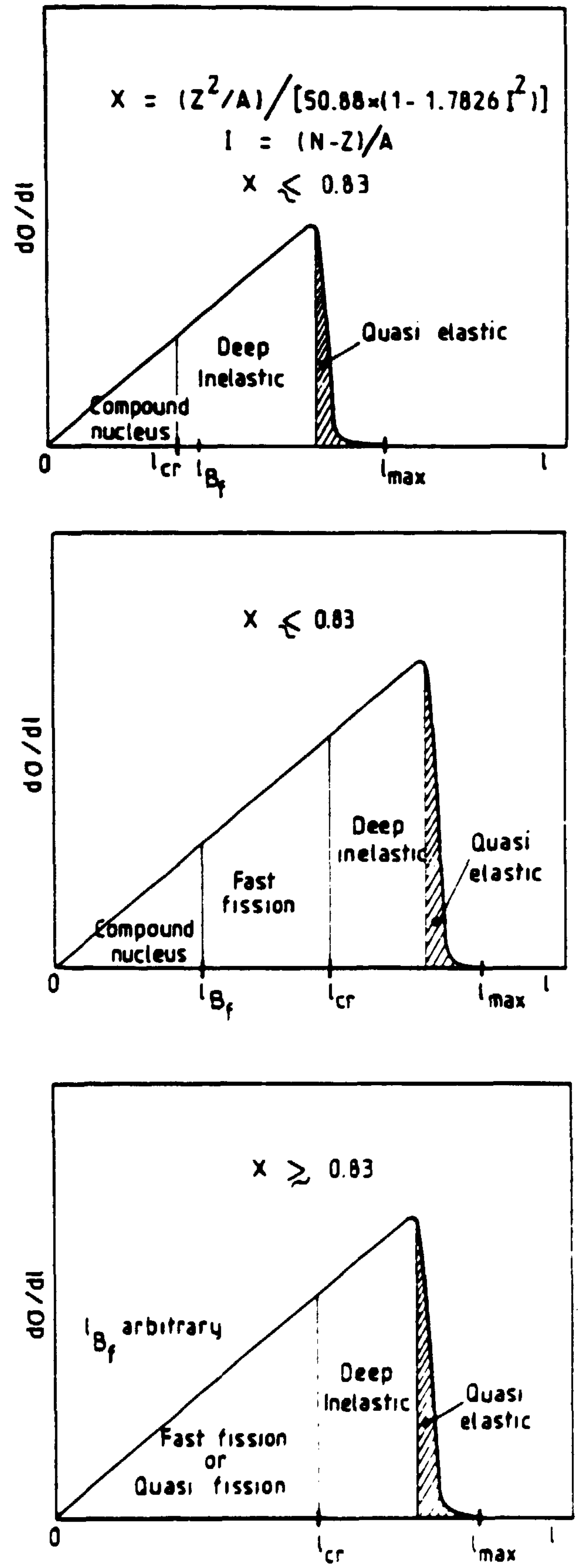

Fig. 6 - Schematic representation of the different ranges of ℓ values associated to the four dissipative mechanisms which can be observed in heavy ion reactions.

Fusion does not mean necessarily compound nucleus formation. To form a real compound nucleus the system should reach the unconditional saddle point. The extra energy above the contact configuration necessary to do that is called the extra extrapush.

III.2 Comparison with the dynamical fast fission model

It is interesting to make a brief comparison between the dynamical extra push and the fast fission models. Indeed both aim to give a good overall understanding of fusion. In table I are summarized the main points in which they differ. In addition to that we should add one more difference : in the extrapush model the two nuclei remain unchanged until they reach the contact configuration. At this step the neck degree of freedom is unfrozen and relaxes very fast to equilibrium ($\sim 10^{-22}$s). At variance, in the fast fission model the transition between the sudden and the adiabatic potential occurs more slowly ($\sim 10^{-21}$s) but starts before the two nuclei are in close contact.

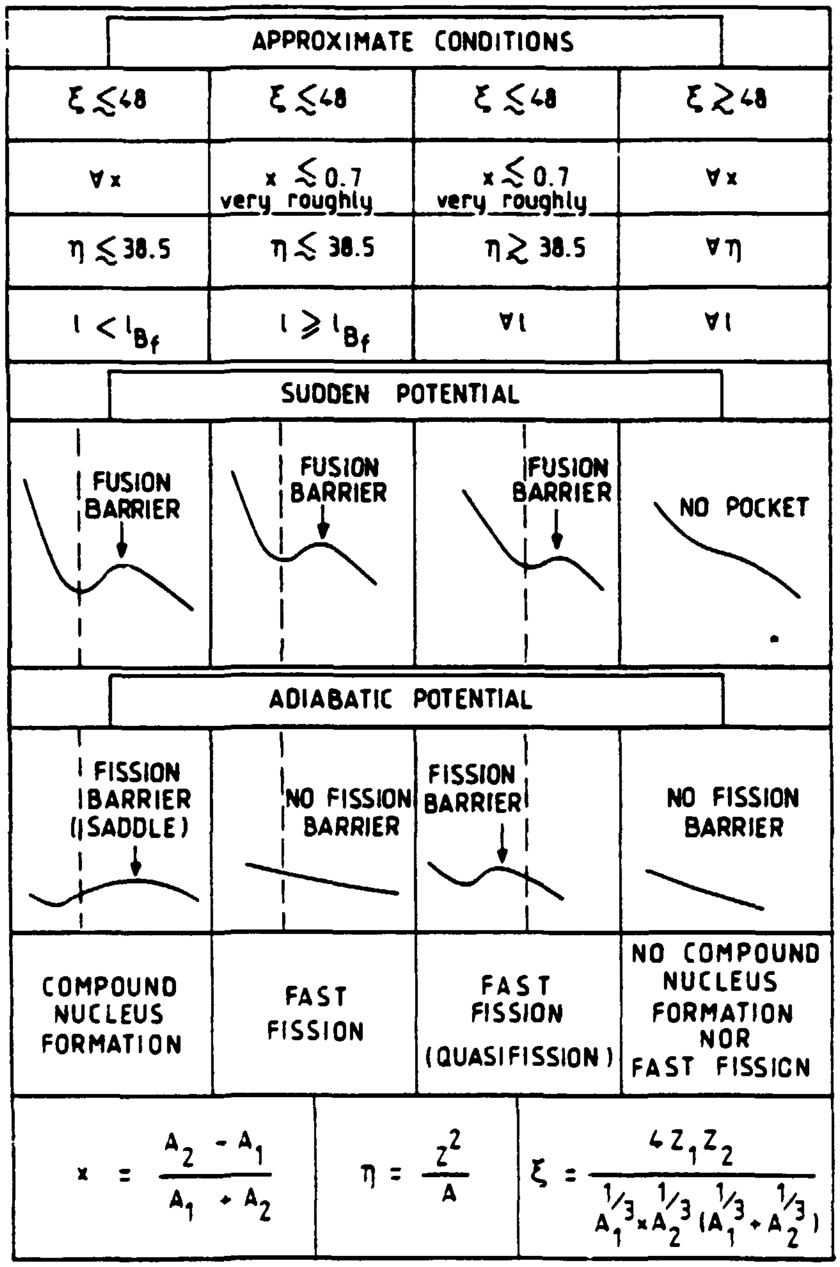

Fig.7 - Schematic summary of the different mechanisms following fusion and their domains of occurence.

Table 1

Comparison between the dynamical fast fusion[3]) and the extrapush models[4])

Physical effects	Fast fission model	Extra push model
Orbital angular momentum	yes	no
Statistical fluctuations	yes	no
Deformations	simulated	yes
Overdamped approximation	no	yes

III.3 The static extrapush model

Swiatecki[4,25]) has parametrized some of the results obtained for a head-on collision by simple analytical formulas. In particular the extra push ΔE can be expressed as a function of the effective fissility parameter $(Z^2/A)_{eff}$ defined in eq.(3) : it is zero below a certain threshold and goes like a parabola

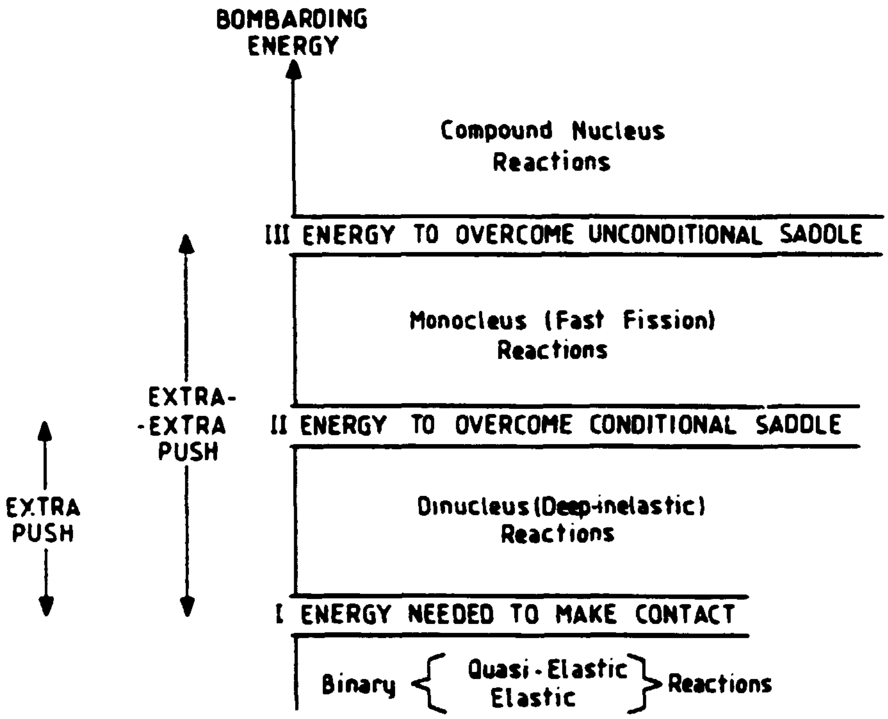

Fig. 8 - Schematic illustration of the different mechanisms which are obtained in the dynamical model of Swiatecki[4]) for head-on collisions. If the bombarding energy is not sufficient to reach the contact configuration (I) we get elastic or quasi elastic processes. If the energy is sufficient to make contact but not to reach the conditional saddle configuration we have to deal with deep inelastic reactions. To reach the conditional saddle from the contact configuration an extra energy is needed : it is the extrapush. If this point is reached there is fusion but not necessarily compound nucleus formation. To reach this latter situation more extra energy is needed (extra extrapush) otherwise there is quasi-fission (fast fission). This figure is taken from ref.[25]).

above. This formula can be extended to non central collision by generalizing $(Z^2/A)_{eff}$ to non zero orbital angular momentum[3]) :

$$\left(\frac{Z^2}{A}\right)_{eff}(\ell) = \left(\frac{Z^2}{A}\right)_{eff} + g(f\ell)^2 \frac{A_1 + A_2}{A_1^{1/3}A_2^{1/3}(A_1^{1/3} + A_2^{1/3})} \qquad (5)$$

To a constant factor, $(Z^2/A)_{eff}(\ell)$ is the sum of the Coulomb and centrifugal forces over the nuclear one at the point where this last quantity is maximum. f is the proportion of angular momentum which remains in the relative motion after tangential friction has acted. We would like to stress that a real problem exists as far as the choice of this quantity is concerned. Several prescriptions can be used, for instance rolling or sticking, but the good choice is still not clear. For example, for the systems investigated at GSI in ref.[15]), the rolling seems to be more appropriate whereas, for the Ar + Ho system, the sticking is better[5]). In fact it should be noted that eq.(5) just simulates angular momentum by an equivalent Coulomb force. However we know that it is only a very rough approximation otherwise the evolution of the fission barrier with angular momentum, or with increasing size would be closely related, which is not the case.

IV. DYNAMICAL FUSION BARRIERS

IV.1 Necessity for the existence of a dynamical barrier

In the extrapush model, an extra energy above the contact configuration was sometimes necessary to reach the conditional saddle point and to get fusion. In other dynamical models for heavy ion collisions the notion of extra energy also exists but has a different meaning. It is illustrated in fig. 9 for a head-on and for a non-central collision. The potential energy surface defines a static barrier. Because some kinetic energy in the relative motion can be lost, due to friction, before the system reaches this barrier, we see that some extra energy above the static fusion threshold is necessary to perform fusion. In other words the dynamical barrier is different from the static one. If ΔE is the energy difference between the dynamical and the static fusion barriers, it is possible to show that[5]) :

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

where $R_{f\ell_{cr}}$ is the position of the static fusion barrier corresponding to $\ell = f\ell_{cr}$. ℓ_{cr} is the critical angular momentum and f the amount of orbital angular momentum remaining in the relative motion. $V(R_{f\ell_{cr}})$ is the value of the nuclear plus Coulomb potentials at distance $R_{f\ell_{cr}}$. The extra energy, ΔE, is zero for light systems as well as for small angular momentum. It can be parametrized by the following expression :

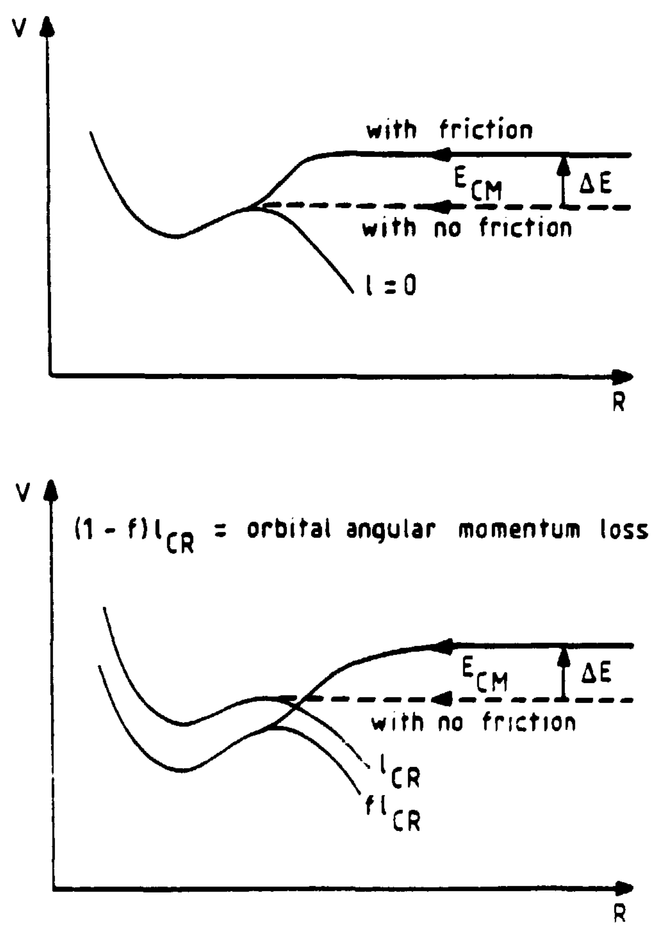

Fig. 9 - Schematic illustration of the fact that some extra kinetic energy is needed to overcome the static fusion barrier : on top is the case of a head-on collision. In the bottom is the case when the orbital angular momentum is equal to ℓ_{cr}. There the total interaction potential including centrifugal energy changes due to angular momentum loss.

$$\Delta E = 0 \qquad \text{for} \quad X < 0.68$$
$$\Delta E \simeq 2000\,(X_{eff} - 0.68)^2 \text{ MeV} \qquad \text{for} \quad X > 0.68 \tag{7}$$

where

$$X_{eff} = \frac{1}{12.54}\left[\frac{Z_1 Z_2 e^2}{C_1 C_2 (C_1 + C_2)} + f^2 \ell^2 \hbar^2 \frac{A_1 + A_2}{A_1 A_2} \frac{1}{C_1 C_2 (C_1 + C_2)^2}\right] \tag{8}$$

where C_1 and C_2 are the central radii of the nuclei. Again we are faced with the choice of the f factor telling us how much angular momentum is dissipated.

The above considerations explain why very heavy systems, like those investigated in ref.[15]), have a reduction of fusion cross section : it is just because the dynamical barrier becomes larger than the static one. For a given system, at large bombarding energies, it also explains the fusion cross section defect because of the same reason.

Since static fusion models based only on potential energy considerations reproduce quite well the fusion data of not too heavy systems and at not too high bombarding energies, it means that the dynamical and static barriers are the same. This is likely to indicate that friction does not extend too far outside and probably extend similarly,for all systems, from the point where the nuclear force is maximum. As Z_1Z_2 increases, or as ℓ increases,the position of the fusion barrier becomes more and more compact and friction can act making a difference between the dynamical and the static barriers.

IV.2 Simple dynamical model for fusion

To check the above ideas, a simple model has been developed in refs.[26,27]) to describe fusion. It uses two macroscopic variables : the distance, R, between the two nuclei and the polar angle θ. Friction forces proportional to the velocities are introduced in the radial and tangential motion with the following form factor :

$$g(R) = \frac{1}{1 + \exp\left(\frac{s - 0.75}{0.2}\right)} \tag{9}$$

where
$$s = R - C_1 - C_2 \tag{10}$$

and C_1, C_2 are the central radii of each nuclei. The friction force in the radial motion is : $- C_R\, g(R)\, \dot{R}$ with $C_R = 31\,000$ MeV.fm^{-2} $\times 10^{-23}$s. The tangential motion is responsible of orbital angular momentum damping which is introduced in the following way :

$$\frac{d\ell}{dt} = -\frac{C_t}{\mu}(\ell - \ell_{st}) \tag{11}$$

where ℓ_{st} is the angular momentum corresponding to sticking and μ the reduced mass. According to the one body picture[23]), $C_t = C_R/2$. The special form (eq.(11)) of the orbital angular momentum loss is chosen to ensure that the sticking limit is not overcome, as expected in the collision of two rigid bodies.

In ref.[27]) the excitation functions of a large number of systems have been calculated and compared with experiment. The agreement turns out to be surprisingly good despite the extreme simplicity of the model. This is illustrated in fig. 10.

This simple macroscopic model gives an overall understanding of the fusion process. The unexpected results quoted in section I are understood in terms of dynamical fusion barriers which become, in some cases, larger than the static one.

V. CONCLUSION

During the last few years a great progress has been done in understanding fusion. New concepts like fast fission, quasifission, extrapush and dynamical barriers have been proposed and seem to be quite successful. This big progress has only be done by a simultaneous attack of the problem by experimentalists and theoreticians showing the efficiency of such a close connection between them. If fusion seems now qualitatively understood, there still remains open problems for a good quantitative description of the data. Especially the role of orbital angular momentum is still not clear and the approximations used to treat it have to be removed in the near future.

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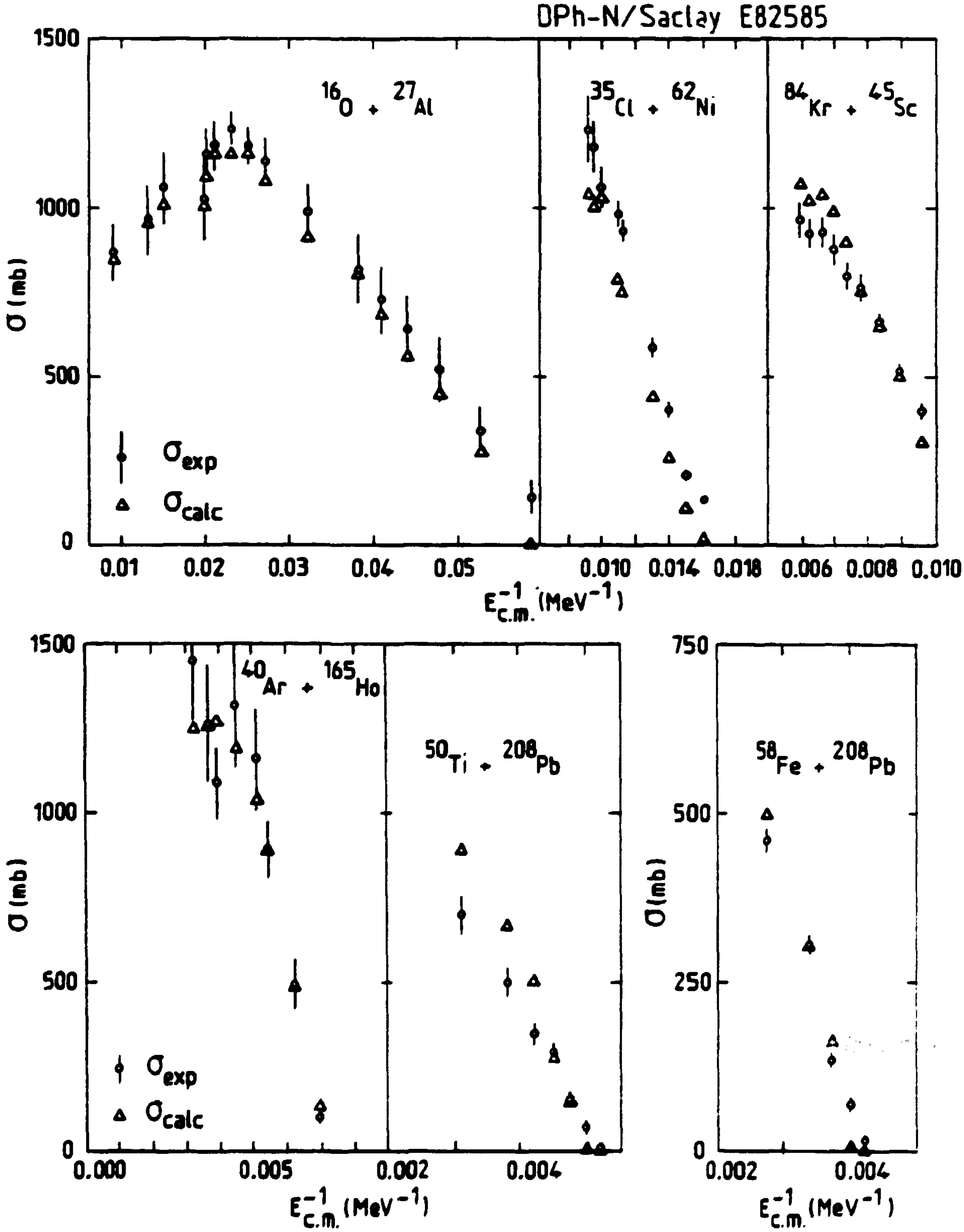

Fig. 10 - Comparison of the experimental cross sections with those computed using the dynamical model of ref.[27]*). Experimental points have been taken from the compilation of ref.*[28]*). This figure has been extracted from ref.*[26]*).*

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