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Discrimination and Competition between Complete fusion and Deep Inelastic Reactions induced by Heavy Ions.

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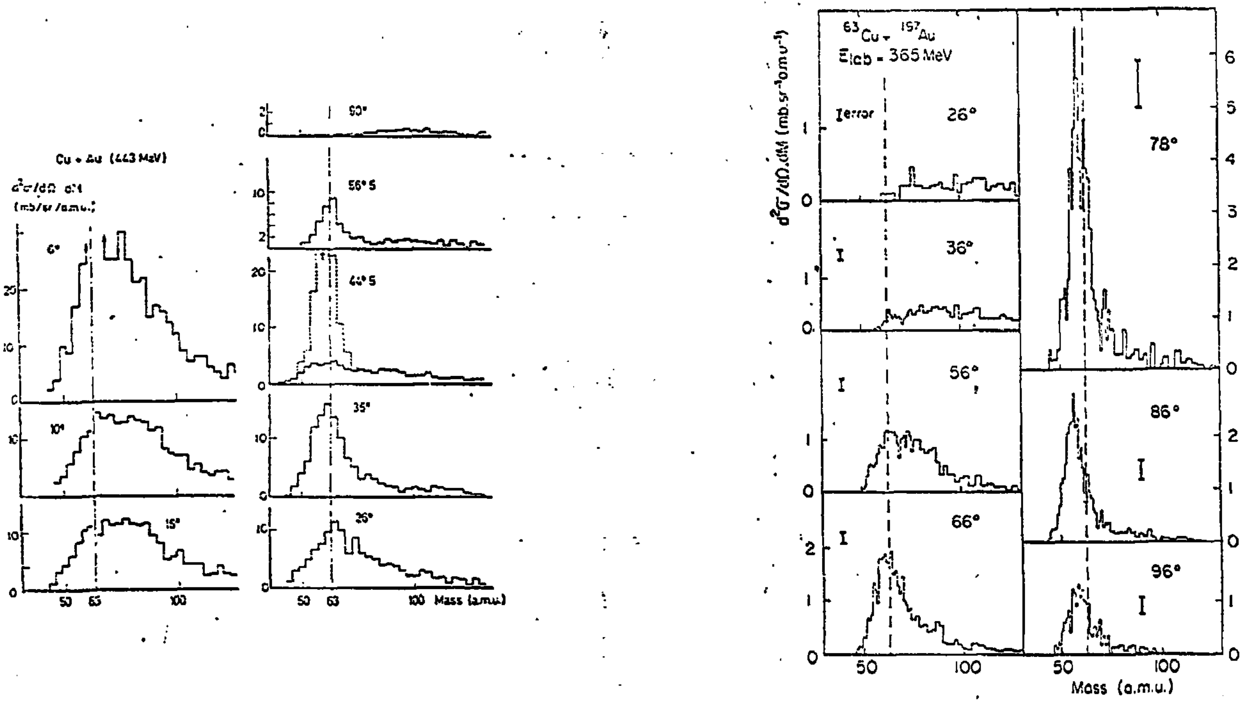
FIGURE 1



Mass distributions for Cu + Au system at 365 and 443 MeV.

1. INTRODUCTION

In this paper, we review some recent results, obtained mainly at Orsay, with special emphasis on the discrimination and the competition between complete fusion and deep inelastic reactions.

First of all, we have to define these two terms and the job is quite difficult. One way would be to use the definition given by Lefort (1) one year ago : "*Complete fusion is an interaction in which both partners are joigned together for a time longer than the collision time and make an intermediate system which decays into the final products without particular remembrance of the composition of the projectile and the target.*" The reverse situation (remembrance of the entrance channel masses) corresponds to the deep inelastic collision, the term "quasi-fission" being reserved to deep inelastic events where the initial relative motion is completely damped.

Such a définition is very clear for light systems at moderate incident energy for which the complete fusion cross-section reduces to the evaporation residue cross-section. However it fails for heavier systems (even at moderate energy) for which the fission channel becomes widely open and where fission following complete fusion and quasi-fission are difficult to separate, (particularly for initial symetric systems or when large mass diffusion occurs for initial asymetric systems).
Cu + Au system is a typical exemple of such a situation. In figure 1, we have reported the mass distributions obtained at two incident energies (365 and 443 MeV) by J. Péter et al 1975 (2) and C. Ngô et al 1976 (3).
For forward angles, a continuous evolution from the "quasi-projectile" fragments to fragments with mass around 130 is seen, and it is really impossible to claim whether or not the symetric events are due to the fission following complete fusion process or to the quasi-fission one.
A similar situation is encoutered by Moretto et al 1976 (4) in the Ar + Au system at 288 and 340 MeV.

We are thus led to ask two questions :

i) Is it really possible to find a signature allowing to distinguish between complete fusion and quasi-fission ? In other words, are they really different mechanisms or is there a continuous evolution from one to the other ?

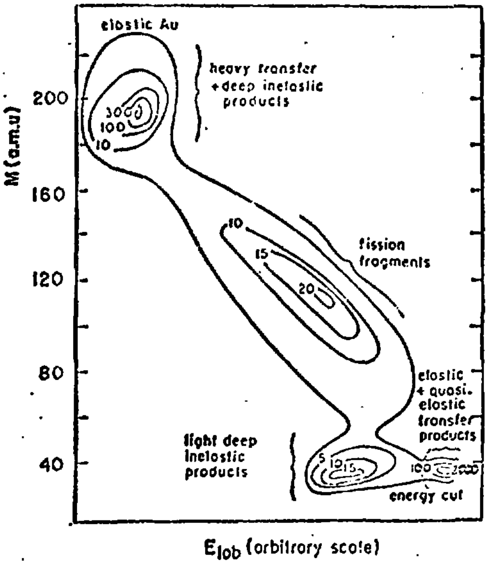
ii) Why is there a so drastic difference between light and heavy systems ? Or why does complete fusion appear more and more replaced by deep inelastic process for heavier and heavier systems ? Typically, the ratien of the complete fusion cross-section σ_{CF} over the total reaction cross-section σ_R , $\frac{\sigma_{CF}}{\sigma_R}$, is $\sim$ 0,7 for O + U at 164 MeV (19) and $<$ 0,05 for Kr + Bi at 525 MeV (20).

Several recent results obtained at Orsay enlight the situation and give at least partial answer to these two questions. Informations will be given through angular and mass or charge distributions, γ-ray, charged particles and neutron multiplicities. Particular attention will be paid to the Ar + Au and the Cu + Au systems for which quite a lot of experimental informations are available (2 - 18).

2. MASS, CHARGE AND ANGULAR DISTRIBUTIONS

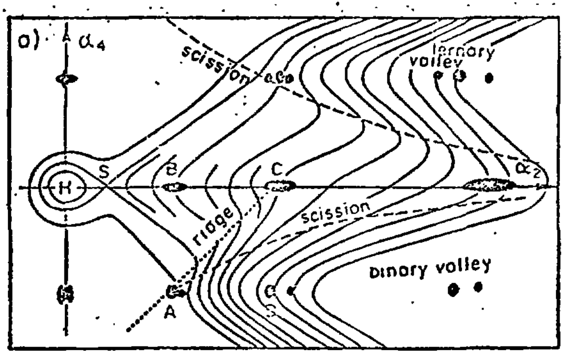
Among other characteristics, mass, charge and angular distributions for the Ar + Au system have been extensively studied at Orsay by two groups (7, 9, 10, 15, 16, 18 and 8).
The reason of this choice was that this system is intermediate between the light ones for which complete fusion is the dominant process and the heaviest ones for which deep inelastic collisions are mostly observed.
One can then expect both mechanisms to be present. The incident energies (7 values between 183 and 250 MeV in the lab system) were chosen low in order to avoid as much as possible a strong mass overlap between the output channels : indeed, the complete fusion nuclei undergo fission and the mass distribution widths are known to increase with the excitation energy for fission. Such a broadening is also likely to be expected for deep inelastic products.

FIGURE 2



Two dimensional plot at θ lab = 46° for the Ar + Au system at 227 MeV.The number of detected events is plotted as a function of their mass and lab. kinetic energy. Fission following fusion events are clearly resolved from the deep inelastic collisions ones.Extracted from (7).

FIGURE 3



Potential Energy map as shown by Swiatecki (30).
α_2 and α_4 are deformation parameters.The incoming system is represented in the binary valley.If its representative point reaches the ridge AC,it undergoes fission.Inversely, if the turning point is not so far,one observe a deep inelastic collision.

The main result for our purpose is shown in figure 2 for the 227 MeV energy (7). It is a contour plot, showing at a given angle the number of detected events as a function of their mass and laboratory kinetic energy. The fission following complete fusion events and the deep inelastic ones are quite resolved. This experimental pattern, even clearer at lower incident energy, allows to answer our first question : complete fusion and deep inelastic processes are distinguishable processes, which correspond to quite different reaction time.

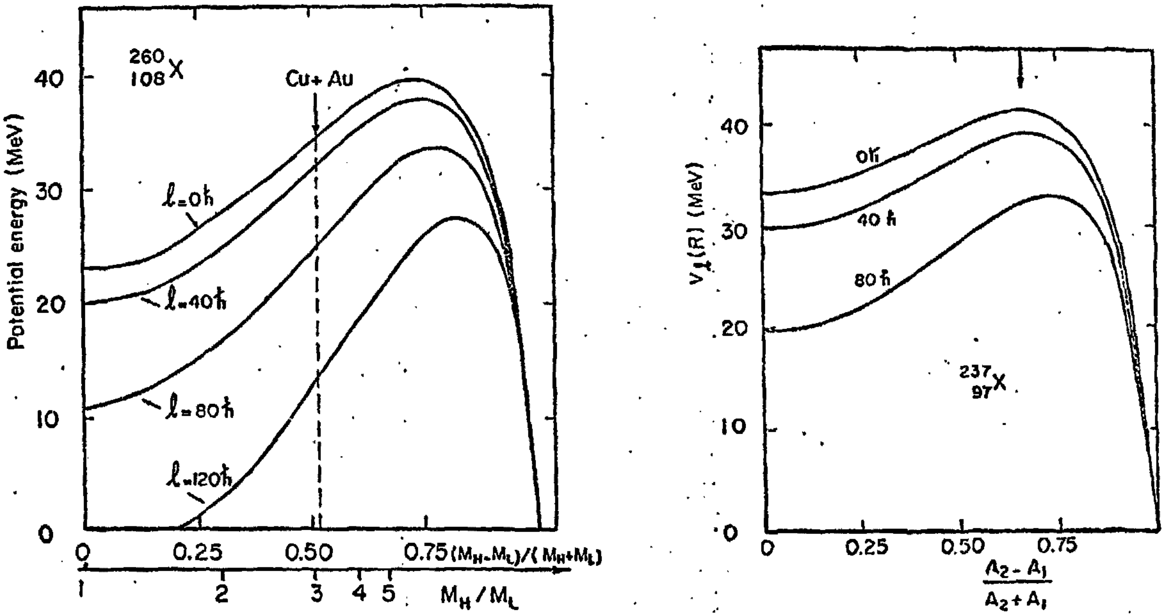
This can be schematized in figure 3 extracted from Swiatecki 1972 (30).

For large impact parameters, the representative point of the system reaches a large distance of closest approach. The turning point is located in the incoming binary valley. For smaller impact parameters, the collision is deeper and deeper (deep inelastic collision), till a particular situation where the turning point reaches the ridge limiting the fusion configuration hollow. If the system overpasses this point, it may be trapped for a long time near the compound nucleus like shape (even if there is no fission barrier) : it is the complete fusion limit. With such a picture, it appears a continuous evolution of mechanisms between deep inelastic collision and complete fusion, but the reaction time for both processes is quite different.

The broadening of the mass (charge) distributions observed when going from 201 MeV to 248 MeV incident energies are due to the increase of the temperature and explains very simply why such a clear separation had not been seen by Moretto et al 1976 (4) at 288 and 340 MeV.
These incident energies are high enough to induce such a temperature that the two bumps corresponding to fission and deep inelastic reactions are no longer resolved.

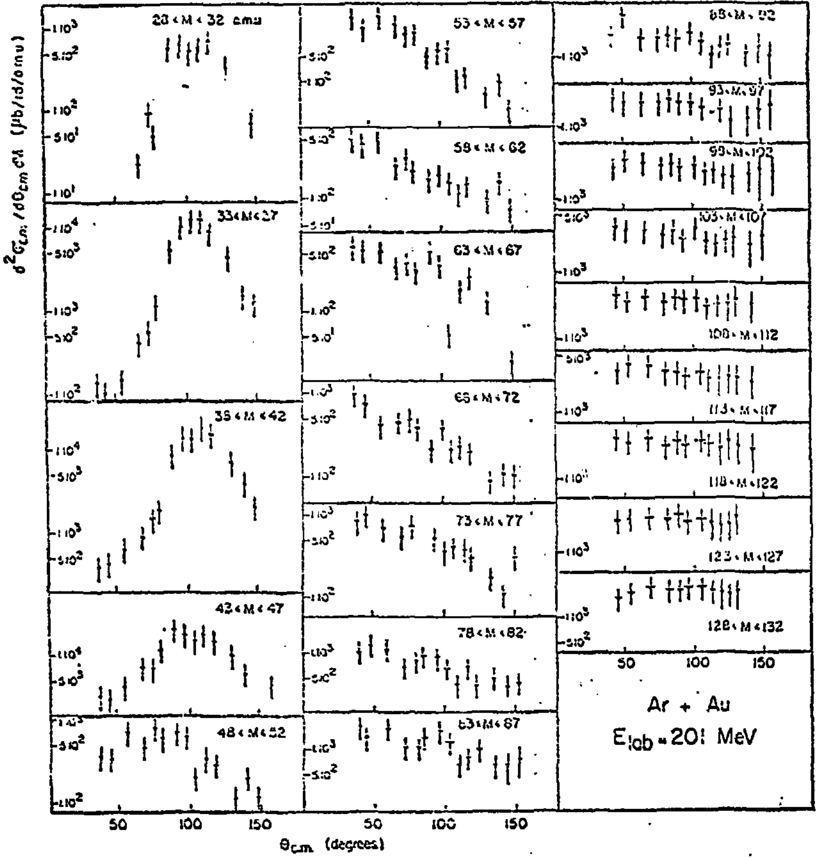
In the case of Cu + Au system, the two bumps are mixed even at low excitation energy. This can be understood by considerong the potential energy of the composite system as a function of the mass asymmetry degree of freedom.

FIGURE 4



Potential Energy for a system of A=A1+A2 nucleons,Z protons,in two cases: A=260,Z=108 (Cu + Au system); A=237,Z=97 (Ar + Au).The various curves are for various angular momenta.These curves have been calculated in the sticking limit.In the Cu + Au case,the driving force towards symmetry is large.It is nearly zero in the Ar + Au system.

FIGURE 5 : Angular distributions of fragments issued from the Ar + Au 201 MeV reaction.It appears a continuous evolution between the curves obtained in the deep inelastic mass region (M 40) and in the fission mass region (M 130). Extracted from (7).



In figure 4 are plotted the potential energy curves of two tangent spheres versus the mass asymmetry for a composite system of 260 nucleons, 108 protons (Cu + Au) and 237 nucleons, 97 protons (Ar + Au) (14) (7).

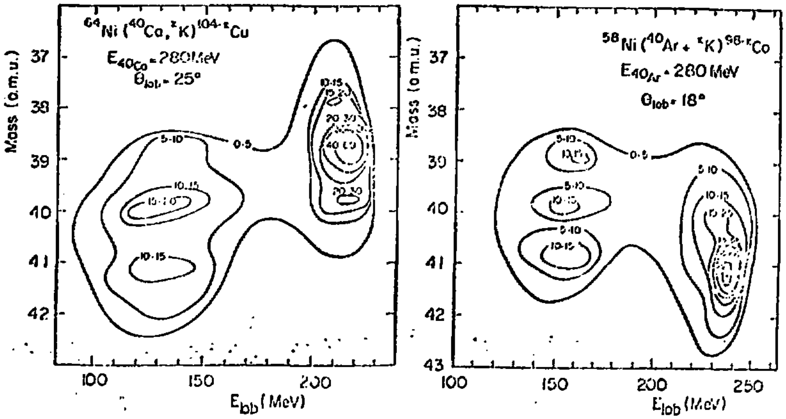
In the Cu + Au case, the driving force towards symmetry is responsible for a shift of the quasi-fission mass distribution. For sufficiently long interaction times, this shift can lead to a symmetric configuration indistinguishable from the configuration obtained through a symmetric fission process, at least from a fragment mass analysis. Inversely, in the Ar + Au case, the driving force at the injection point is very small and even for long interaction times the mass distributions for the deep inelastic collision remain peaked around the entrance channel masses. This difference between both systems for zero l-waves is even enhanced for the l-waves involved in deep inelastic collisions.

For the purpose of separating the fission and deep inelastic contributions by observing the mass distribution, the Ar + Au system at least at moderate excitation energy appears to be a very privileged case.

One could think that the shapes of the angular distributions would be a good test to measure the life time associated to both mechanisms. However, the life time associated with deep inelastic reactions extends from very low values to values exceeding the rotation period of the system. This fact is observed in all the studied systems and specially in the Ar + Au one for all the incident energies (4) (7). Recent exemples can be found in Galin et al 1977 (28).

In figure 5, it appears a continuous evolution of the shape of the angular distributions from the projectile (or target) mass region (dominant deep inelastic mass region) to the symmetric mass region (dominant fission region). The $d\sigma/d\theta$ curves become more and more flat, exhibiting larger and larger interaction time without discontinuity. As in the case of a complete fusion mechanism, deep inelastic composite system can rotate several times before scission.

FIGURE 6



N/Z equilibration in deep inelastic collisions. Two systems of quite different N/Z ratios have been studied. The initial N/Z ratios are seen in the quasi-elastic component (high energy component). The deep inelastic fragments exhibit the same N/Z ratio for both systems, which indicates the fast equilibration of this degree of freedom. Extracted from reference (23).

Two conceptual differences exist however between processes : i) the number of rotation is greater in the fission following fusion case and ii) the axis of elongation is well defined during the deep inelastic process whereas in the fission case, the initial axis of approach is destroyed, and the fission direction is later chosen independently. As far as angular distribution are considered, these two differences do not give experimental evidence.

Neutron excess equilibration.

As a possible test to distinguish between both mechanisms on the basis of the fragments characteristics analysis, one can mention the N/Z ratio.
Experiments have been performed by three groups (21 - 23) and very good agreement exists between the main results : the N/Z ratio is a very rapidly equilibrated degree of freedom in the deep inelastic process and it depends only on the composite system properties as it is the case of fission following fusion.
One exemple extracted from (23) is reported in the figure 6.

3. DEEXCITATION PROCESSES

At this stage of our discussion, one knows from Ar + Au experiments that deep inelastic collisions and fission following complete fusion are distinguishable processes. It remains to find other experimental evidences allowing the distinction between both processes for other systems (as Cu + Au). In the following sections, we try to find these experimental evidences in recent studies, made at Orsay, on the deexcitation mechanism in both processes.
Experimental results have been obtained for γ-ray, charged particles and neutron multiplicities.

3.1. γ-ray multiplicity.

The most extended experiments concern γ-ray multiplicity. Two kinds of systems can be distinguished : the relatively light systems (projectile lighter than copper) for which the deep inelastic channel is not the dominant one and the heavier systems where the deep inelastic cross-section is the largest part of the total reaction cross-section. In the first cases, the initial ℓ-waves associated with deep inelastic channel is well defined, a little lower than the ℓmax value and the l-values range is narrow. In the second cases, a large range of ℓ-values contribute to the large deep inelastic cross-section. We studied systems belonging to both classes : Ar + Au MeV ($70\,\hbar < \ell_{DIC} < 85\,\hbar$) ; Cu + Au at 365 MeV ($0\,\hbar < \ell_{DIC} < 95\,\hbar$) and 443 MeV ($0\,\hbar < \ell_{DIC} < 175\,\hbar$). The information obtained in both cases are quite different.

But let us first recall some model considerations. When the two nuclei interact, one of the most important questions is to know that mechanism is responsible for the energy damping : What is the relative importance of the radial and tangential components of the friction force ? What fraction of the initial angular momentum will be transferred by the tangential friction component to the fragments before scission (see models references in 24 - 25) ? The angular momentum transfer can be considered to pass through different stages.
In the initial stage, the two nuclei slide on each other, and the viscous forces caused by sliding exert a torque on each fragment which sets them into rotation until the peripheral velocities are matched, the system reaches then the "rolling" stage. Finally, rolling friction can slow down the rolling until the fragments rotate rigidly in a "sticking" configuration. At the onset of sliding, the moment of inertia characterizing the system is μR^2 where μ is the reduced mass, and R the distance between the center of the two fragments. For the sticking configuration, it becomes $\mu R^2 + J_H + J_L$ where J_H and J_L are the moments of inertia of each fragment around its own axis. In this case the proportion of angular momentum transferred to the outgoing nuclei is maximum and is

$$\frac{\Delta\ell}{\ell_i} = \frac{J_H + J_L}{\mu R^2 + J_H + J_L} \quad (1),$$

whereas in the rolling stage one has $\frac{\Delta\ell}{\ell_i} = \frac{2}{7}$ (2)

The question we are interested in here is : Is the sticking stage reached in deep inelastic collisions ? In the fission following complete fusion, we know that it is of course achieved. To distinguish between the rolling and the sticking stages, relation (1) and (2) have to give differents values, what is only obtained when the masses of the outgoing fragments are quite different. This is one of the reason making asymmetric systems like Ar + Au and Cu + Au very suitable.

Several remarks have to be done on such experiments. First the measured quantity is the average γ-ray multiplicity $\langle M_\gamma \rangle$ and not $\Delta\ell$. $\Delta\ell$ is then calculated assuming that the detected γ-rays correspond mostly to "stretched E_2" transitions. This assumption is supported by spectroscopy measurements performed on the γ deexcitation of compound nuclei (26). No experiment on the multipolarity of the γ-ray emitted in deep inelastic reactions has been performed but the pattern of the gamma ray energy spectra is quite similar to the one observed in the γ deexcitation of compound nuclei (see fig 7 and (24) (26) : Indeed, the energy spectra exhibit a bump, the maximum energy of which is compatible with $E_{\gamma max}$ of stretched E_2 yrast transitions. A high energy tail corresponds to much less abundant E_1 transitions about 10 %. We think that the above assumption can not be wrong because it would be difficult to understand how the deexcitation chain for a given nucleus at given excitation energy and angular momentum could be different depending on the way it has been formed (deep inelastic composite system or compound nucleus) : indeed if the shapes involved in both mechanisms are different, the γ-ray deexcitation is a slow process and the nuclei are then no longer deformed.

More serious is the question of the angular momentum removed by charged particles and neutron, before, after or at scission. This problem is a big one for many light systems (24) but it is of decreasing importance for heavier systems for which charged particle emission rate is low, in this case the neutron emission is thought to be predominant and it is known that a neutron cannot remove a large angular momentum (a value of 1 ħ is usually assumed (27).

The results obtained in the Ar + Au at 227 MeV case concern both the fission following fusion component and the deep inelastic one (12). In the fission case, $\langle M_\gamma \rangle = 8{,}5$ has been found. The mean value of initial ℓ-waves contributing to complete fusion being 46 $\hbar$, one is led to a calculated mean multiplicity of 6,5. The difference between the measured and the calculated values is due to an additionnal angular momentum brough in the fragments by a bending mode, as it will be discussed later. In the deep inelastic case, the measured multiplicity ($\langle M_\gamma \rangle = 7{,}5$) is much lower than the value calculated in assuming a sticking situation ($\langle M_\gamma \rangle = 15$), and one can then conclude that the sticking stage has not been reached by the composite system. Similar conclusion has been drawn from the γ-ray energy spectra. We have already mentioned (figure7) that these spectra exhibit two parts : a statistical part (high energy tail) and an yrast one characterized by a bump. Let assume that in the Ar + Au system, the sticking stage has been reached : the transferred angular momentum $\Delta\ell$ given by relation (1) is shared between the fragments nuclei in proportion to their moment of inertia. The angular momentum removed by the "quasi-Au" nucleus ℓ_{Au} is then the largest part of $\Delta\ell$. One would then expect to observe a bump limited by the γ-ray energy corresponding to the transition $\ell_{Au} \to \ell_{Au} - 2$

which is $\dfrac{\hbar^2}{2\, J_{Au} \left[2\, \ell_{Au} - 1 \right]}$, with $\ell_{Au} = \dfrac{\ell_i\, J_{Au}}{J_{Au} + J_{Cu} + \mu R^2}$.

$E_{\gamma Max}$ would thus be ∿ 0.7 MeV compared to the experimental value $E_{\gamma Max}$ ∿ 1.2 MeV. Again, we conclude that the sticking limit has not been reached. Let us consider the rolling stage : the distinction of $\Delta\ell$ between both fragments is quite different and the "copper" contribution is no more negligible. The corresponding $E_{\gamma Max}$ value is around the experimental one in taking the experimental $\Delta\ell$ value. The experimental $E_{\gamma Max}$ and $\langle M_\gamma \rangle$ values are then coherent. However, they are too low if we assume that the incoming angular momentum is around 70 $\hbar$ as it has been determined in (7). This is however coherent with the slow energy relaxation observed for the same system at similar detection angles (7) (8). It appears thus that for this system, the deep inelastic composite system would not have reached the sticking

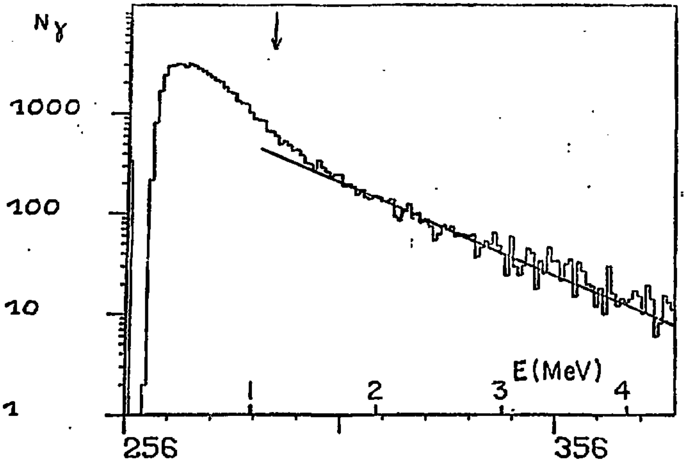


FIGURE 7 : Cu + Au reaction at 443 MeV. spectrum coincident with quasi-fission fragments detected at 35°.The arrow indicates the theoritical maximum Yrast energy.

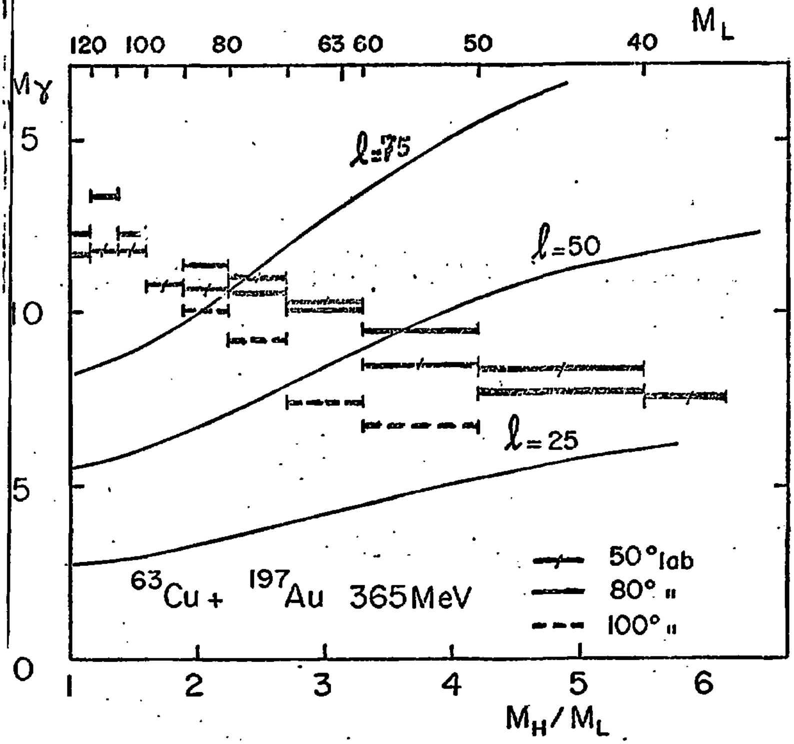


FIGURE 8 :M versus the mass ratio of the quasi-fission products at 3 angles. The thin lines are calculated with the sticking hypothesis for different incoming l-waves.

limit as it does in the fusion case.
In fact, the actual experimental situation is rather complex since similar results obtained on relatively light systems indicate that the sticking limit has or has not been reached depending on the observation angle or on the incident energy. For exemple, the variation of $\Delta\ell$ with the mass ratio asymmetry for the Ne + Ag at 175 MeV system is that expected from calculations made in the sticking hypothesis at 35° and 90° fragments detection angles, and is that corresponding to a calculated rolling hypothesis at 25° lab angle (31) ; in the O + Ni at 96 MeV case (32), the variation with the mass asymmetry is coherent with a sticking hypothesis whereas the overall multiplicity is too low ; in the N + Nb at 120 MeV experiment (33), the result are well interpreted in a sticking hypothesis.

For heavy systems, the situation is not clearer : in the Cu + Au system studied at Orsay, the sticking limit seems to be reached at 365 MeV and not at 443 MeV (14) where the energy to be lost is greater and it is impossible to check whether or not the symmetric events are complete fusion events.
Fortunately, for these systems, the variation of the γ-ray multiplicity versus the mass asymmetry is very helpful. The 365 MeV curve is drawn in figure 8 (14). It appears that the variation of M_γ with M_H/M_L is opposite to the one predicted by the sticking hypothesis. Such a result was also obtained by Moretto 1977 (35) and this author has interpreted it by using the potential energy curves as drawn in figure 4. One can see that the driving force toward symmetry for the Cu + Au system increases with the angular momentum. So, large mass transfer are favored for high ℓ-waves. With such a picture, one can understand the feature drawn in the figure 8. The low M_H/M_L ratios correspond to largest γ-ray multiplicities because they are associated with ℓ-waves.
This fact gives also an answer to the problem of distinction between fission and mass symmetric deep inelastic events in the Cu + Au system. It is now clear that these events are mostly deep inelastic one because the corresponding initial angular momentum are about 75 $\hbar$ (365 MeV case) whereas maximum ℓ-range which could be available for complete fusion was 0 - 25 $\hbar$ (6)

(This value of 25 $\hbar$ has been obtained in assuming : i) that all the symmetric events observed were fission events, ii) that the fission mass distribution width was that extrapolated from measured values in fission of heavy compound nuclei. It is a maximum value. For more precise explanations, see ref (6).

We are thus led to the conclusion : in the Ar + Au case, the complete fusion is a probable process whereas this channel has completely disappeared in the Cu + Au system. The limit for complete fusion lies thus between these two systems and corresponds to a Z_1Z_2 product of about 2000 in the entrance channel. One could argue that in the Ar + Au case, a lot symmetric events are also deep inelastic ones. Our answer is that the proportion of this kind of symmetric events is less than 10 %. Indeed, if almost of the symmetric bump seen in the Ar + Au mass distribution was due to a deep inelastic mechanism, one should have observe much more symmetric scissions in the Cu + Au system for which i) the driving force is much stronger, ii) the injection point is closer to symmetry and iii) the reaction time is longer.

Another objection would be to claim that complete fusion is not associated with the lowest ℓ-waves (36) (37). We will not consider here such an hypothesis for two reasons. First, if it was correct, the ℓ range to be associated with complete fusion would be around 75 $\hbar$ which is not supported by the results of Cabot et al 1976 (38). Secondly, the only data supporting the existence of a ℓ_{crit} minimum concern excitation functions of (HI , xn) reactions and it is not evident that there is no other explanation (1) (53).

3.2. The Bending Mode.

It is well known that in low energy fission without initial angular momentum, the γ-ray multiplicity is not equal to zero (39). This was explained in assuming that during the descent from the saddle point to the scission point, a "bending mode" induces opposite angular momenta in the nascent fragments (40).

One could expect that such a slow process is not observed in deep inelastic reactions. This could allow to discriminate between fission and deep inelastic processes. This point was checked on our usual systems Ar + Au at 227 MeV and Cu + Au at 365 and 443 MeV by looking at the angular distribution of the emitted γ-rays. Indeed, because of the "stretched E_2" nature of these transitions, γ-rays are mainly emitted perpendicularly to the angular momentum of the fragments and if no bending mode or disaligment occurs, they are then expected mainly in the reaction plane defined by the directions of the coïncident fragments, exhibiting thus a minimum in the direction perpendicular to this plane.

For all the systems where the out of plane angular distribution of emitted γ-rays was studied, the results show that the counting rate in the perpendicular direction reacties 80 - 95 % of the "in plane" counting rate (11) (12) (14) (33). This fact cannot be explained neither by a high contribution of E_1 transition (which is about 10 % in our systems), nor by angular incertainities (which would be due to the solid angles of various detectors), nor by some disaligment induced by neutron or charged particle emission (indeed the neutron effect is certainly low and the α-multiplicity is only 0.2 for similar systems (41)), nor by some disaligment along the γ-deexcitation chain. We are thus led to assume that as in fission following fusion an "additionnal" angular momentum, independant from the incident one, is brought into the fragments. Simple geometrical consideration show that this supplementary part is in a plane perpendicular to the c.m. flight direction of the fragments.

Several arguments support the existence of this bending mode :

i) calculation based on the Nix and Swiatecki model (40) of the corresponding characteristic time for the bending mode is about the interaction time in deep inelastic collision (time necessary for the system to rotate to the observed angle),

ii) the order of magnitude of the angular momentum brought in the fragments in spontaneous fission of heavy nuclei is about 15 - 20 ħ compatible with that simply calculated for deep inelastic reactions. Such an amount of angular momentum is quite enough to destroy the aligment of only about 60 ħ or less as observed as total angular momentum transferred in our systems.

iii) the aligment seems to be progressively destroyed for more and more relaxed events (41), this can be understood if we note that decay time increases for more relaxed fragments, corresponding thus to a stronger effect of the bending mode.

Another recent work performed by Dyer et al 1977 (42) supports also the existence of a bending mode in deep inelastic collisions. Looking to the angular distributions of the fragments issued from "sequential fission" of the highly excited "quasi-bismuth" nuclei obtained in the deep inelastic reaction on the 610 MeV Kr + Bi system, these authors observed that
i) most of the fission fragments were detected in the deep inelastic reaction plane
ii) in that plane, the angular distribution was not isotropic.
The first result is simply due to the fact that the initial angular momentum involved in their reaction was very large ($\ell_{max} \sim 235$). A 20 $\hbar$ bending mode contribution is clearly not high enough to destroy the aligment. But, the second result can be nicely explained by the effect of a bending mode : indeed if the aligment is not perturbed, the "in-plane" angular distribution would be isotropic. Let us assume now that the bending mode has added 20 $\hbar$. This additionnal angular momentum is oriented perpendicularly to the flight direction of the deep inelastic products. These "sequential fission" of the "quasi-bismuth" is no longer isotropic in the deep inelastic reaction plane. The forward and backward directions are slightly favored as observed by the authors : the "in-plane" angular correlation which can be extracted from their curve corresponds to an additionnal angular momentum of about 10 - 20 $\hbar$.

3.3. Neutron emission in deep inelastic reactions.

One experiment has been very recently performed by Pêter et al 1977 (43) to determine the number of neutrons emitted in deep inelastic processes and their repartition between both fragments. The chosen system is Cu + Au at 365 MeV for which we know that nearly no fission occurs.

Some partial analysis of the results can be found in (43). Let us focuse *on the result allowing to discriminate between deep inelastic collisions* and fission following complete fusion. It lies in the repartition of the excitation energy between both fragments. It has been shown that for the quasi-fission events, the excitation energy is not shared proportionally to the masses of the fragments but that the ν_L/ν_H ratio of the number of neutrons emitted by the light and the heavy fragments was greater than the ratio M_L/M_H of the fragments masses.

This very surprising result is opposite to the known trend of high energy symmetric fission for which ν_L/ν_H is lower than M_L/M_H. The authors think that in the Cu + Au case, this effect is due to the deformation of the quasi-fragments and can be interpreted in assuming i) a constant temperature at the scission point ; ii) a scission point configuration consisting in two equally deformed fragments (43).
New experiments are clearly necessary to confirm this result which indicates that the shapes at the scission point are different in a fission following complete fusion reaction and in a quasi-fission reaction. Complete discussion and experimental details on these results will be soon published (44)

3.4. Charged particles emission.

Neutrons and γ-rays emission come with deep inelastic and complete fusion processes in all systems, removing respectively a large part of the excitation energy and angular momentum. Inversely charged particles emission is more system dependent. Although the charged particles multiplicities and angular distribution can give a great improvement of our knowledge of the primary mechanism (namely spin distribution, degree of aligment, excitation energies and structure effects), the actual results are difficult to interpret particularly for our purpose to distinguish between fission following fusion and quasi-fission. For instance the sharing of the excitation energy between the two outgoing fragments will be more complicated to extract than in neutron emission experiments on heavy systems for wich the charged particle multiplicity is very low (46).

Charged particles evaporation and its competition with neutron evaporation and fission is well understood in the compound nucleus deexcitation, eventual final stage of a complete fusion reaction. If a large part of charged particles multiplicities observed in complete fusion and deep inelastic reactions can actually be attributed to the evaporation from highly excited equilibrated compound nuclei or fragments, the origin of at least a part of the charged particles emission involves other hypothesis : i) direct process resulting in a fusion reaction with only a part of the projectile ; ii) emission by the composite system before or after it has reached complete equilibrium ; iii) emission by the not totally equilibrated fragments or by the highly excited neck (45).

Already obtained results (see 45 for references) are very promising but it is prematurate to draw firm conclusions. They surely indicate the need of experiments where as many as possible different characteristics are accumulated on the same system.

Review of this exciting field will be given by Galin et al 1977 (45) at the Tokyo Meeting.

4. ON THE LIMIT TO COMPLETE FUSION

Some years ago, it was proposed that the limit to complete fusion can be described by the concept of a "critical distance" (47) (48). In the case of very heavy systems induced by heavy projectiles like Kr + Bi, this concept holds for quasi-fission phenoma. It appeared then that the critical distance was an universal concept fitting the fusion cross-section for projectiles ut to argon and the quasi-fission cross-section for systems where the fusion is replaced by it (49).

However, what about systems like Ar + Au for which both mechanisms are of comparable importance ? If the critical distance concept fits the complete fusion or the quasi-fission cross-section when one of the two processes is quite dominant, it has to fit the sum of both processes contributions.

For Ar + Au system for which the excitation function for complete fusion and deep inelastic reactions was measured from 183 up to

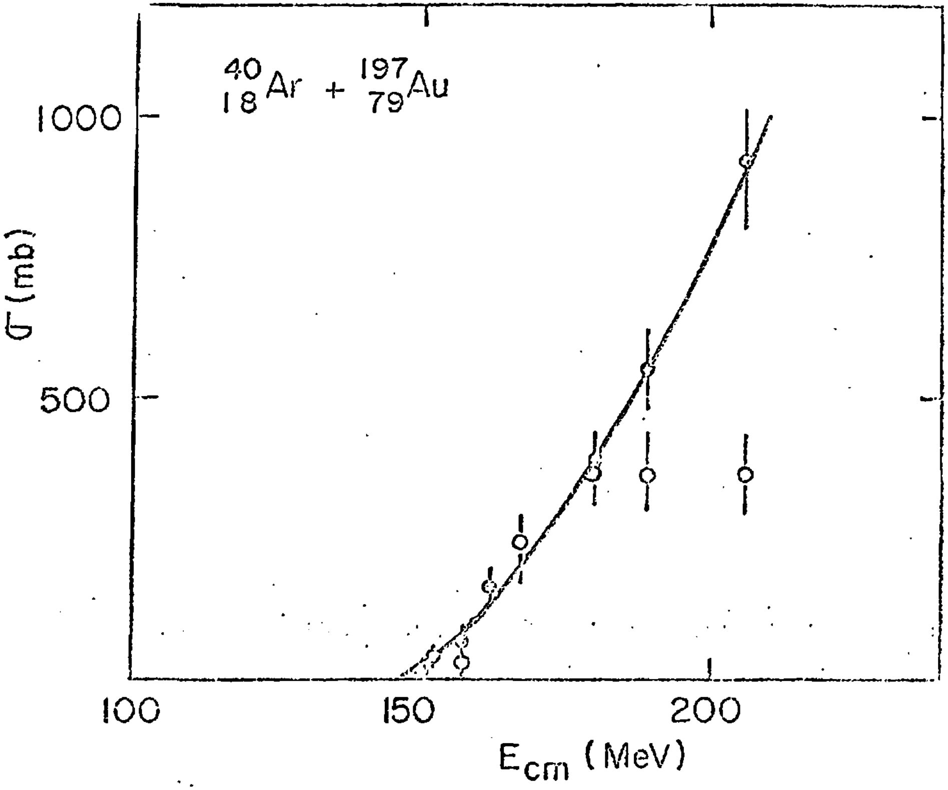


Fig. 9 Excitation function for complete fusion (full points) and for DI reactio (open points). The full curve is just to guide the eyes.
Extracted from (7).

248 MeV lab incident energy (figure 9) and others systems ranging from O + Al to Kr + Bi where both cross-sections are known, a good agreement was obtained with a critical distance of 1.08 fm.

In fact, this does not mean that the system have to reach such a critical distance to undergo complete fusion and this concept is only a useful parametrisation of the results where the "sudden approximation" method used in the calculations neglects the friction forces, the role of which is known to be very important. This critical distance concept means only that the two partners have to mix enough their nuclear matter distribution to be able to induce a large energy relaxation leading in the extreme case to a quasi-fission or a complete fusion process.

What decides between quasi-fission and fusion ? Cohen et al 1974 (50) have expressed the limit to complete fusion in terms of a zero fission barrier for the compound nucleus. But this would lead to a limiting angular momentum value $\ell_{Bf = o}$ for complete fusion which would be independent of the incident energy. This is not at all observed experimentally. $\ell_{Bf = o}$ is certainly a limiting value for compound nucleus formation but not for complete fusion.
One can indeed think that in the fusion process the system is trapped for some time in a compound nucleus like shape configuration even if this configuration is unstable towards a definite deformation. This trapping would be the main qualitative difference between complete fusion and quasi-fission processes and would also be responsible for the difference of the reaction time for both processes. In the complete fusion process, the composite system would loose the memory of its initial deformation axis before finding, after several random oscillations, a fission direction.

The role of the potential energy in function of the mass asymmetry degree of freedom can explain the choice between fusion and quasi-fission. For a given incoming ℓ-wave, the system will evoluate toward symmetry (quasi-fission) or toward asymmetry (limit case = complete fusion) depending mainly on the injection point position. This concept, first used by Moretto and Sventeck 1975 (51) in deep inelastic collisions, has been used here to calculate the proportion of quasi-fission and complete fusion cross-sections for Kr + Bi, Cu + Au, Ar + Au, Ar + Ag, O + Al systems.

The gross features of the experimental cross-sections have been reproduced (no fusion for Cu + Au, Kr + Bi, nearly no quasi-fission for O + Al, comparable contributions of both mechanisms in the Ar + Au case) (54). However, in such a model, the limiting ℓ-wave for complete fusion is again independent of the incident energy, which is in contradiction with most experimental results. Moreover, one would expect a difference of more than 20 MeV between the thresholds for both mechanisms (54), which is not observed.

Such contradictions can probably be removed if one consider the influence of the fluctuations in the interaction process (52) : fluctuations will populate mass asymmetry ratios all around the injection point and because of the much deep decrease of the popential energy toward asymmetry than toward symmetry, complete fusion will be favored. This effect is stronger for higher temperature increasing then the fusion cross-section for higher excitations energies.
Such fluctuations calculations are being done by several authors (52).

5. CONCLUSION

Some evidences allowing to distinguish between fission following complete fusion and deep inelastic reaction induced by heavy ions have been found among experimental data obtained recently. It has been shown that from the Ar + Au results, fission and deep inelastic processes are quite different reaction mechanisms, characterized by different interaction times. Gamma-ray multiplicities have been used to prove that no fusion was accomplished in the Cu + Au at 365 and 443 MeV and Kr + Bi at 525 MeV systems. Among the various results obtained from the study of the deexcitation of observed products, neutron emission appears to be a promising way to distinguish between fission following fusion and deep inelastic or quasi-fission mechanisms.
All the results can be interpreted, at least partially, by looking at the evolution of the potential energy of the composite system with the mass asymmetry ; but some puzzling effects have however to be solved using

dynamical calculations including fluctuations, which appear as a good way to progress.

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