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CEA-CONF -- 8160

L3

Rapport DPh-N/Saclay n°2303

HEAVY ION PHYSCIS AROUND THE FERMI ENERGY

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Communication présentée à : Topical meeting on phase space approach to nuclear dynamics

Trieste (Italy)
30 Sep - 4 Oct 1985

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ABSTRACT

Some aspect of heavy-ion physics between ~ 20-50 MeV/u are reviewed on two examples. First, one describes the present situation concerning the amount of linear momentum that a projectile can transfer to a fused system. One shows that this amount depends on the bombarding energy and on the mass of the projectile. The limit of incomplete fusion is discussed in terms of the maximum energy content of a nuclear system. Second, one describes some new results obtained with Kr projectiles on medium and heavy targets where one observes strongly inelastic events. These products are interpreted qualitatively in terms of a participants-spectators picture modified by the mean field interaction. The difference between Kr and lighter projectiles induced reactions is interpreted in terms of the Coulomb interaction as it is also the case at low bombarding energies.

INTRODUCTION

Due to accelerator possibilities, heavy-ion physics has been divided in three main areas of investigations : the low energy domain, where the bombarding energy per nucleon, E, is smaller than ~ 10-20 MeV/u, the medium energy one where 20 < E < 100 MeV/u. This corresponds to energy regions where the kinetic energy in the relative motion is small, of the same order, or larger than the kinetic energy associated with the Fermi motion of the nucleons.

A lot of experiments have been performed at low bombarding energies and many fascinating phenomena have been found[1]). It is still a very active field and the discovery of collective dissipative motions, around the seventies, has played a major role in the evolution of this area. The physical processes are dominated by the mean field and the mean free path of the nucleons is large compared to the nuclear dimensions because of the Pauli blocking.

At high bombarding energies the mean free path becomes smmaller than the system's dimensions and the interaction time is very short. Consequently, the signals concerning the mean field are not able to propagate over large distances. This domain is dominated by the nucleon-nucleon interaction and coherent processes have practically disappeared. Many experimental studies have been devoted to this bombarding energy region over the last 10 years[2]).

Studies in the medium energy domain are now starting using new accelerator facilities like GANIL, MSU or SARA. This domain is a transition region between the low energy area, dominated by the mean field, and the high energy one, dominated by the nucleon-nucleon interaction. Many questions can be raised and let us quote a few of them :

- At wich energy does a transition occur between the low and the high energy domains?
- Is this transition smooth or not?
- Do we observe new phenomena of collective nature?

- How does the dissipation processes, which are of one-body type at low energy, evolve? Do we get a transition to a two-body type of dissipation?

Many experiments are now trying to answer these questions. However, since they have been performed rather recently the physical situation is still not clear enough at the moment for drawing definite conclusions. Nevertheless, one starts to get a rough idea of what happens in this medium bombarding energy domain. Due to the lack of time we shall illustrate the experimental situation in this domai with only two subjects. The first one concerns the amount of linear momentum that a projectile can transfer to a fused system. The second subject describes some new results in the interaction of two heavy ions when the projectile and the target have a mass > 80 a.m.u.

1. TRANSFER OF LINEAR MOMENTUM

1.1 Scope of the problem

At low bombarding energies, and if fusion is possible, the fused system is composed of all the nucleons of the projectile and of the target. It recoils, in the laboratory frame, with a well defined velocity, V, which is equal to the velocity of the system center of mass, $V_{C.M.}$. This situation is denominated complete fusion. As the bombarding energy increases above ~ 8-10 MeV/u particles (prompt particles) can escape from the projectile and from the target before the two remnants fuse[3]). The particles originating from the projectile are fast in the laboratory frame whereas those coming from the target are slow. The fused system does not consist of all the initial nucleons and for that reason this process has been denominated incomplete fusion. Several theoretical explanations have been proposed to explain the emission of prompt particles : PEP's (promptly emitted particles) also called fermi jets[4]), preequilibrium emission[5]), emission from a hot spot[6]), inertial emission (in the case of composite particles[7]). At the moment the experimental situation is not able to decide which, of the preceding explanations, is the correct one. In any case it might as be that several of the above possibilities occur at the same time. However, it is an experimental fact that prompt particles are emitted. Since they have some linear as well as some orbital angular momentum it means that the fused system will have a linear and an angular momentum smaller than in the case of complete fusion. In particular the recoiling velocity, V, will be smaller than $V_{C.M.}$. It follows that the amount of linear momentum transferred from the projectile to the fused system, ρ, defined, as :

$$\rho = \frac{P_F}{P_1} \tag{1}$$

where P_F and P_1 are the projection of the linear momentum in the beam direction for the fused system and the projectile, respectively, should be smaller than unity (ρ=1 when complete fusion occurs).

1.2 Principle of measurement

The fused system is excited and will de-excite either by particle evaporation, leading to evaporation residues, or by fission. In the first case the measurement of the recoiling velocity distribution of the evaporation residues will allow one to get informations about ρ [ref.[8])]. In the second situation the information about ρ will be obtained from the folding angle distribution of the two fission fragments[9]). It is this last experimental method which has been mostly used[10-24]). As a matter of fact ρ is not a single number but a distribution around a most probable value which we shall denote by $\tilde{\rho}$. Experimentally it is rather easy to obtain $\tilde{\rho}$ from the measurements. However, it is difficult to obtain the whole ρ distribution. The reason is that both the evaporation residues and the fission fragments are excited and therefore, they deexcite before reaching the detectors. Consequently, this evaporation process induces a broadening in the recoiling velocity distribution of the fission fragments. These effects are difficult to correct exactly. For this reason most of the experimental data are relative to $\tilde{\rho}$ values.

1.3 Summary of the experimental results

Most of the experimental investigations concerning $\tilde{\rho}$ have been made with light projectiles (< Ne) and heavy targets (in order to use the fission fragment folding angle technique). It was found that $\tilde{\rho}$ decreases as the bombarding energy per nucleon, E, increase. When plotting $\tilde{\rho}$ as a function of $\sqrt{E}$ it was found[14]) that all the systems follow an average behaviour which can be parametrized as follows[16]) :

$$\begin{aligned} \tilde{\rho} &= -\,0.0092\sqrt{\frac{E}{A}} + 1.\,273 \qquad \text{for} \quad \sqrt{\frac{E}{A}} > 3.2\ [\mathrm{MeV/u}]^{1/2} \\ \tilde{\rho} &= 1 \qquad\qquad\qquad\qquad\quad\ \text{for} \quad \sqrt{\frac{E}{A}} < 3.2\ [\mathrm{MeV/u}]^{1/2} \end{aligned} \qquad (2)$$

The above parametrization has been found to be valid for C projectiles for instance up to 84 MeV/u. It should nevertheless be kept in mind that there is an appreciable scattering of the data points around this average parametrization as can be seen in fig. 12 of ref.[16]).

When heavier projectiles, like Ar, are involved one gets unexpected results as E increases[15,17,20]). This is illustrated in fig. 1 where the experimental folding angle, θ_{fold}, of the fission fragments, observed in the Ar + U reaction, is displayed at 4 different E values. The measurements have been performed by Patin et al.[23]) at 19.6 and 35 MeV/u, by Jacquet et al.[24]) at 27 MeV/u and by Charvet et al.[15,17]) at 44 MeV/u. At 19.6 MeV/u the θ_{fold} distribution shows two pronounced peaks. One located at about $\theta_{fold} = 120°$ corresponds to fission following incomplete fusion and contains the events we are interested in. A second one, located at $\theta_{fold} = 170°$, can be ascribed to a low inelasticity interaction between the projectile and the target followed by a sequential fission of the excited quasi-target (sequential fission). A similar situation is observed at 27 MeV/u in an experiment performed by a Orsay group[24]). However, at 35 and 44 MeV/u the situation changes drastically. The first peak at low θ_{fold} values has disappeared while the peak associated with sequential fission is still present. It is not

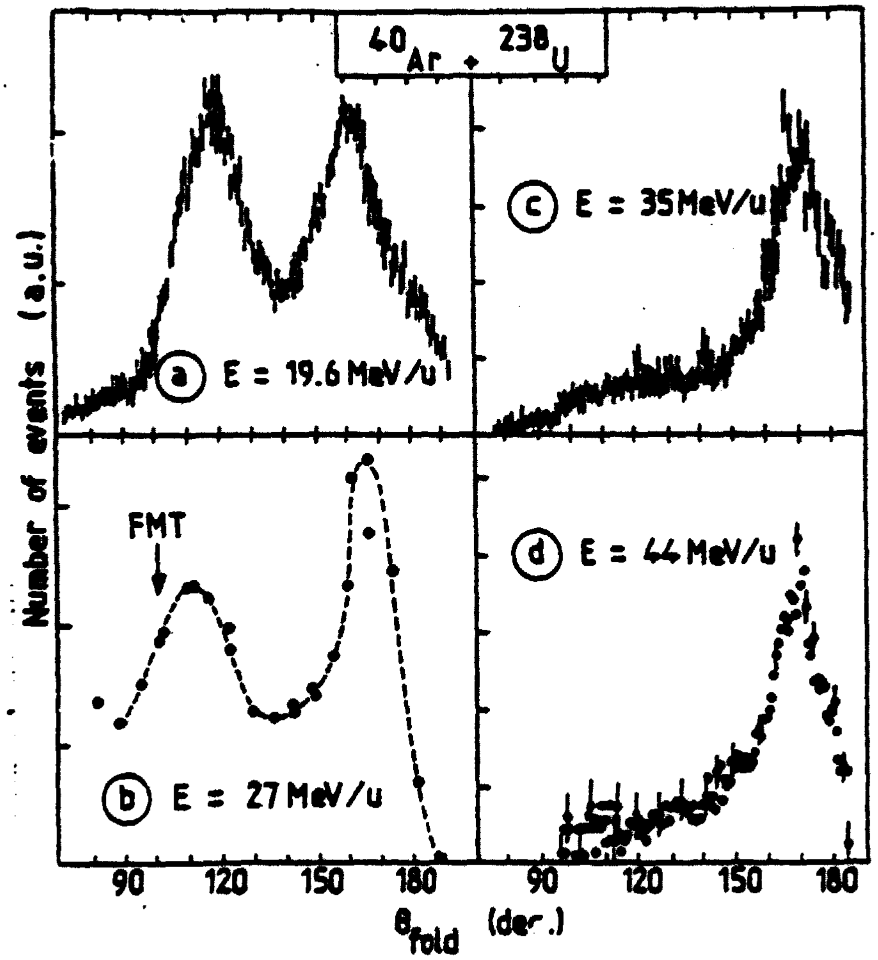

Fig. 1 - Folding angle distribution of the fission fragments associated with the Ar + U system at different bombarding energies : the results are from Patin et al.[23]) at 19.6 and 35 MeV/u, from Jacquet et al.[24]) at 27 MeV/u and from Charvet et al.[15]) at 44 MeV/u.

possible to extract a $\tilde{\rho}$ value for incomplete fusion. However, since sequential fission cannot readily contribute to counts in the region where θ_{fold} is lower than 140°, it means that there remains a certain contribution of incomplete fusion events. Nevertheless, the $\tilde{\rho}$ value certainly lies well outside the systematic behaviour observed with lighter projectiles and represented by eq.(2).

The conclusion of the experimental investigations seems that $\tilde{\rho}$ does not only depend on E but that it also depends on the size of the projectile. This is supported by the results of the model developed in ref.[25]) where $\tilde{\rho}$ was calculated after evaluating the number of prompt particles emitted prior to fusion by simple phase space considerations. It was found that the projectile and the target emit roughly the same number of prompt nucleons which means that $\tilde{\rho}_1$ measured in a $A_1 + A_2$ reaction should be different from $\tilde{\rho}_2$ measured in the inverse kinetics $A_2 + A_1$ where the projectile and the target have been permuted, provided $A_1 \neq A_2$. This conclusion is in contradiction with what would be obtained if the systematics described by eq.(2) would be valid since, in this case, $\tilde{\rho}_1 = \tilde{\rho}_2$. There are indeed some experimental results which indicates that $\tilde{\rho}_1 \neq \tilde{\rho}_2$ [ref.[26])].

Finally, as it can be seen in fig. 1, something happens, as E increases, when heavier projectiles like Ar are involved. It seems very likely that this is related to the disappearance of the incomplete fusion process. It seems, by inspection of fig. 1, that there is rather a smooth decrease of the incomplete fusion cross section, than a rapid one. This might indicate that the transition between the low and the high energy domains occurs around 30-40 MeV/u.

1.4 Maximum excitation energy content of a nucleus

In order to form a fused nucleus one needs to have global statistical equilibrium over the whole system. Therefore, the fusion problem is closely related to the maximum amount of energy that one can deposit in a nucleus. This is related in turns to nuclear boiling. If the boiling of a nucleus would give a gas of free nucleons the maximum excitation energy per nucleon, ε^*_{max}, that one could deposit would be the mean nucleon binding energy, i.e. ~ 7-8 MeV. However, in intermediate heavy ion collisions many composite particles (clusters) seem to be observed in central collisions with a mass distribution of $A_c^{-\tau}$, where A_c is the cluster mass and τ an exponent $\approx 7/3$ [ref.[27])]. There have been many theoretical propositions to explain this experimental fact : liquid-gas phase transition[27,28]), cold multifragmentation[29]), percolation phenomena[30]) etc... However, up to now one does not know which explanation is right. Nevertheless, the experimental results indicate that there is a maximum amount of energy that one can deposit in a nucleus before it decomposes by thermal, mechanical or chemical instabilities. Therefore, since one gains energy in forming clusters it means that the maximum energy deposit, as evaluated above, has to be decreased by the mean cluster binding energy. In ref.20) ε^*_{max} was evaluated for different nuclei assuming different values for the τ parameter (because τ is found experimentally to be spread around $\tau = 7/3$). The results are shown in fig. 2 for $\tau = 7/3$. One observes that ε^*_{max} is about 5 MeV but it is worth noting that medium nuclei can accomodate more excitation energy per nucleon than heavy nuclei. A compilation of the experimental data31) seems also to incidate that ε^*_{max} is close to this value. One is of course tempted to convert ε^*_{max} to a temperature value T_{max}. In doing so one has to be aware that the result is model dependent because one needs to introduce a level density parameter, a. At low excitation energies $a = A/8$, where A is the mass of the nucleus under consideration. Several calculations have shown that it does not vary too much

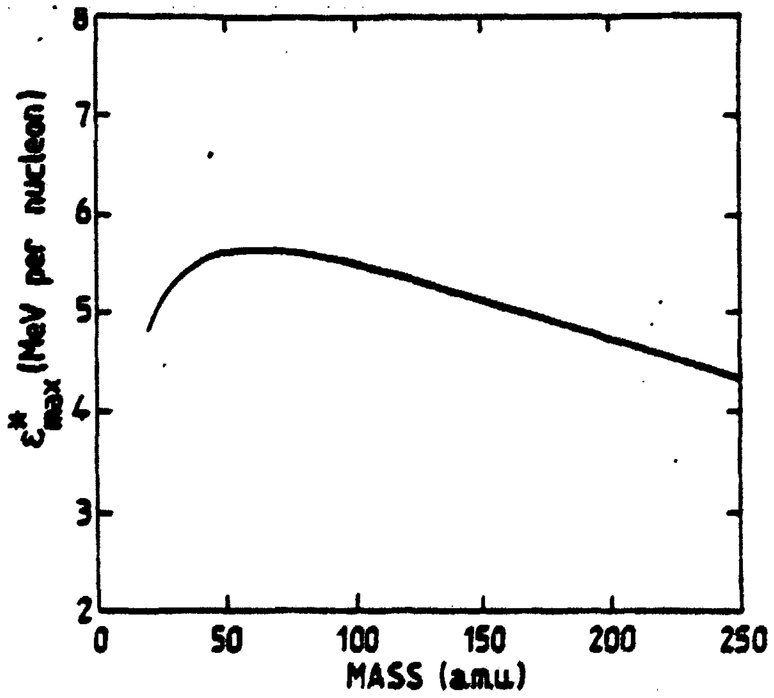

Fig. 2 - Maximum excitation energy per nucleon, for nuclei along the beta stability line, calculated assuming that clusters of mass A_c are formed with a probability $A_c^{-\tau}$. From ref.20).

with the excitation energy[32]). Using this value one finds that T_{max} = 6.5 MeV.

This condition that the maximum excitation energy density per nucleon ε^* should be smaller than ε^*_{max} could possibly explain the results shown in fig. 1. Indeed, at 19.6 MeV and 27 MeV/u $\varepsilon^* < \varepsilon^*_{max}$ whereas, at 35 and 44 MeV/u there starts to have limitations for some of the ρ values which are around those given by the systematic described by eq.(2). In ref.[25]) the preceding condition has been used, together with the results of the phase space model concerning $\tilde{\rho}$, to evaluate ε_{max}, the maximum bombarding energy per nucleon, for which a fused system can still survive. Results of such computations are displayed in fig. 3. One observes that for a given $\tilde{\rho}$ value ε_{max} depends very much on the asymmetry, x, of the system defined as :

$$x = \frac{A_2 - A_1}{A_1 + A_2} \qquad (3)$$

where A_1 and A_2 are the mass of the projectile and of the target, respectively. For full linear momentum transfer ($\tilde{\rho}$ = 1), for instance, one has ε_{max} = 92, 36 and 20 MeV/u for the ^{12}C + ^{197}Au, ^{40}Ar + ^{197}Au and ^{84}Kr + ^{92}Mo systems respectively. This shows that the fusion process is also very closely related to the amount of excitation energy that one can deposit in a nuclear system with the condition of global statistical equilibrium.

2. KRYPTON INDUCED REACTIONS

Before we present some of the experimental results obtained with krypton projectiles at intermediate bombarding energies it is useful to briefly recollect the situation below 10 MeV/u. There, it has been found that fusion of Kr projectiles and heavy targets was impossible[33]) because of the strong coulomb interaction between the two nuclei which cannot be counteracted by the nuclear forces[34]). A similar situation should also occur at intermediate bombarding energies because, in the interaction region, one has a similar situation as at low bombarding

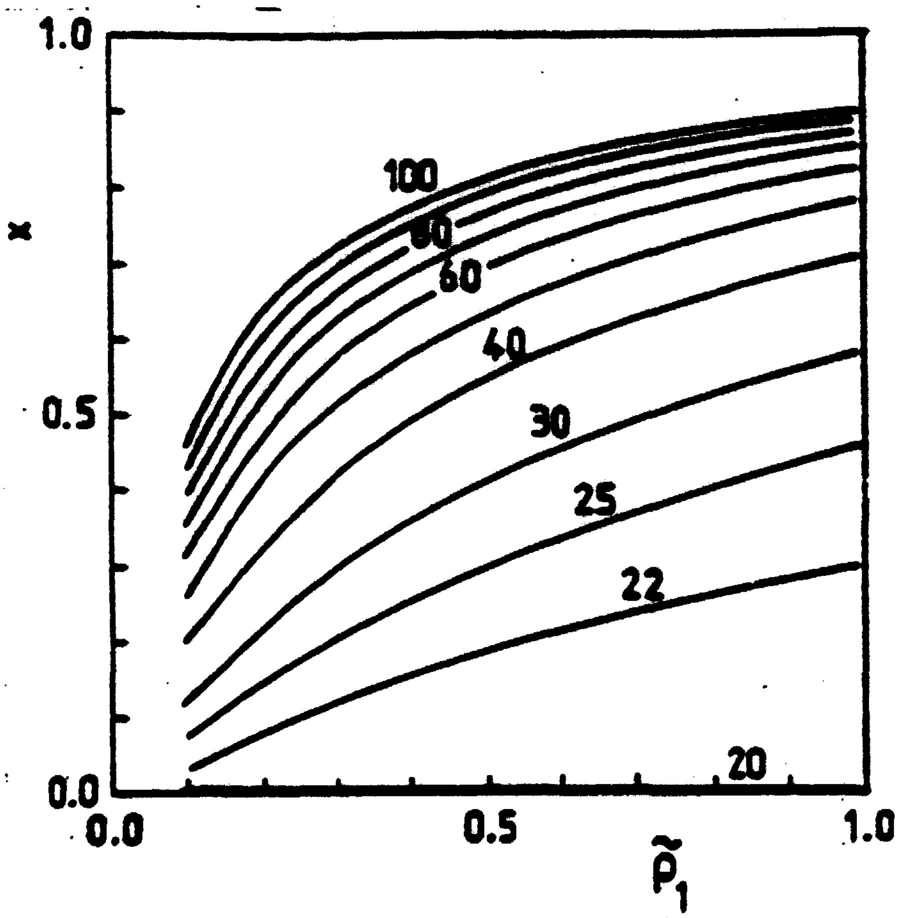

Fig. 3 - Maximum bombarding energy per nucleon that a system can sustain while maintaining statistical equilibrium as a function of both the mass asymmetry parameter x and $\tilde{\rho}$. From ref.[25]).

energies. We shall now concentrate on the Kr + ^{197}Au, ^{nat}Ag and ^{92,98}Mo systems which have been investigated at 22 MeV/u [refs.[35,36])]. In addition to fragmentation products which are observed at and below the grazing angle, one detects fragments with large inelasticities. These fragments are especially visible at angles larger than the grazing angle because fragmentation products have practically disappeared in this region. However, these products are also present at forward angles. The correlation between the mass, A, and the laboratory kinetic energy, E, of the products lighter than the projectile is displayed in fig. 4 for the Kr + Au system. One observes two ridges in this two dimensional plot : one extending from the projectile mass and kinetic

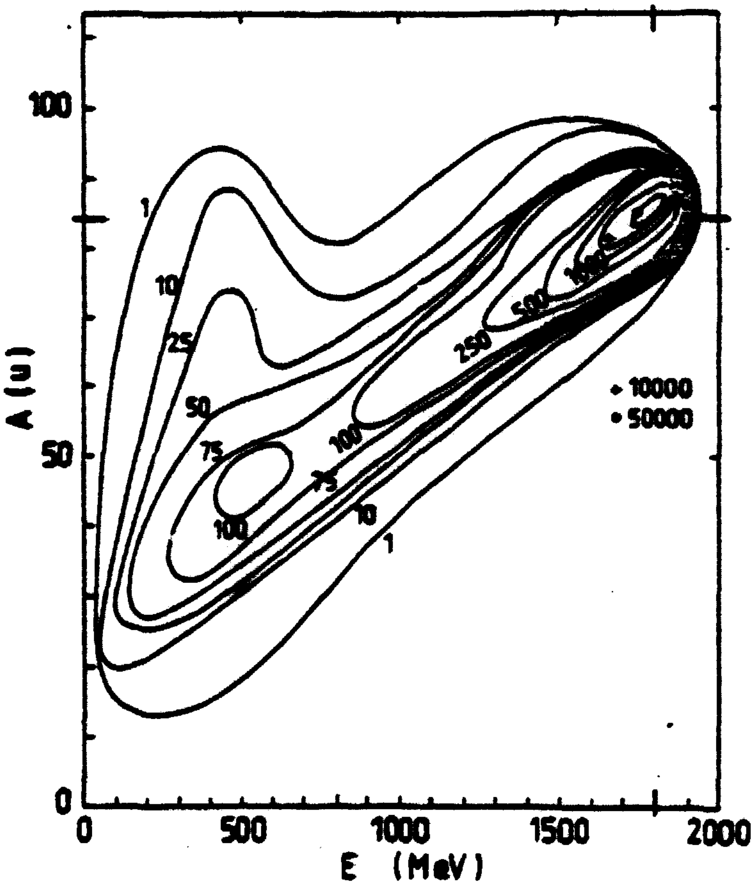

Fig. 4 - Correlation between the mass (A) and the kinetic energy E of the products detected between 6° and 12° in the 22 MeV/u Kr + Au reaction. From ref.[36]).

energy down to small A and E values, and a second one nearly parallel to the A axis at about E = 500 MeV. If these products would have been formed in a two-body collision with full momentum transfer (like for instance in a deep inelastic collision), then they would correspond to a tremendous energy loss. In ref.[36]) it has been shown that it is difficult to interpret these fragments as the result of a deep inelastic collision followed by a de-excitation of the products by evaporation. Furthermore, a recent experiment performed with 35 and 44 MeV/u krypton projectiles[37,38]) has shown that similar products could be observed. One of the important point of this experiment is that two products, similar to those described above, could be detected in coincidence on the same side of the beam with a kinetic energy which is about the same apart from the coulomb repulsion between them[38]). This result indicates that one has to deal with at least a ternary process.

Another possibility to interpret these events would be to imagine that one has a kind of participants-spectators picture as it seems to be the case at much higher bombarding energies[39]). Let us recollect that in this picture, which is schematically pictured in fig. 5, one distinguishes three main zones after the interaction process : the participants domain which is the volume common to the projectile and to the target. This zone is highly excited and eventually compressed. In the case of two equal nuclei it moves in the laboratory at half the beam velocity. The remaining parts of the projectile and of the target are only little excited. They are called the spectators zones. The projectile spectators move with the beam velocity whereas the target spectators are at rest. Such a picture would also lead to two ridges in the E versus A plane. However it cannot quantitatively explain the data[36]). This might not be too surprising since this picture is a high energy one and is not expected to apply in our bombarding energy region where the mean field still plays an important role. One can try to imagine how the mean field could possibly modify the participants-spectators picture. The simplest way of course would be that it makes a fusion of the three parts, the participants and the two spectator pieces, after the participants zone has eventually emitted prompt particles. Such a scenario could be a description of the incomplete fusion process we discussed before. However, when krypton projectiles and heavy targets

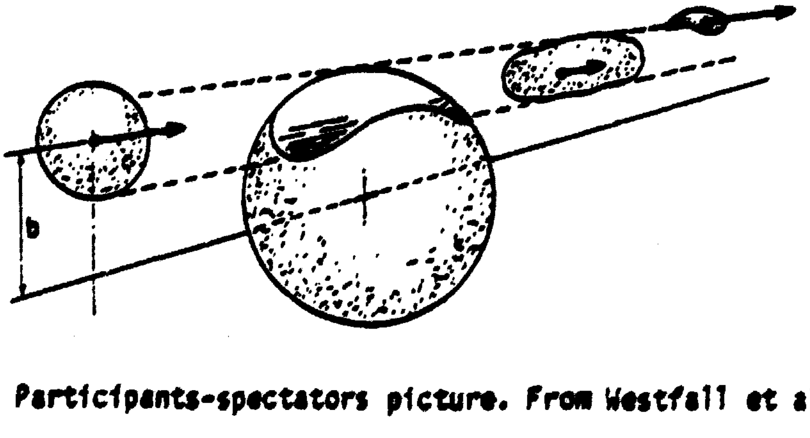

Fig. 5 - Participants-spectators picture. From Westfall et al.[39]).

are involved one knows that the coulomb field will prevent such a situation to occur. An alternative possibility is that the participants zone fuses with one of the spectators domain. Let us look at the case where the projectile spectators fuse with the participants. Then the formed system will move with a velocity which is a continuous function of the mass of the participants domain. Two possibilities might subsequently occur : either there is a global thermalization and one gets a highly excited nucleus which might for instance break in several pieces (multifragmentation)[40,29], or it could possibly reseparate as is schematically pictured in fig. 6. In this latter case there would not be any global thermalization but a reseparation in two-pieces which are practically the initial participants and projectile spectators zones. However, compared to the usual participants-spectators picture these two zones will move at the same velocity except for the coulomb repulsion which will make only a small difference. Such a reseparation would be possible if a mechanism similar to calefaction, which is observed in macroscopic systems, could occur. Let us recall that calefaction phenomenon can be for instance observed when one pours water on an overheated plate. By using simple kinematics and treating the evaporation of the excited products in a schematic way, one can calculate the E-A correlation and compare these results with the most probable values observed experimentaly (ridges of the correlation displayed in fig. 4). This comparaison is displayed in fig. 7. One observes a not to bad

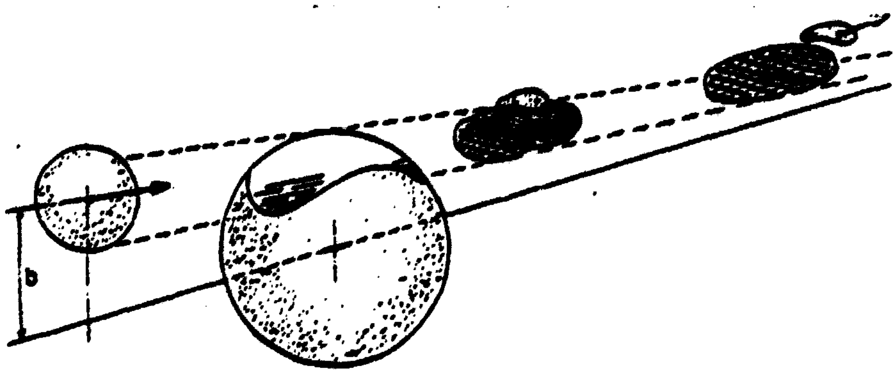

Fig. 6 - Partial fusion of the participants zone with the projectile spectators domain followed by reseparation.

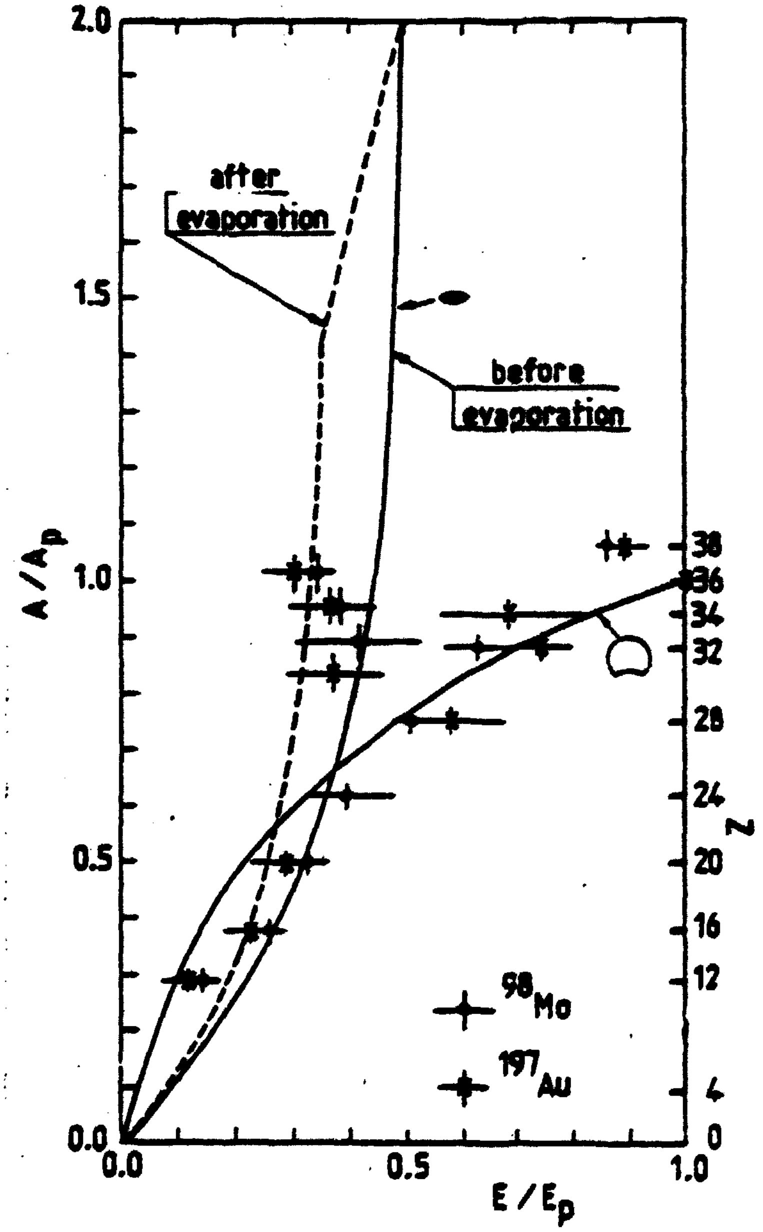

Fig. 7 - Comparisson between the experimental data and the mechanism displayed in fig. 6. For the participant zone (●) the full line corresponds to products before evaporation and the dashed to fragments after evaporation. From ref.[36]).

agreement between the hypothesis and the data. However, since these measurements are inclusive several more involved checks have to be done in the future by more exclusive measurements. As we already pointed out above, preliminary experiments do indicate[38]) that one can observe two products on the same side of the beam with similar values of the kinetic energy. It is also important to note that a multifragmentation of the partially fused system could also possibly give similar results[38,40]. The difference between the two mechanisms : partial fusion followed by calefaction, or by multifragmentation, is that in the first case one observes three bodies in the exit channel, whereas, in the second case one should observe much more fragments. At the moment it is difficult to make any choice between the two mechanisms. However it might be promising to investigate these reactions in the near future.

CONCLUSIONS

We have presented two examples of experimental studies performed in intermediate energy heavy ion physics. The first one, concerning incomplete fusion and linear momentum transfer is closely related to the low bombarding energy domain. Incomplete fusion is a natural evolution of the fusion process. We have seen that a possible limitation for this mechanism might be the maximum amount of energy that one can deposit in a nucleus. In the second example we have described briefly some results obtained with krypton projectiles. Similarly to what has been observed at low bombarding energy one observes differences with heavy ion reactions induced with lighter projectiles. In particular the incomplete fusion process might be replaced by a mecanism we have tried to describe : partial fusion followed either by calefaction phenomenon or by multifragmentation. In both cases it looks like a participants-spectators picture modified by the mean field interaction.

The first studies performed at medium bombarding energies seem to indicate that the transition between the low and the high energy domains occurs around 30 to 40 MeV/u with Ar ions; With krypton ions this might occur at a bit lower bombarding energy (~ 20 MeV/u). Indeed, at lower bombarding energies one seems to still observe deep inelastic phenomenon on the 18.2 MeV/u Mo + Mo system[41]. This transition might be closely related to the amount of excitation energy that one can deposit in a nucleus. For instance, by inspection of fig. 3 one sees that for $\tilde{\rho} = 1$ the maximum bombarding energy corresponding to it is equal to ≈ 26 MeV/u for the Ar + Au system whereas it is only about 20 MeV/u for the Kr + Mo system.

ACKNOWLEDGMENTS

Most of the experimental results presented in this review have been obtained in a collaboration between the laboratories of Bruyères-le-Châtel, Lyon and Saclay. They have been published in details in refs.20), 23) and 36) and I would like to deeply thank all the participants to this collaboration. I would also like to acknowledge Mrs F. Lepage and E. Thureau for preparing with great efficiency this manuscript, and Mr J. Matuszek for drawing the figures.

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