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# SOME ASPECTS OF HEAVY ION MACROPHYSICS

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ABSTRACT

In these notes we review, in a schematic way, some aspect of the physics with heavy ions. In the first lecture we review how is possible to describe the dissipative phenomena observed above the Coulomb barrier, up to 10-15 MeV/u, using transport theories. The second lecture is devoted to the question of fusion and the appearance of a new mechanism : fast fission. It is shown that one can now have a global understanding of these phenomena within single picture. The third lecture presents, in a simplified way, some results obtained recently with heavy ions in the range of 30-50 MeV/u at GANIL and SARA.

Lecture I : Dissipative phenomena in heavy ion physics.

Lecture II : Fusion and fast fission.

Lecture III : Some aspects of the physics between 20 and 50 MeV/u.

## Lecture 1 : DISSIPATIVE PHENOMENA IN HEAVY ION PHYSICS

With nuclei we can investigate two sorts of things. First we can try to understand their structure using different probes like electrons, nucleons, nuclei, ... which we use to bombard target nuclei. From the experimental information obtained in these experiments, we try to understand how they are made and why they exist. For that it is necessary to develop models which explain their structure and could possibly do also predictions. The problem is really understood when the explanation, as well as the description of their nuclear structure, becomes simple but based on microscopic grounds.

It is also interesting to understand what happens when two nuclei interact with each other. This concerns the investigation of the reaction mechanisms and is a second thing which can be done with nuclei. Such studies become very interesting if what we observe is different from what is expected from the simple free nucleon- nucleon interaction when it is folded to take into account of the size of the nuclei. This is for instance the case when a coherent motion of nucleons can be observed, because it is really a new feature compared to a result consisting of only an interaction between single free nucleons.

The domain of heavy ion reactions corresponding to bombarding energies $<$ 10 MeV/u has shown the existence of collective dissipative motions.[1] This fact is rather unique in nuclear physics and the domain dealing with these cooperative phenomena has been called macrophysics. This field allows to study microsystems in strong interaction at, and out, of equilibrium. This is a rather unique opportunity for statistical physics. Furthermore quantum effects are also present in some cases, and the possibility of providing the system with an excitation energy going from zero to large values, allows to study the transition between a quantum system and a nearly classical one. The time scales which characterize the coherent motions as well as the individual ones are not so different. This situation is in constrast with the one of macrosystems which we are used to. This rather unique feature has called for extensions of usual statistical theories. In addition to that there will be also the possibility to see non Markovian effects and this might be a direction of interest in the near future.

The richness of macrophysics has been such over the last decade, that it now occupies a large part, both financially and in manpower, of the nuclear physics efforts. In this first lecture, I would like to give a feeling of how it is possible to explain collective dissipative motions in heavy ions reactions at bombarding energies $<$ 10 MeV/u. We shall restrict ourselves to the physical ideas and therefore stay a simple as possible.

## 1. DISSIPATIVE PHENOMENA IN HEAVY ION PHYSICS

In heavy ion reactions at bombarding energies $\leqslant$ 10 MeV/u, it is possible to observe products with a total kinetic energy which is much smaller than the incident one. This means that a large part of the kinetic energy in the relative motion can be converted into intrinsic excitation (heat). The reactions where this surprising phenomenon can be observed are usually called deep inelastic collisions.[1] Since heavy ion reactions can be described, to a good approximation, by classical mechanics, one may try to describe the dynamical evolution of the system by introducing friction forces in the interaction region. These forces will pump the energy which is in the relative motion and transform it into intrinsic excitation energy. In other words they will convert organized energy into desorganized one. The simplest form for the friction force we may think of, is a one which is proportional to the relative velocity with a form factor which lets it to occur only in the interaction region. This prescription was used in the past with great success[1,2]. It allowed to qualitatively understand a large body of experimental data concerning not only deep inelastic collisions but also fusion which is the most dissipative mechanism which can be observed in heavy ion reactions.

In order to illustrate the method, let us consider that the two heavy ions can be described by two classical particles which interact by means of the Coulomb and nuclear interaction potentials. Then the natural coordinates of the problem are the distance r separating their center and the polar angle $\theta$. For a conservative system the equations for motion would be :

$$\mu\ddot{r} = -\frac{\partial V_N(r)}{\partial r} + \frac{Z_1 Z_2 e^2}{r^2} + \frac{\ell(\ell+1)\hbar^2}{\mu r^3} \quad (1)$$

$$\frac{d}{dt}(\mu r^2\dot{\theta}) = 0 \quad (2)$$

where $\mu$ is the reduced mass, $Z_1$ and $Z_2$ the atomic numbers of the colliding ions, $\ell$ the initial orbital angular momentum and $V_N(r)$ the nuclear interaction potential. A dot above a variable denotes a time derivative.

These equations of motion can be deduced from the following Lagrangian :

$$= \frac{1}{2}\mu\dot{r}^2 + \frac{1}{2}\mu r^2\dot{\theta}^2 - V_N(r) - \frac{Z_1 Z_2 e^2}{r} \quad (3)$$

The above dynamics only leads to an elastic scattering of the two nuclei. Dissipation can be obtained by adding in the right hand side of equations (1) and (2) friction forces of the form : $- C_r\, f(r)\dot{r}$ for the radial motion, and $- C_\theta\, r^2\, f(r)\,\dot{\theta}$ for the

Tangential one, where $C_r$ and $C_\theta$ are the radial and Tangential friction constants, and $f(r)$ is a form factor which is usually taken in such a way that it fits the data for a large number of systems.

By modifying eqs.(1) and (2) as indicated above, the colliding system becomes dissipative. The energy loss per unit of time, dE/dt, is equal to :

$$\frac{dE}{dt} = - C_r\, f(\dot{r})\, r^2 - C_\theta\, f(r)\, r^2 \dot{\theta}^2 \qquad (4)$$

The above model can be generalized to take into account of a larger number of macroscopic variables like for instance the deformations of the two nuclei or their internal rotations. If these macroscopic variables are denoted by $q^i$ the equation of motion can be deduced from the following Lagrangian :

$$= \frac{1}{2} m_{ij} \dot{q}^i \dot{q}^j - V(\{q^k\}) \qquad (5)$$

where $m_{ij}$ is the inertia tensor (in the above example we had $m_{rr} = \mu$, $m_{\theta\theta} = \mu r^2$). Dissipation is taken care of by introducing the Raleigh dissipation function, J, which can be expressed as :

$$J = \frac{1}{2} \gamma_{ij}\, q^i q^j \qquad (6)$$

the equations of motion have then the following form :

$$\frac{d}{dt} \frac{\partial}{\partial \dot{q}^i} - \frac{\partial}{\partial q^i} = - \frac{\partial J}{\partial \dot{q}^i} \qquad (7)$$

And the energy loss per unit of time is just :

$$\frac{dE}{dt} = - 2J \qquad (8)$$

## 2. NATURE OF THE DISSIPATION

Introducing friction forces is a convenient way to reproduce the data. However a theoretical justification for doing so is needed. Up to now there are several microscopic theories which have shown that friction forces proportional to the collective velocities can occur in heavy ion collisions [refs.[1,3,4]]. These theories are based on the fact that it is possible to divide the degrees of freedom of the system in two categories : the macroscopic, or collective degrees, which have a rather slow time evolution towards equilibration (a few $10^{-22}$s to ~ $10^{-21}$-$10^{-20}$s), and the intrinsic degrees which relax quickly to equilibrium (~ $10^{-22}$s or smaller). Under these assumptions it is possible to derive equations of motion for the macroscopic variables. This was done for instance by Hofmann and Siemens[3] using linear response theory. Let us briefly sketch the principle of such a derivation :

We shall divide our total system in two parts S and B. S will consist of the macroscopic variables and B will consist of the intrinsic degrees. The total Hamiltonian of the system is assumed to be splitted in three parts :

$$\hat{H} = \hat{H}_S + \hat{H}_B + \hat{H}_{SB} \tag{9}$$

$\hat{H}_S$ is the Hamiltonian operator associated to the subsystem S, $\hat{H}_B$ the one connected to subsystem B, and $\hat{H}_{SB}$ represents the interaction between both subsystems. It is this part which allows energy to be transferred from one subsystem to the other.

The evolution of the total system is governed by the total density operator $\hat{W}(t)$ which depends explicitely upon all the variables of the system. However, in many cases we are not interested in the properties of the system B. Rather, we want to follow the time evolution of the subsystem S. The only thing we need to know on B is how it influences the evolution of S. Therefore the important quantity is the reduced density operator $\hat{\rho}$ which is obtained by averaging over the B-degrees of freedom :

$$\hat{\rho}(t) = Tr_B\, \hat{W}(t) \tag{10}$$

where $Tr_B$ means that the trace of is taken with respect to the B subsystem only. To get the equation of motion for $\hat{\rho}$, one starts from the Von Neumann equation :

$$i\hbar\, \dot{\hat{W}} = [\hat{H},\hat{W}] \tag{11}$$

and projects out this equation in the subspace S. This can be done by the projection method developped by Nakajima and Zwanzig which is fully described in the paper of Haake.[5] Let us just quote the result of such manipulations which lead to the so called Nakajima-Zwanzig equation :

$$\dot{\hat{\rho}} = - i\, \hat{L}_S^{eff}\, \hat{\rho} + \int_0^t ds\, \hat{K}(s)\, \hat{\rho}(t-s) + \hat{I}(t) \tag{12}$$

where $\hat{L}_S^{eff}$ is some effective liouvillian operator, $\hat{K}(s)$ a kernel and $\hat{I}(t)$ corresponds to an inhomogeneity term. This equation is still reversible and the interesting thing is that it is non local in time (see second term of the right hand side). Of course such an equation is useless in this form for practical purposes and approximations, taking care of the physical situation under interest, have to be done. In the case of the Hofmann and Siemens theory they are the following :

1. It is assumed that at the beginning of the reaction the total density matrix factorises in two terms : one for subsystem B, the other for subsystem S. This amounts to say that, before they touch, the two subsystems do not interact. This is certainly true in the case of heavy ion collisions. As a consequence $\hat{I}(t)=0$.

2. Since the relaxation time for the intrinsic degrees is smaller than the one associated to the macroscopic variables it is possible to assume that at each stage of the reaction the intrinsic degrees are in statistical equilib-brium and play the role of a heat bath for the macroscopic degrees. Furthermore, one may assume that this statistical equilibrium can be described by a temperature (canonical ensemble). Since we have to deal with a microsystem, this last approximation is by no means obvious but it can be shown[6] that it leads to a reasonable error compared to the case where, as it should be done, a microcanonical distribution is used.

The time scale difference between the internal and the collective degrees allows to do the Markov approximation as a further simplification. It means that the equation of motion for $\rho(t)$ will become local in time.

At this stage a remark should be done : the collective motions have a relaxation time which is larger, but not so much, than the one corresponding to the intrinsic degrees. Consequently the above approximations are only valid to a certain extend. In particular one might think that non Markovian effects could be present and it is a challenge for the experimentalists to find them.

3. Hofmann and Siemens have further assumed that the coupling between S and B is small. This allowed them to make perturbation theory on the kernel K(t). Assuming that this coupling takes the form :

$$\hat{H}_{SB} = \sum_j \hat{Q}^j \; F_j(\hat{X}^i) \qquad (13)$$

where $\hat{Q}$ is the operator associated to the collective degree $Q^j$ and $\hat{F}_j$ the corresponding field operator for the intrinsic degrees ($X_i$ are the intrinsic variables), they could use the methods of linear response theory.

It is interesting to note that the field $\hat{F}_j(\hat{X}^i)$ is a one-body operator. This is equivalent to say that the dissipation process is governed by the mean field. This is a reasonable approximation since the nucleons have a long mean free path in the nucleus due to the Pauli exclusion principle. Consequently most of the collisions that the nucleons will suffer occur with the mean field. That is the reason why such kind of friction has been called one-body dissipation in contrast to the two-body dissipation which is usual in our macroscopic world.

Let us call $\tau^*$ and $\tau^{coll}$ respectively the relaxation time associated to the intrinsic and collective motions. If we consider the system during a time $\Delta t$ around t , where $\Delta t$ is microscopically large ($\Delta t >> \tau^*$) but macroscopically small ($\Delta t << \tau_{coll}$), it is possible to show that the dynamical evolution of the macroscopic system can be described by a quantum master equation. It is necessary to choose $\Delta t$ as indicated above because of the following reasons : $\Delta t$ should be sufficiently large to allow the intrinsic degrees to relax to equilibrium. Consequently they play the role of a heat bath for the collective degrees. However $\Delta t$ should be sufficiently small for the collective variables to remain almost constant during this amount of time.

If we consider, for the sake of simplicity, only one macroscopic variable Q, then during $\Delta t$ it will not change very much around its mean value $Q_0 = \langle Q \rangle_{t_0}$. The coupling between S and B is known to be strong (indeed we know that in a deep inelastic reaction several tens MeV can be easily lost in the relative motion) and it is not possible to apply to it perturbation theory for which this coupling has to be small. However the difference :

$$\hat{H}_{SB}(\hat{Q},\hat{X}^i) - \hat{H}_{SB}(Q_0,\hat{X}^i) \approx (Q-Q_0) \left.\frac{\partial\hat{H}_{SB}}{\partial Q}\right|_{Q_0} \qquad (14)$$

is small and can be treated by perturbation theory. One has then to renormalize the Hamiltonian of the heat bath :

$$H_B^{ren} = \hat{H}_B + \hat{H}_{SB}(Q_0,\hat{X}^i) \qquad (15)$$

the renormalization of the intrinsic Hamiltonian at each stage of the reaction is the essence of the Hofmann and Siemens approach. It allows to remove a large past of the coupling but one needs, except for a pure harmonic motion, that the fluctuations around the mean values remain small.

The above prescription can be generalized to the whole trajectory followed by the two heavy ions, and a quantum equation of motion for the macroscopic system can be obtained. Since, in most of the cases, the collective motions show a classical behaviour, it is possible to go to the classical limit. A transport equation (Fokker Planck equation in the phase space of the collective degrees) is then obtained. This equation has a similar form as the one used to describe transport phenomena in macroscopic systems (see section 4). It contains, in addition to conservative terms, friction and diffusion coefficients. Such an equation allows a large amplitude collective motion to be described, if it is slow. This is the case for most of the col-lective motions observed in deep inelastic reactions.

If one has to deal with fast collective motions (we will see an example in section 5), they can exhibit quantum features and it is not possible to apply to them a classical transport equation. However it is possible, only in the case of a harmonic motion, to derive a transport equation for the Wigner transform of the reduced density matrix. We will see later (section 4) that this equation has the same mathematical structure as the classical one.

To obtain these transport equations an average over the intrinsic system has been done in order to get the reduced density operator $\hat{\rho}$. Since the collective motions are coupled to the intrinsic degrees, it is necessary to know something about the intrinsic system. It appears that the two only informations which are needed on the heat bath, are the response, and the correlation functions. If we know them it is possible to describe the dynamical evolution of the macroscopic system. Considerable effort have been and are made to calculate these quantities microscopically.[7] Indeed their knowledge allows the calculation of the friction and diffusion coefficients which are the key quantities entering the equations of motion of the macroscopic system (see section 4).

Several microscopic theories have been developed in the literature.[1,2,3] They differ in the way how to treat the coupling between the macroscopic and the microscopic system. However they all end up with a transport equation for the macroscopic variables in which enter friction and diffusion terms. This transport equation is similar to the one describing the evolution of a brownian particle.

## 3. SIMPLIFIED APPROACHES TO DISSIPATION

In the above approach, friction is strongly connected to the mean field in which the nucleons evolve. The existence of a coupling between the macroscopic and the microscopic systems, together with the difference of time scales associated with them, leads to an irreversible flow of energy from the collective motions to the intrinsic degrees. During the process, a lot of 1p-1h excitations are created in the intrinsic system. Due to the residual interactions these excitations decay into more complicated states (heat). It is the existence of these residual interactions which make the relaxation time for the internal variables, $\tau^*$, to be so small. Indeed microscopic calculations,[6,7] as well as measurements,[8] seem to indicate that $\tau^* \leq 10^{-22}s$).

In a schematic classical picture, dissipation can be visualized in the following way :

Nucleons are assumed to be a free Fermi gas enclosed in a container which simulates their mean field. Since the mean free path of the nucleons is large compared to the dimension of the system, most of the collisions that the particles suffer will be with the walls of the container. Such a gas is usually called a Knudsen gas. It is assumed that after a collision with the wall, the particle velocity is randomly distributed. This hypothesis is nothing more than saying that the internal degrees of freedom have a relaxation time shorter than the one of the macroscopic variables.

A moving wall will be a source of dissipation. If the wall velocity is much smaller than the Fermi velocity of the nucleons, a friction force proportional to the wall velocity will appear, and the motion of the wall will be slowed down. This has been demonstrated first by Gross[9] (piston model) and worked out in details by Blocki et al.[10] (wall formula).

When two nuclei are connected to each other by a window, nucleons can be transferred from one container to the other. With the same hypothesis of randomization as above and assuming that a transferred nucleon never comes back, one can also show that a friction force, proportional to the relative velocity of the two nuclei, appears (window formula).[10] An interesting result of such a description is that the friction coefficient in the radial directions is twice as large as the one in the tangential motion.[10]

With the simple above picture in mind, it is possible to calculate the friction coefficients. Several calculations have been done in this direction.[11-16] The most important physical effects to be taken into account in these approaches are the following : tunneling of the single particle potential barrier separating the two nuclei, influence of the temperature on the occupation probabilities of the nucleons and on single particle potential, Pauli blocking and window velocity with respect to each nuclei (see ref [17] for a review).

Before we close this section, it should be noted that there can also exist a coupling between the macroscopic variables. This allows an energy transfer between the different collective motions. This is the way for instance how surface vibrations or giant resonances can be excited.[18] Since these collective motions can be coupled to the intrinsic system, they can be damped. The coupling between collective modes can play an important role in the sense that energy can be transferred from the relative motion to some other collective mode (surface vibration for instance) which can be in turn strongly damped. In this case one may have a strong dissipation in the relative motion because the second collective mode plays the role of a doorway state (or of a catalyser).

## 4. ILLUSTRATION OF A TRANSPORT EQUATION

We shall now illustrate the physics which is contained in a transport equation. For that we shall consider only one collective degree Q (P will the conjugate momentum), and assume that the associated motion is harmonic. Consequently the collective Hamiltonian reads :

$$H_{coll} = \frac{P^2}{2B} + \frac{1}{2} C Q^2 \tag{16}$$

where B and C are respectively the inertia and the stiffness coefficient associated to the harmonic oscillator. The collective motion will be coupled to a heat bath at temperature T. Hofmann and Siemens[3] have shown that the dynamical evolution of the oscillator is governed by a transport equation which has the following form :

$$\frac{\partial f}{\partial t} = \{H_{coll}, f\} + \gamma \frac{\partial}{\partial P} \frac{P}{B} f + D \frac{\partial^2 f}{\partial P^2} \tag{17}$$

In this equation f is the distribution function in collective phase space. In the case of a classical oscillator f is the classical distribution, whereas for a quantum oscillator f has to be understood as the Wigner transform of the reduced density matrix.[19] $\gamma$ and D are respectively the friction and the diffusion coefficients. The first term in the right hand side is a Poisson bracket :

$$\{H_{coll}, f\} = \frac{\partial H_{coll}}{\partial Q} \frac{\partial f}{\partial P} - \frac{\partial H_{coll}}{\partial P} \frac{\partial f}{\partial Q} \tag{18}$$

Using eq.(16) it can be rewritten as :

$$\{H_{coll}, f\} = - \frac{P}{B} \frac{\partial f}{\partial Q} + C\, Q \frac{\partial f}{\partial P} \tag{19}$$

In transport theory, friction and diffusion are intimately related by means of the so called fluctuation dissipation theorem which can be expressed here by means of the Einstein relation

$$D = \gamma\, T \tag{20}$$

where T is the temperature. The above relation holds only if we have a classical harmonic oscillator. In the case of a quantum one, the connection between D and $\gamma$ reads[19] :

$$D = \gamma\, T^* \tag{21}$$

where

$$T^* = \frac{\hbar\Omega}{2} \text{Cotgh} \frac{\hbar\Omega}{2T} \tag{22}$$

It should be noted that in the case of high temperature ($T \gg h\Omega$) the generalized Einstein relation (21) goes to the classical one (eq.(20)).

It is interesting to write down the equations of motion for the mean macroscopic variables $\langle Q\rangle$ and $\langle P\rangle$. They can be obtained from the transport eq.(17) by multiplying it by Q or P and integrating the phase space :

$$\frac{d\langle Q\rangle}{dt} = \frac{\langle P\rangle}{B} \tag{23}$$

$$\frac{d\langle P\rangle}{dt} = C\langle Q\rangle - \gamma \frac{\langle P\rangle}{B} \tag{24}$$

or

$$B \frac{d^2\langle Q\rangle}{dt^2} + - \Omega^2\langle Q\rangle - \gamma \frac{d}{dt} \langle Q\rangle \tag{25}$$

we recognize in eq.(25) the classical equation of motion of a harmonic oscillator subject to a friction force proportional to the velocity. Therefore the transport equation, which is derived on microscopic grounds, provides a justification of the friction force introduced in the classical models for heavy ion collisions. In addition it gives the fluctuations around the mean values. In the case of a classical oscillator these fluctuations are of statistical nature, whereas, in the case of a quantum harmonic oscillator, they have a quantum origin (zero point motion).

In the case of the harmonic oscillator, the solution of the transport equation is a Gaussian which is therefore completely determined by the first and the second moments of Q and P. We have seen that the first moments obey eqs.(23,24). As far as the second moments are concerned, they obey the fol- lowing set of linear coupled differential equations :

$$\frac{d\Sigma_{PP}}{dt} = -2C\Sigma_{PQ} - \frac{2\gamma}{B}\Sigma_{PP} + \gamma T^* \tag{26}$$

$$\frac{d\Sigma_{QQ}}{dt} = \frac{2}{B}\Sigma_{PQ} \tag{27}$$

$$\frac{d\Sigma_{PQ}}{dt} = \frac{\Sigma_{PQ}}{B} - C\Sigma_{QQ} - \frac{\gamma}{B}\Sigma_{PQ} \tag{28}$$

where

$$\Sigma_{QQ} = \frac{1}{2} \int dQ\ dP\ f(Q,P,t)\ (Q - \langle Q \rangle)^2 \tag{29}$$

$$\Sigma_{PQ} = \frac{1}{2} \int dQ\ dP\ f(Q,P,t)\ (Q - \langle Q \rangle)\ (P - \langle P \rangle) \tag{30}$$

$$\Sigma_{PP} = \frac{1}{2} \int dQ\ dP\ f(Q,P,t)\ (P - \langle P \rangle)^2 \tag{31}$$

are the second moments. Note that in the case of a classical harmonic oscillator $T^* = T$.

We can check that as $t \to \infty$ we get the equilibrium distribution. Indeed, at equilibrium

$$Q = 0\ ,\ \Sigma_{PQ} = 0\ ,\ \Sigma_{PP} = \frac{BT^*}{2} \quad \text{and} \quad \Sigma_{QQ} = \frac{T^*}{2C} \tag{32}$$

as it should be.

It is interesting to illustrate the difference between statistical and quantum fluctuations. This is shown in Fig. 1. In both cases considered there, we have an oscillator with the same stiffness coefficient coupled to a heat bath at temperature T = 2 MeV. The inertia is chosen in such a way that, on the left hand side, the phonon energy is equal to 8 MeV, whereas on the right hand side, it is equal to 0.5 MeV. It means that the levels are separated by 8 MeV on the left, and by 0.5 MeV on the right. The oscillator which is on the left is called a quantum oscillator

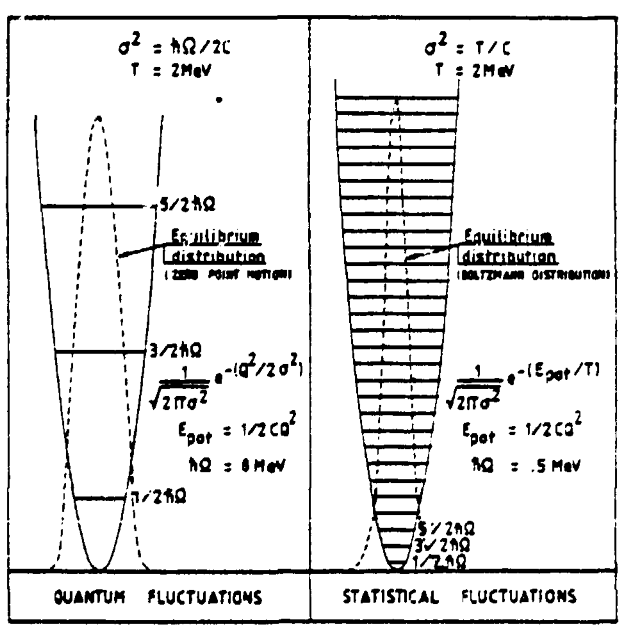


**Fig. 1 - Schematic presentation of the difference between statistical and quantum fluctuations in the case of a harmonic oscillator (see text).**

whereas the one on the right is a classical one. Since the levels of the quantum oscillator are spaced by 8 MeV, which is much larger than T = 2 MeV, the heat bath does not excite the oscillator which remains in its ground state. We observe the zero point motion and the equilibrium distribution is represented by the dashed line. On the contrary, in the case of the classical oscillator, $\hbar\Omega \ll T$, consequently it will be excited by the heat bath. The equilibrium distribution is the Boltzmann distribution represented by the dashed line.

The above considerations concerned the equilibrium stage which is reached after a time larger than the relaxation time associated to the harmonic oscillator. Now, we shall illustrate the role of the different terms entering the transport equation. This is schematically shown in Fig. 2. If we would only consider the first term in the right hand side of eq.(17), we would

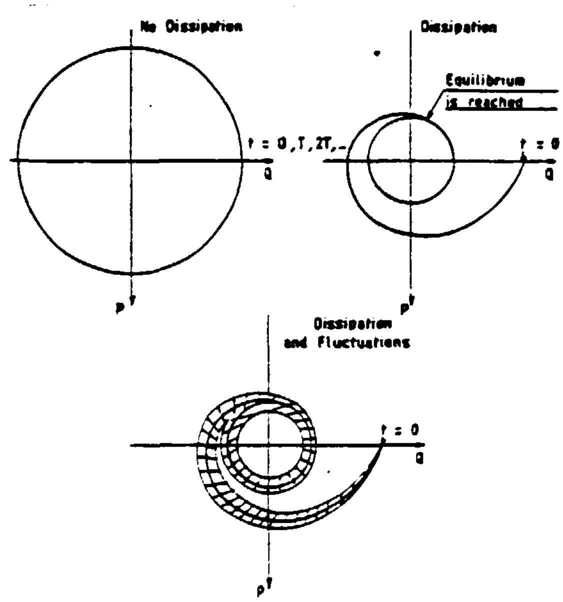


**Fig. 2 - Schematic presentation of different type of trajectories in phase space when the system is conservative (top left), where there is friction (top right) and when there is friction and fluctuations (bottom). See text.**

just have a Liouville equation in phase space. This would correspond to no friction and the trajectory followed by the system in phase space is shown on top of the left hand side of Fig. 2 (the units have been chosen in such a way that it is a circle). The second term on the left hand side of eq.(17), proportional to $\gamma$, leads to dissipation. It will be responsible for a drift of the mean value towards equilibrium. The trajectory will have the form schematically shown on top of the right side of Fig. 2 (in the figure we show the trajectory for a quantum harmonic oscillator). In this case equilibrium corresponds to a circle. If the oscillator becomes classical the radius of the circle will go to zero. Each time we have dissipation, we know that we have also fluctuations. The effect of the fluctuations is given by the last term in eq.(17). The physical effect of this term is to spread the density distribution in phase space like a diffusion process. The distribution will broaden when the time increases until it reaches equilibrium. This is illustrated in the lower part of Fig. 2 where the dashed area represents, say, some percentage of the density distribution.

## 5. APPLICATIONS OF TRANSPORT THEORY

The method which has been described schematically above can of course be generalized to more complicated situations where several collective degrees are taken into account explicitly. A lot of calculations have been done and compared with experimental data.[1] They give an overall understanding of the deep inelastic process. We just would like to show two typical examples of such calculations.

The first one corresponds to the case where the collective motion behave classically. Then only statistical fluctuations can be observed. These models are able to calculate multidifferential cross section with respect to various macroscopic variables.[20] The higher is the order of the differential cross section, the more difficult it is to reproduce. Therefore we show in Fig. 3 the calculated Wilczynski plot corresponding to several Z values ($d^3\sigma/dEdZd\theta$) for the 280 MeV Ar + Ni system measured in ref. 22. The experimental data are displayed in Fig. 4. We see that the overall experimental picture is reproduced but still not the details.

The second example will concern charge equilibration which is known to be a fast collective mode exhibiting, in some cases, quantum features.[23] This is in particular the case for the 430 MeV $^{86}Kr + ^{92}Mo$ investigated in ref. [23]. The observable which is directly related to charge equilibration is the isobaric distribution (atomic number distribution for fixed value of the mass). The FWHM of this distribution turns out to be, at equilibrium, much too large to be explained by statistical fluctuations. Furthermore, when equilibrium is reached, it remains practically constant as a function of the excitation energy (temperature). Indeed, charge equilibration can be decribed by an harmonic oscillator coupled to a heat bath. In the case of statistical fluctuations we would expect for the variance $\sigma^2$ of the isobaric distribution :

$$\sigma^2 = \frac{T}{C} \qquad (33)$$

where T anc C are respectively the temperature and the stiffness coefficient. For quantum fluctuation $\sigma^2$ would be larger and given by :

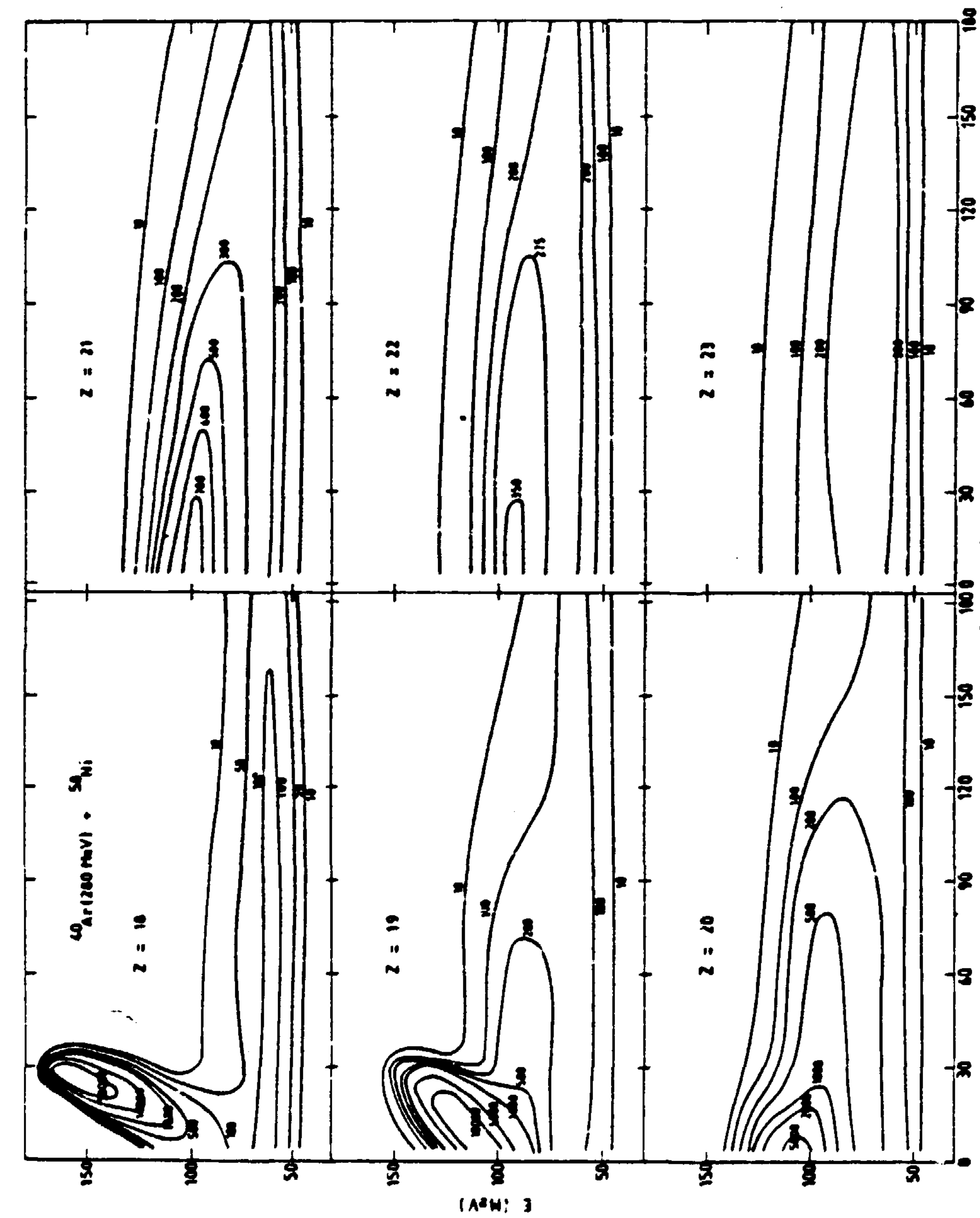


Fig. 3 - Calculated differential cross section $d^3\sigma/dEdZ\theta$ in μb/MeV/rad/(charge unit) for the Ar + Ni system at 280 MeV. Calculation done in ref.[21].

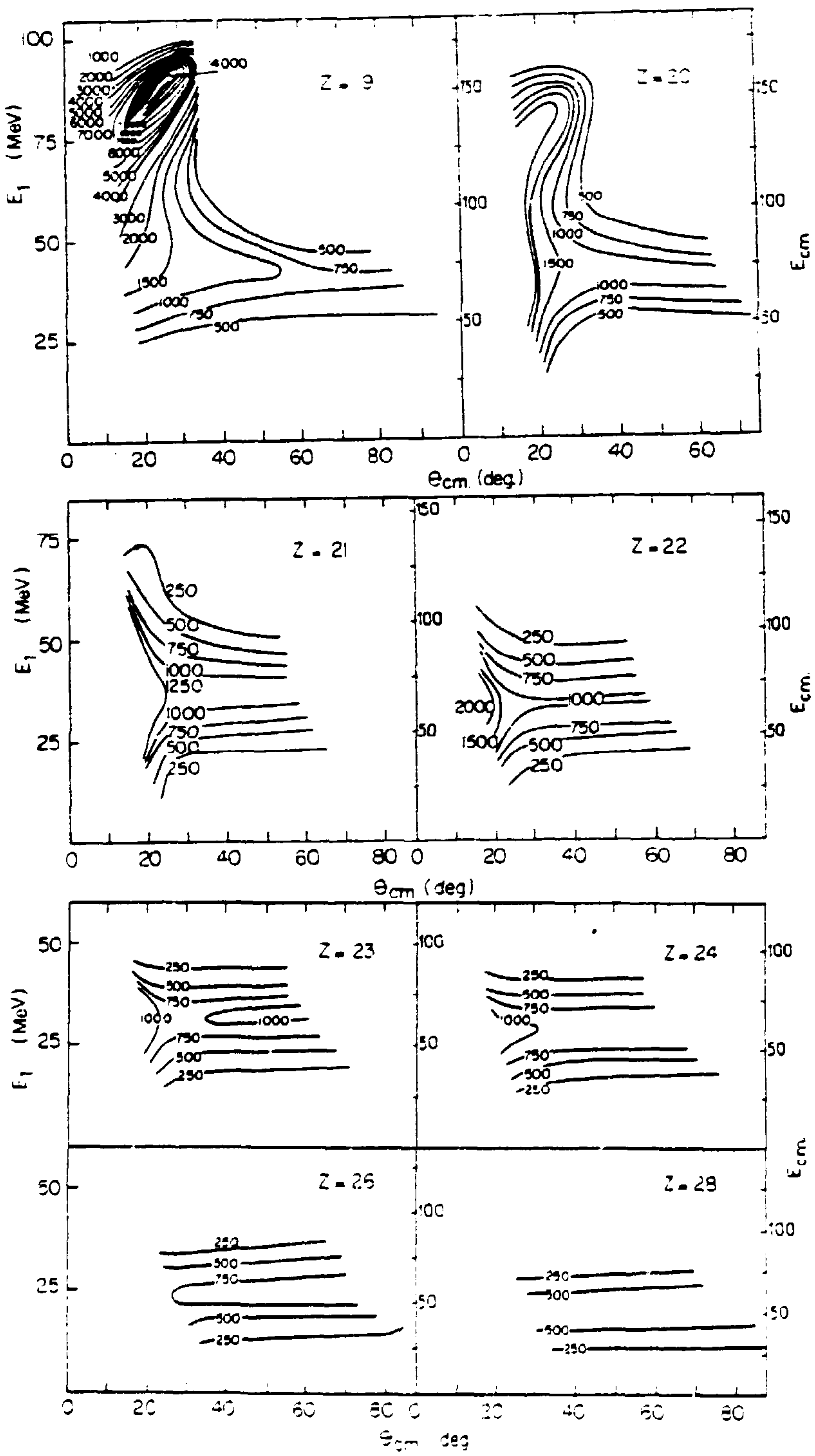


Fig. 4 - Experimental curves corresponding to Fig. 3 measured in ref.[22].

$$\sigma^2 = \frac{T^*}{C} \qquad (34)$$

where $T^*$ is defined by eq.(22). The experiment indicates that, for the Kr + Mo system, we are likely to observe quantum fluctuations. In Fig. 5 we show a comparison between the model based on a transport equation, and the data. We see that they agree quite well. In fact TDHF calculations have shown that the mode associated to charge equilibration seems to be related to the longitudinal component of the giant dipole resonance of the composite system.[24]

These two short examples have shown us the power of transport theory for explaining dissipative phenomena in heavy ion physics. We are now at a stage where these calculations are refined in order to describe finer details of heavy ion collisions. A lot of work remains to be done in order to obtain extensively microscopic transport coefficients. On the experimental side, it is probably interesting to try to study the possible existence of non Markovian effects. For this, high resolution is needed and this is along the line of the new accelerators.

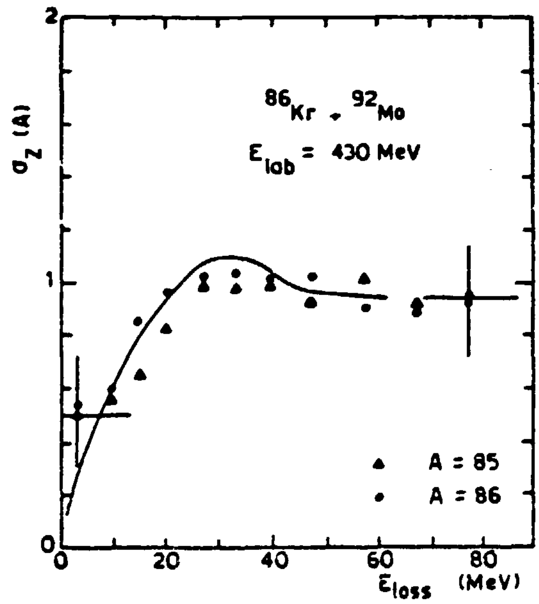


Fig. 5 - Calculation of the standard deviation of the isobaric distribution of A = 86 for the 430 MeV Kr + Mo system (full line) done in ref. 19 compared to the experimental data of ref.[23].

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## Lecture II : FUSION AND FAST FISSION

### I. FUSION

#### a) General considerations

Fusion is the most dissipative phenomenon observed in heavy ion reactions. Indeed all the nucleons are involved, all the kinetic energy in the relative motion is transformed into intrinsic excitation energy of the compound system and all the initial orbital angular momentum is transformed into spin of the fused nucleus. It is of fundamental importance to know under which conditions two heavy ions fuse together and to calculate the probability of such a process. It is also interesting to know what happens to the fused system.

Experimentally it turns out that two heavy nuclei with a product of the atomic numbers $Z_1Z_2 > 2500$-$3000$ cannot fuse.[1] For this reason, even if the superheavy element would exist, it would not be possible to synthesize it by the fusion of two heavy nuclei. The reason why there is no fusion, in the case of very heavy systems, comes from the disappearance of the pocket in the total interaction potential.[2] This is due to the Coulomb force which becomes so attractive that it cannot be counteracted by the nuclear force at any separation distance. It is possible to calculate, in a static way, the condition for which the pocket disappears in the case of a head-on collision.[3] One finds that when :

$$\frac{Z_1Z_2}{C_1C_2(C_1 + C_2)} > 8.7 \qquad (1)$$

the pocket disappears and fusion is no longer possible. In eq.(1) $C_1$ and $C_2$ are the central radii of the projectile and of the target :

$$C_i = R_i - 1/R_i \qquad (2)$$

and

$$R_i = 1.16\, A_i^{1/3} \qquad (3)$$

However dynamical effects decrease a bit this limit of 8.7 and we shall see the reason below.

For a given system, where fusion is possible, one observes that, if the bombarding energy is not too far above the Coulomb barrier, the fusion cross section goes almost linearly as a function of the inverse of the center of mass bombarding energy. However at higher energies, when larger values of the orbital angular momentum are involved, the measured fusion cross section becomes smaller than what can be expected by an extrapolation the precedings straight line (see Fig. 1). Such a fusion cross section defect is also observed for systems in the region where fusion just disappears[4] (heavy systems). This can be understood as due to an increase of the fusion threshold (see Fig. 2).

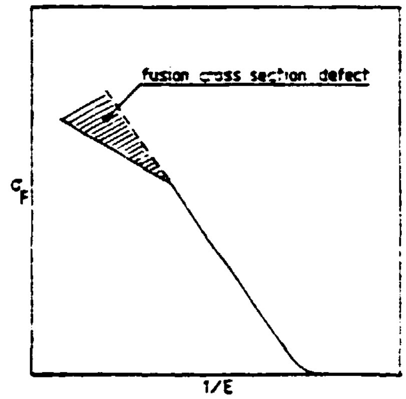


**Fig. 1 - Schematic presentation of the fusion excitation function as a function of 1/E, the inverse of the center of mass bombarding energy. At high bombarding energies a fusion cross section defect is observed compared to the behaviour followed just above the fusion threshold.**

The precedings experimental facts have to be understood in a single picture. In this lecture, I would like to present a simple dynamical model which is able to do that.[5] We will see that it is only based on very simple physical arguments.

Up to now there is no simple picture which is able to describe the fusion cross sections for all the heavy ion combinations that we can imagine and with bombarding energies in a range going from the Coulomb barrier to about ~ 10-15 MeV/u. The reason

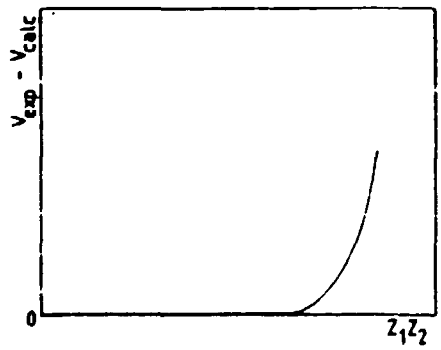


**Fig. 2 - Schematic plot of the difference between the experimental and the theoretical fusion threshold as a function of the product $Z_1Z_2$ of the atomic numbers of the two ions.**

~ 10-15 MeV/u. The reason for that can be found in the fact that the dynamics plays a very important role in heavy ion collisions. We have seen, in the preceding lecture, that dissipation occurs as soon as the two heavy nuclei start to strongly interact. Therefore friction will also play an important role in the fusion process. In a pure static picture, fusion can be obtained, for a given value of the initial orbital angular moment $\ell$, if the bombarding energy is larger than the corresponding static fusion barrier associated to this particular collision (see Fig. 3). However friction may act before the system reaches this barrier and some energy loss in the relative motion will result. This is illustrated in Fig. 4 for a head-on and a non central collision. We see that for the system to reach the barrier, it will be necessary to provide it with a certain amount of extra energy above the static fusion barrier. This supplement of kinetic energy is necessary to compensate the friction forces which are acting before the system reaches the barrier. Let us write down the condition for fusion. For that we need to introduce the critical angular momentum, $\ell_{CR}$, which is the largest $\ell$ value leading to fusion. The experimental fusion cross section, $\sigma_F$, is usually expressed in terms of $\ell_{cr}$ by means of the following relation :

$$\sigma_F = \frac{\pi}{k^2} (\ell_{CR} + 1)^2 \qquad (4)$$

where k is the wave number. Eq.(4) assumes that they are the lowest $\ell$ values which contribute to fusion, up to the largest one $\ell_{CR}$, and that the sharp cut off approximation is valid.

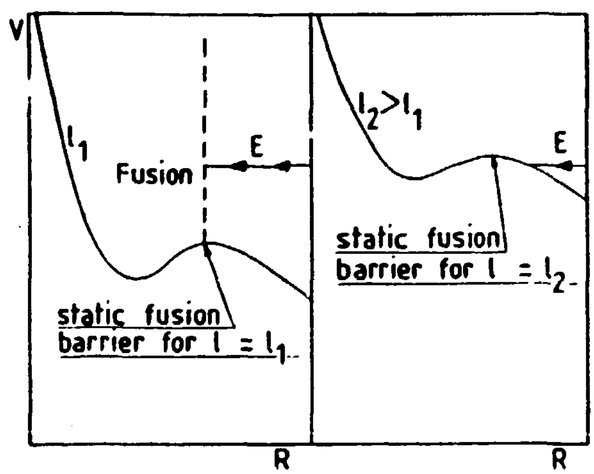


Fig. 3 - In a static picture we can have fusion if the bombarding energy is larger than the static fusion barrier. On the left this is possible, but not on the right.

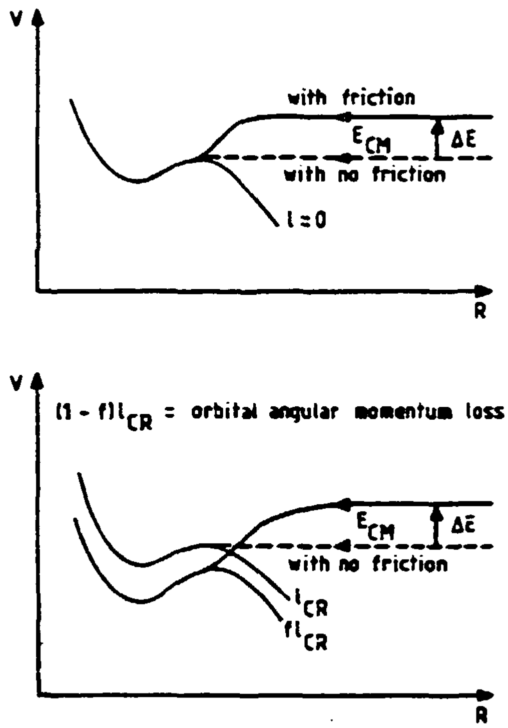


**Fig. 4 - Schematic illustration of the fact that some extra kinetic energy is needed to overcome the static fusion barrier : on top is the case of a head-on collision. In the bottom is the case when the orbital angular momentum is equal to $\ell_{CR}$. There the total interaction potential including centrifugal energy changes due to angular momentum loss.**

Since $\ell_{CR}$ is the largest $\ell$ value which is able to pass the fusion barrier, it should satisfy the following equation:

$$E = V(R_{f\ell_{CR}}) + \frac{f^2 \ell_{CR} \hbar^2}{2\mu \; R^2_{f\ell_{CR}}} + \Delta E_R + \Delta E_t \qquad (5)$$

where E is the center of mass bombarding energy, $R_{f\ell_{CR}}$ the position of the fusion barrier for $\ell = f\ell_{CR}$ (f being the fraction of orbital angular momentum which remains in the relative motion after tangential friction has acted) and $\mu$ the reduced mass. V(R) represents the total interaction potential *(nuclear + Coulomb)* for a head-on collision. $\Delta E_R$ and $\Delta E_t$ are respectively the energy losses in the radial and in the tangential motions. Since in dynamical calculations the energy loss in the tangential motion is, to a good approximation, equal to the change in the rotational energy,[6] we can rewrite eq.(5) as follows :

$$E = V(R_{f\ell_{CR}}) + \frac{\ell_{CR}^2 \hbar^2}{2\mu\, R_{f\ell_{CR}}^2} + \Delta E \qquad (6)$$

where $\Delta E$ will be the dynamical energy surplus. It is the extra energy which one has to provide the system with, in order to compensate for friction forces. Therefore for a given $\ell$ value, we can define a dynamical fusion barrier which equals the static one plus the dynamical energy surplus :

| Dynamical fusion barrier = static fusion barrier + dynamical energy surplus |
|---|

Since it is possible to reproduce the fusion cross section for many systems at not too high bombarding energy using static barriers,[3] it means that the dynamical energy surplus is zero for them. Let us now try to estimate $\Delta E$ from experiment.

For that we shall use equation (6). For a given system we shall take the bombarding energy E. Then $R_{f\ell_{CR}}$ and $V(R_{f\ell_{CR}})$ will be calculated using the energy density potential[3,7] which has proved to be very successful in reproducing the fusion thresholds for a large body of systems. From eq.(6) we can deduce a value for the dynamical energy surplus, and try to plot this quantity as a function of a variable which should be strongly correlated to it. A natural one we may think of is the following[8] :

$$X_{eff} = \frac{1}{4\pi\gamma}\left(\frac{Z_1 Z_2 e^2}{C_1 C_2 (C_1 + C_2)} + \frac{f^2 \ell^2 \hbar^2}{m} \frac{A_1 + A_2}{A_1 A_2} \frac{1}{C_1 C_2 (C_1 + C_2)^2}\right) \qquad (7)$$

where $\gamma$ is the surface tension coefficient of nuclear matter ($\gamma \approx 1$ MeV/fm$^2$) and m the nucleon mass. $X_{eff}$ represents the ratio between the Coulomb plus centrifugal forces, over the nuclear force, at distance $C_1 + C_2$. We see that in the definition of $X_{eff}$ it enters the factor f, which is the proportion of orbital angular momentum remaining in the relative motion after tangential friction has acted. The choice of a value for f is not clear[3] : indeed should we take the sticking or the rolling limit?, or something else? This is illustrated in Fig. 5 where $\Delta E$ has been plotted as a function of $X_{eff}$ for the heavy systems investigated at GSI [ref.[4]] (circles) and for the Ar + Ho system measured in ref.[9] (crosses). In the former case f was taken to be equal to 5/7 (rolling) whereas in the later case f was taken for the sticking limit. It is only with these choices that $\Delta E$ could exhibit a similar mean behaviour and this tells us that a static approach of the problem will be difficult since, for a given system, we do not know how to choose this factor f. Therefore we should now really consider the dynamics of the problem.

b) Dynamical approach to fusion

In order to check the above qualitative ideas about fusion, a simple dynamical model has been developed in ref.[5] to describe the fusion process. It describes the collision of the two heavy ions by means of two macroscopic variables : the distance R separating the center of mass of the two nuclei, and the polar angle $\theta$. The dynamical evolution of the system will be treated in a similar way as the one described in the first section of lecture I. The nuclear potential between the two heavy ions, which was deduced using the energy density formalism, is taken from ref.[3]. Friction forces proportional to the velocities are introduced in the radial

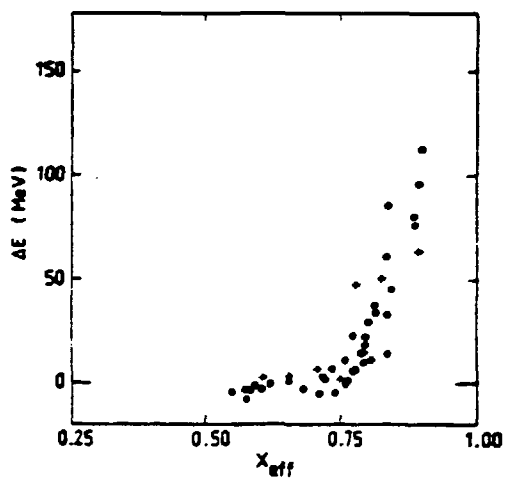


**Fig. 5 - The dynamical energy surplus is plotted as a function of $X_{eff}$ defined in eq.(7). The circles are associated to the systems investigated in ref.[4] with f = 5/7 (Rolling). The crosses correspond to the Ar + Ho system of ref.[9] with f given by the sticking condition. From ref.[3].**

and tangential motions. The equations of motion which have been used are the following :

$$\mu \frac{d^2R}{dt^2} = - \frac{\partial V_\ell(R)}{\partial R} - C_R\, g(R)\, \dot{R} \qquad (9)$$

$$\frac{d\ell}{dt} = - \frac{C_t}{\mu}\, g(R)\, (\ell - \ell_{st}) \qquad (10)$$

$C_R$ and $C_t$ are respectively the radial and the tangential friction coefficients. According to the-one body picture [10] they are such that $C_R = 2\, C_t$. In eq.(9) a limiting value for the orbital angular momentum has been introduced : it is the sticking limit which should not be overcomed if we consider the two nuclei as two solid objects. $V_\ell(R)$ is the total interaction potential (nuclear + Coulomb + centrifugal energy) and g(R) the form factor which was chosen as follows :

$$g(R) = \frac{1}{1 + \exp(\frac{s-0.75}{0.2})} \qquad (11)$$

where

$$s = R - C_1 - C_2 \qquad (12)$$

represents the separation distance between the surfaces of the two nuclei at half density. The fact that the form factor depends explicitely upon s rather than upon R is from our belief that the friction between the two heavy ions is dominatedby a surface-surface effect. It turns out that if we take $C_R$ = 31 000 MeV $fm^{-2}$ $(10^{-23}s)^2$ it is possible, with this value kept fixed, to reproduce the fusion cross section for a large number of systems. We refer the readers to ref.[5] where a lot of comparisons between experimental and theoretical fusion excitation functions are shown. In Fig. 6 we just illustrate the model with a few systems going from light to heavy ones. We observe a rather good agreement between experiment and theory which encourages us to believe that the dynamics is of great importance in the fusion of two heavy ions.

From the dynamical calculation it is interesting to see if the dynamical energy surplus has a strong correlation with some quantity which is easily accessible. This turns out to be the case and is shown in Fig. 7 where ΔE is plotted as a function of, $s_{f\ell_{CR}}$, the position of the static fusion barrier corresponding to $\ell = f\ \ell_{CR}$. We observe that all the points are focussed around a mean behaviour which can be parametrized as follows :

$$\Delta E = 1100\,(1.57 - s_{f\ell_{CR}})^3 \quad \text{when} \quad s < 1.57 \text{ fm}$$

and (13)

$$\Delta E = 0 \quad \text{when} \quad s > 1.57 \text{ fm}$$

We observe in Fig. 7 that ΔE increases a lot when the interdistance between the two surfaces becomes smaller than 1.4 fm. It is necessary for the system to reach a distance smaller than ~ 1 fm, ΔE will become so large that fusion will no longer be possible in practice. This shows the existence of a saturation distance beyond which fusion will not be possible.

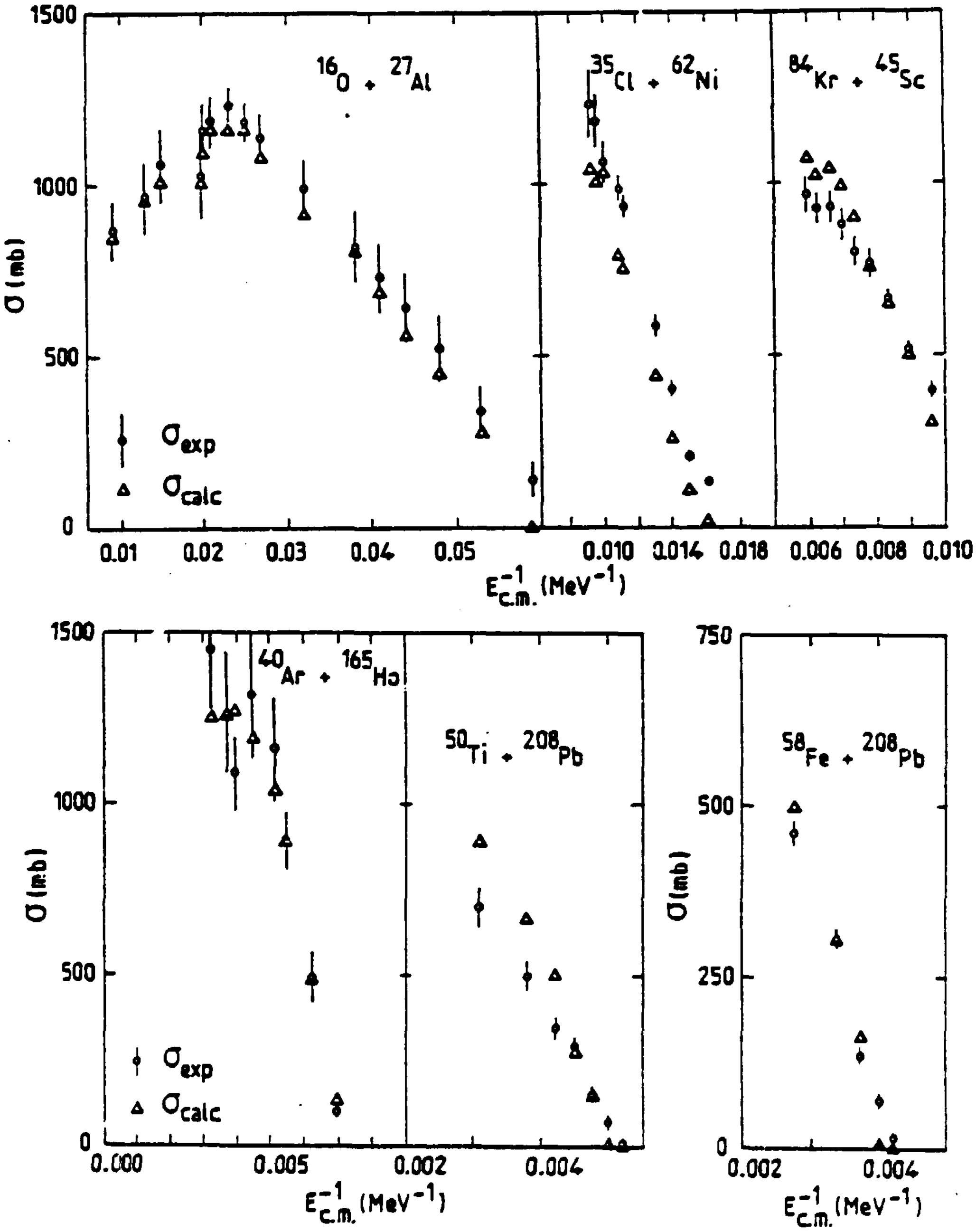


Fig. 6 - Comparaison of the experimental cross sections with those computed using the dynamical model of ref.[5]. References corresponding to experimental points can be found also in this reference. This figure has been extracted from ref.[11].

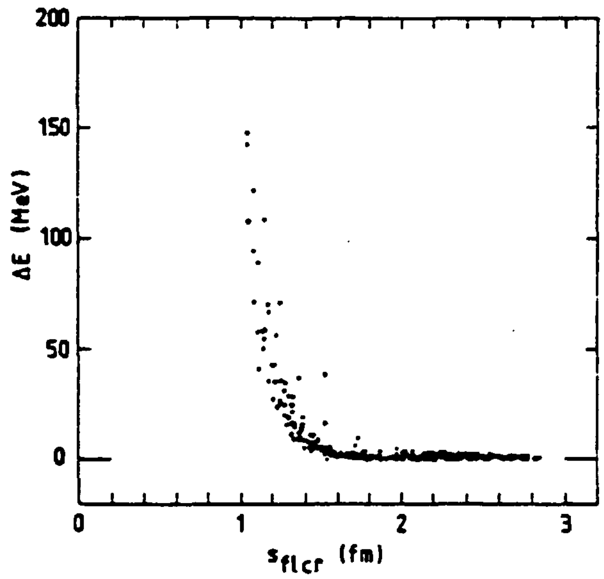


**Fig. 7 - Dynamical energy surplus needed to pass the fusion barrier as a function of $s_{f\ell_{CR}}$ the position of the fusion barrier for $\ell = f\ell_{CR}$. From ref.[5].**

Let us now summarize the results of the model[1] in simple physical terms : from eq.(6) we see that the fusion cross section is given by the following expression :

$$\sigma_F = \pi R^2{}_{f\ell_{CR}} \left(1 - \frac{V(R_{f\ell_{CR}}) + \Delta E}{E}\right) \qquad (14)$$

For a given system where fusion is possible, when we increase the bombarding energy, we increase the critical orbital angular momenta but at the same time the position of the static barrier decreases. At the beginning (in the region just above the fusion threshold) $s_{f\ell_{CR}}$ is in general large enough for $\Delta E$ to be zero. But as $\ell_{CR}$ increases, $s_{f\ell_{CR}}$ is decreasing and can reach the region where $\Delta E = 0$. Then the dynamical fusion barrier becomes different from the static one and a fusion cross section defect $\approx R^2_{f\ell_{CR}}\ \Delta E/E$ is observed. At very high bombarding energies, either $\Delta E$ becomes too large, or the pocket in the total interaction potential has disappeared due to the centrifugal energy, and the critical angular momentum saturates.

For a given value of the initial orbital angular momentum, say $\ell=0$ for instance, the position of the static fusion barrier will decrease when the size of the nuclei increases due to the Coulomb field. In the region where fusion first disappears (systems investigated in ref.[4]) $s_{f\ell_{CR}}$ will reach the region where

$\Delta E \neq 0$ and the dynamical fusion barrier will be larger than the static one lead in this way to a fusion cross ssection defect.

Therefore dynamical effects allow to understand, in a single picture, the fusion process. Furthermore the success of this simple model in reproducing the experimental data indicates that fusion is mainly determined in the entrance channel, before the minimum distance of approach is reached.

## 2. FAST FISSION

We have seen how fusion occurs and we shall now investigate what happens to the fused system. In particular we shall try to answer the question : do we always form a compound nucleus when two heavy nuclei fuse together?

### a) Compound nucleus formation and fusion

A compound nucleus is an entity which has completely forgotten about its formation except for some macroscopic parameters which should satisfy conservation laws. Such a nucleus is characterized by an excitation energy and an angular momentum. It will be unstable with respect to particle evaporation (leading to residual nuclei) but it may also undergo fission. The fission probability depends of course on the height of fission barrier which in turns, decreases strongly with increasing angular momentum.[11] For a certain value of $\ell$, which we shall denote by $\ell_{B_f}$ the fission barrier even vanishes. Since some amount of time is needed to form a compound nucleus in the real sense, it is reasonable to think that it is not possible to form it if it has no fission barrier ($\ell > \ell_{B_f}$). In the case where fusion would be identical to compound nucleus formation $\ell_{CR}$ should always be smaller than $\ell_{B_f}$. However a compilation of the existing data shows that this is not true and several measurements indicate that $\ell_{CR}$ can considerably exceed $\ell_{B_f}$[ref.[12]]. A possibility to explain the data would be to say that $\sigma_F$ does not only contain complete fusion but that there is a contribution of incomplete fusion. This last mechanism corresponds to the case where fast particles are emitted before the two remaining fragments fuse together. However, measurements of light particles associated to this process show a too small multiplicity[13] and cannot account for the difference between $\ell_{CR}$ and $\ell_{B_f}$. Therefore we are led to conclude that fusion cannot be identified with compound nucleus formation and a new question appears : what happens when $\ell_{B_f} < \ell < \ell_{CR}$ for which there is fusion but not compound nucleus formation?

A series of experiments has given some insight into this problem. In ref.[9] the evolution of the full width half maximum (FWHM) of the fission-like products has been investigated as a function of the excitation energy of the "compound nucleus", for the Ar + Ho system. It was observed that the FWHM increases with the excitation energy $E^*$ (see Fig. 8). Because the temperature T also increases with $E^*$, we expect the mass distribution to broaden due to statistical fluctuations. However, an estimation of this

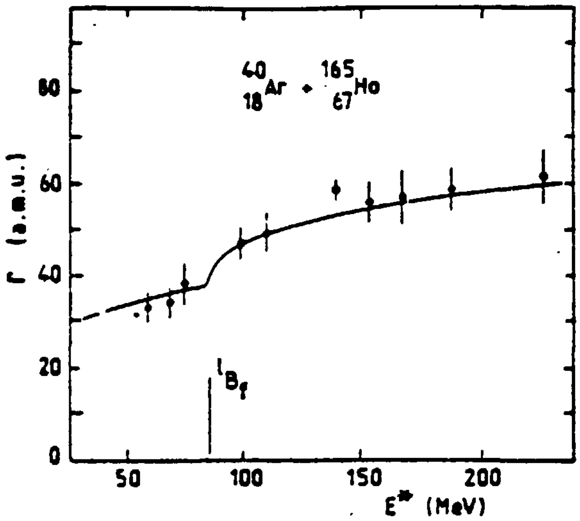


**Fig. 8 - Full width half maximum, Γ, of the fission like mass distribution, as a function of the excitaion energy of the fused system, for Ar + Ho. The dots are the experimental points in ref.[9]. The full curve is the result of the calculation of ref.[12].**

effect gives a too small increase compared to what is observed experimentally. This is likely due to a change of the stiffness coefficient of the potential energy surface along the mass asymmetry coordinate which decreases with increasing $\ell$ value. If we notice, in Fig. 8, that the FWHM changes a lot in tne region which is close to ~ 80 MeV, we are tempted to say that a mechanism different from ordinary fission contributes at high bombarding energies. It is precisely in this region that $\ell$ values larger than $\ell_{B_f}$ start to contribute to the fusion process. Therefore one might suggest the existence of a mechanism which is different from fission following compound nucleus formation and which occurs when $\ell_{B_f} < \ell < \ell_{CR}$. This preliminary conclusion is supported by investigations on heavier systems (Cl + Au in ref.[13] and Cl + U in ref.[14]). Indeed, as the system becomes more massive, $\ell_{B_f}$ decreases and for the Cl + U system, for example most of the $\ell$ values are greater than $\ell_{B_f}$. In this case the FWHM is almost constant over investigated bombarding energy range (240-350 MeV) whereas it varies in the case of the Cl + Au system (204-31 MeV) but to a smaller extend than for the Ar + Ho combination.

The fact that there exists a new mechanism when $\ell_{B_f} < \ell < \ell_{CR}$ which we will call later on fast fission is, from the experimental point of view, just a guess. We shall see below that there exists theoretical calculations which predict this mechanism in a natural way.

b) Fast fission

In heavy ion collisions, the two nuclei are assumed to be spherical, or close to this configuration, when they are far apart from each other. When they reach the interaction region various shape degrees of freedom are excited. For instance a neck appears between the two heavy ions creating in this way a single composite system with two centers. If we want follow the future evolution of the fused system to be followed, we need to have a good description of these changes of shape. In fact these excitations will transform a potential landscape where the two nuclei are spherical (sudden potential) in one where some the shape degrees of freedom have relaxed to equilibrium (adiabatic potential). Instead of trying to describe explicitly the deformation degrees of freedom, which is an enormous task when one tries to describe also the fluctuations which are associated to these macroscopic variables, it is tempting to simulate this transition between the sudden and the adiabatic potential, in a phenomenological way. This has been done in ref.[15] where a dynamical transition between a sudden interaction potential in the entrance channel, and an adiabatic one in the exit channel has been done. The degree of completeness of the transition depends, of course, upon the overlap between the two ions.

The physics which is behind this simulation is to see whether a transition between the fusion valley (that the system follows in the entrance channel) and the fission valley, is possible under certain circumstances. This notion of two valleys has been pointed out by Swiatecki[16] and confirmed recently by microscopic calculations.[17]

In the model of ref.[15] the collision between the two nuclei is described by means of four macroscopic variables ; the distance separating the center of mass of the two nuclei, the polar angle, the mass asymmetry of the system and the neutron excess of one of the fragments. The deformations are simulated as it is indicated above. The dynamical evolution of the collision is followed by means of a transport equation which was derived by Hofmann and Siemens and which we have discussed in the first lecture.

When some conditions are fulfilled, the model reveals the existence of a mechanism which is intermediate between deep inelastic reactions and compound nucleus formation. This is illustrated in Fig. 9 where typical mean trajectories are shown as a function of the mean mass asymmetry, and of the mean radial distance, for the 340 MeV Ar + Ho system.

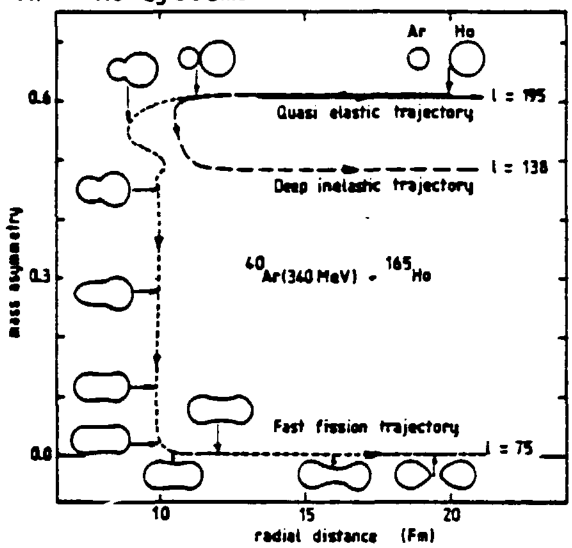


**Fig. 9 - Few mean trajectories for various initial values of the orbital angular momentum, $\ell$, plotted in the plane radial distance-mass asymmetry. Three kinds of mechanisms are illustrated in this plot : 1) quasi-elastic process for $\ell$=195, 2) deep inelastic collision for $\ell$=138 and 3) fast fission phenomenon for $\ell$=75. For $\ell < \ell_{B_f}$ = 72, a compound nucleus is formed. This figure has been extracted from ref.[15].**

- $\ell$=195 is a quasi-elastic trajectory with little mass and energy exchanged between the two nuclei.

- $\ell$=138 is typical of a deep inelastic collision : some mass transfer occurs between the two ions and a large damping of the initial kinetic energy is observed.

- $\ell$=75 shows a new kind of phenomenon. The system is trapped in the pocket of the entrance potential. Mass asymmetry relaxes to equilibrium and, at the same time, the sudden potential switches to the adiabatic one. However with this value of the angular momentum the compound nucleus has no fission barrier. Consequently there exists no pocket in the adiabatic potential to keep the system for a while : it will decay in almost two equal fragments. This mechanism has been called fast fission since it proceeds faster than ordinary fission where the stage of forming a compound nucleus is needed. In contrast to ordinary fission which corresponds to a decay of a one-center system, fast fission results from a decay of a two-center composite nucleus (see Fig. 10). The interaction time turns out to be of the order of ~ $10^{-20}$s which is intermediate between a deep inelastic collision and a compound

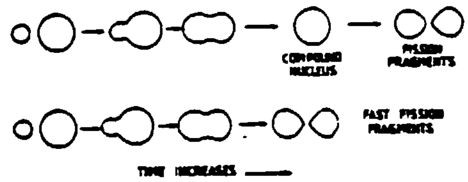

**Fig. 10 - Schematic picture of compound nucleus fission and fast fission.**

nucleus formation. The fast fission mechanism provides a way to go directly from the fusion valley to the fission valley without passing by the compound nucleus stage (see Fig. 11).

- When $\ell < 72 = \ell_{B_f}$, the system is trapped in the entrance potential but remains trapped in the adiabatic one because the fission barrier is non zero : we form a real compound nucleus.

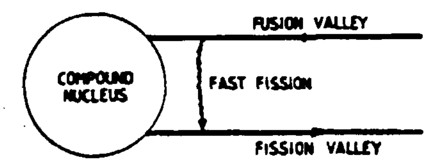


**Fig. 11 - Schematic representation of fast fission as a mechanism which allows to go directly from the fusion to the fission valley.**

To summarize, for a system like Ar + Ho, we can observe fast fission only if $\ell_{B_f} < \ell < \ell_{CR}$.

When the fissility parameter $Z^2/A$ of the compound system 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 :

$$\frac{Z^2}{A} > 38.5 \qquad (14)$$

In this case, even if $\ell < \ell_{B_f}$, the system which is trapped in the pocket of the entrance potential cannot remain trapped in the adiabatic one, although there exists a fission barrier, because it is located already outside the saddle configuration. We have again fast fission but this special case has been called quasi-fission by Swiatecki[8] who was the first to point out such a possibility.

The macroscopic model described above predicts that fast fission has properties which are very similar to those of fission following compound nucleus formation. This makes difficult to get an unambiguous experimental evidence of this mechanism. At this stage the model explains, in a simple way, the data which were not understood before but that is all. The most advanced experimental proof that might be found is the measurements of Ho et al. who found evidence of light particles evaporated by a two-center system similar to the one leading to fast fission.

It is interesting to have a look at the fusion excitation function of the Ar + Ho system (Fig. 12). The fusion cross section is the sum of the compound nucleus and of the fast fission cross sections. We observe that just above the fusion threshold we have, for this particular system, only compound nucleus formation. Fast fission starts to contribute only when $\ell$ values larger than $\ell_{B_f}$ fuse. Since a transport equation is used to describe the dynamics, one can calculate the statistical fluctuations in the mass asymmetry coordinate, construct the fast fission mass distribution at a given bombarding and add to it the one corresponding to fission following compound nucleus formation (taken from ref.[19]). In Fig. 8 the calculated FWHM of the fission-like mass distribution (full line) is compared with the data and the agreement appears to be rather good.

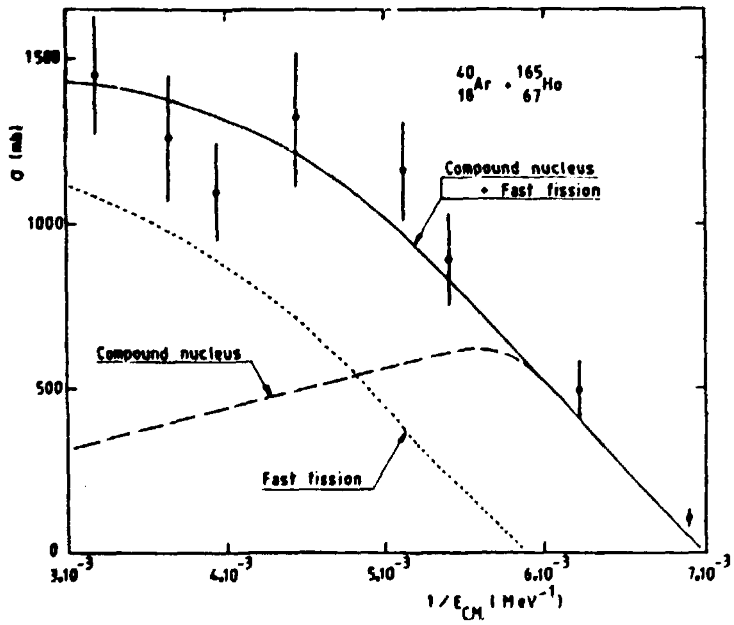


Fig. 12 - Experimental fusion cross section (dots) from ref.[9] plotted as a function of $1/E_{CM}$, the inverse of the center of mass bombarding energy. It is compared with the calculated fusion cross section of ref.[15] (full curve). The fusion cross section is the sum of the compound nucleus and of the fast fission cross sections. Their corresponding excitation functions are also shown in the figure. This figure is extracted from ref.[15].

Four classes of dissipative heavy ion collision can be predicted by the macroscopic model of ref.[15]. This is schematically illustrated in Fig. 13 where the sudden and the adiabatic potentials are represented as a function the interdistance R separating the two nuclei. This one dimensional plot is just to get a feeling of the collision which in fact occurs in multidimensional space.

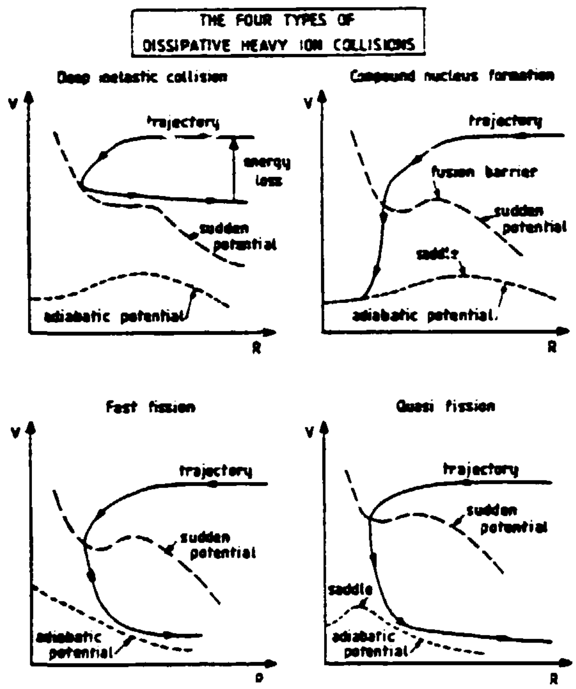


**Fig. 13 - Typical illustration of the four dissipative mechanisms occuring in a heavy ion reaction : Top left** : the system is not trapped but it looses a lot of kinetic energy in the relative motion : we have a deep inelastic collision. **Top right** : the system is trapped in the entrance channel. 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.

In Fig. 14 we show the range of $\ell$ values to which these dissipative phenomena are associated and, in Fig. 15 we summarize the conditions under which fusion, fast fission and quasi-fission occur.

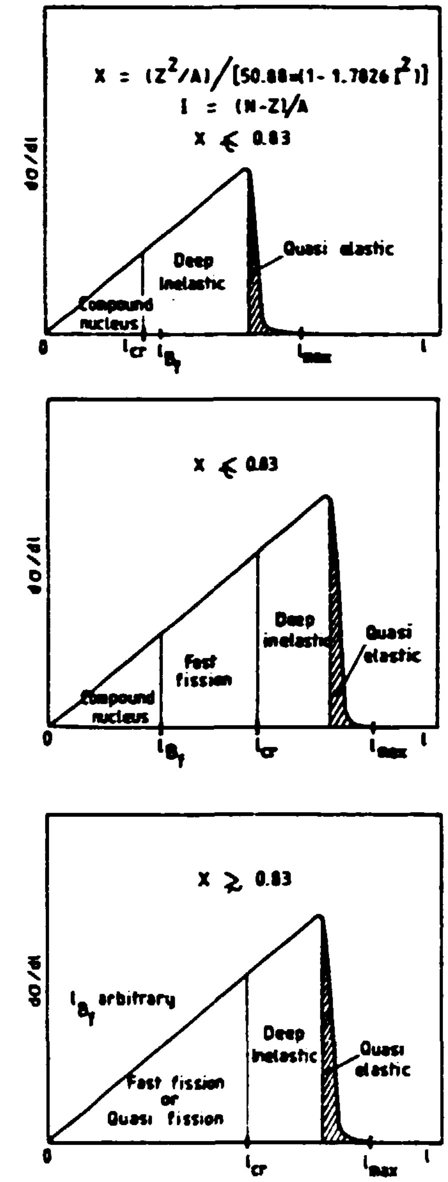


Fig. 14 - Schematic representation of the different ranges of $\ell$ values associated to the four dissipative mechanisms which can be observed in heavy ion reactions.

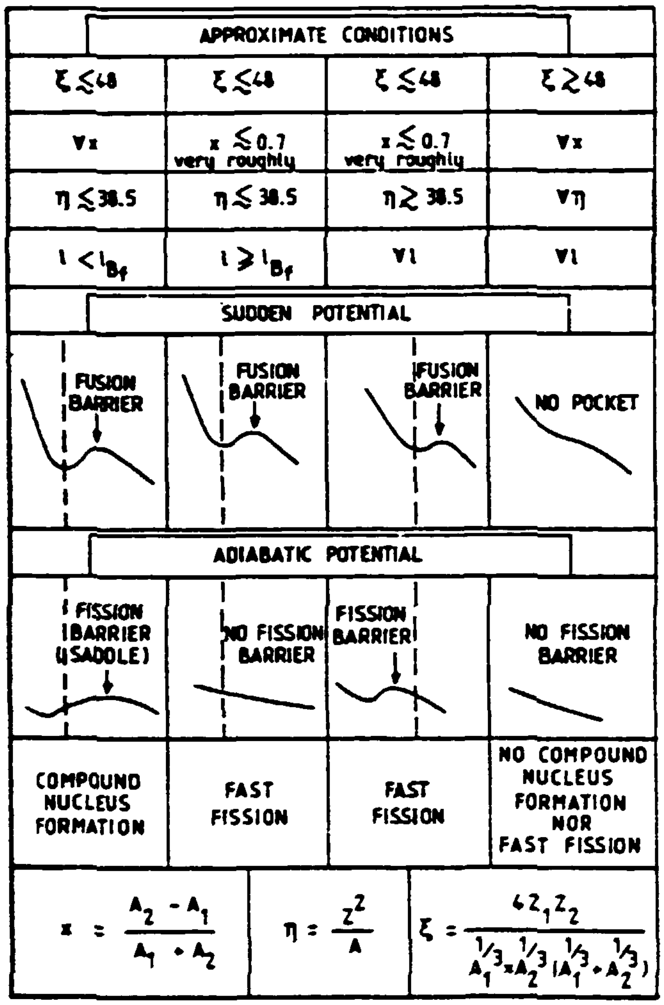


**Fig. 15 - Schematic summary of the different mechanisms following fusion and their domains of occurence.**

## CONCLUSION

During the recent years a great progress has been done in the understanding of fusion. New ideas have been introduced and we have now a rather good description of this phenomenon. Other dynamical descriptions have also been proposed for fusion[8] and they reach conclusions which are similar in the average (see ref.[3] for a comparison between the different approaches). It seems that at present the models are beyond the experiment and are able to predict new phenomena like fast fission which still need to be really confirmed experimentally. Therefore many clever experiments at high resolution are needed in order to agree or to contradict the models.

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## Lecture III : SOME ASPECTS OF THE PHYSICS BETWEEN 20 AND 50 MeV/u

The heavy ion mechanisms at bombarding energies smaller than about 10-20 MeV/u are dominated by the mean field.[1] As a consequence it is possible to observe dissipative phenomena for the collective motions which are excited during the collision. The situation changes a lot at very high bombarding energies (> 100 MeV/u) where it is found that the physics is dominated by the nucleon-nucleon interaction and where a collective behaviour seems to be very scarce.[1]

The intermediate bombarding energy region, which is located between 20 and 100 MeV/u is now being available. It is interesting to see how the transition between the regime dominated by collective motions and the one dominated by the nucleon-nucleon interaction takes place. This region is interesting to investigate because the incident kinetic energy of the nucleons can be of the same order than the Fermi energy. As the bombarding energy will be raised from 20 to 100 MeV/u, we expect the Pauli principle, which prevents, for a large part, the collisions between nucleons, to be less and less effective. Consequently one might expect, as a simple guess (and if dissipation is still present) some kind of a transition between the one-body and the two-body friction. We would then become closer to an hydrodynamic picture. However increasing the incident velocity of the projectile means also that the interaction time will decrease. Consequently the collective motions which have a relaxation time which is much larger than this interaction time will no longer be excited. This means that, if collective motions of the same nature as those seen at smaller bombarding energy can still be observed, it will only be those who have a short relaxation time (charge equilibration for instance). We have seen, in the first lecture, that the relaxation time for the intrinsic degrees was very short : of the order of $\sim 10^{-22}$s. However if the collision time becomes of that order, the problem of equilibration and statistical equilibrium of the internal degrees becomes questionable and connected to it, the possible existence of dissipation. If there is no global statistical equilibrium, memory effects can be present (non Markoviar process) and the reaction might also proceed by other mechanisms different from the ones observed at low bombarding energy.

The differences between the reaction mechanisms in the three energy domains discussed above, might probably find their origin in the relative balance between the intrinsic velocity of the nucleons and the relative velocity of the two ions. This is schematically represented in Fig. 1. At low bombarding energy the relative velocity of the two ions is much smaller than the mean velocity of the nucleons. Therefore we understand why there are collective motions which are slow compared to the time evolution of the intrinsic system. The interaction between the two nuclei will create a perturbation of the mean field but not a complete destruction. At very high bombarding energies it is the contrary. The relative velocity of the two nuclei is much larger than the instrinsic velocity of the nucleons and their binding is negligeable compared to the incident kinetic energy. The mean field represents a very small perturbation in the system which will be dominated by the nucleon-nucleon interaction. At medium bombarding energies both velocities become of the same order and it will not be possible to neglect either one compared to the other. We are in a transition region which will not be easy to treat theoretically and experiments will also not be easy to do since, in addition to heavy fragments, a non negligible amount of light particles, which are not all of evaporative nature, will be present.

In this energy domain there are several questions which we would like to answer. Let us briefly quote some of them in an arbitrary way :

- Can we still observe collective motions of nucleons in this energy range?

- Do we have dissipative phenomena and what will be the nature of friction? Will it be of one-body type (1p-1h excitations followed by a decay to more complicated states) or will we observe two-body friction as it is the case for macroscopic objects?

- Can we observe a gas-liquid transition[2]?

- How much energy, linear and angular momenta can we deposit in the fragments? Such a question is strongly connected to the fusion process. Indeed if we can deposit a large amount of excitation energy in the fused system, we can reach the boiling of nuclear matter which should occur at temperatures of the order of $\sim$ 8 MeV.

In heavy ion reactions which are induced in this energy range, it is interesting to know whether the available incident energy will be converted into temperature, or into compressional energy. In fact we very likely will observe a mixture of both kinds of energy but one needs to know the relative proportion of them. The compressed system will expand, afterwards probably at constant entropy.[3] This will produce a cooling which can possibly lead to condensation of nuclear matter into a liquid and a gas phase. If such a process is also dissipative there will be nevertheless entropy production in the expansion phase.

In this lecture I would like to give a feeling, in a simplified manner, of some aspects of the results which have been obtained between 20 and 50 MeV/u. The first aspect will concern linear momentum transfer and the second one the possible fracture of nuclei when they collide at such high velocities. This last problem is related to the question of whether nuclei can behave, under some circumstances, as a crystal.

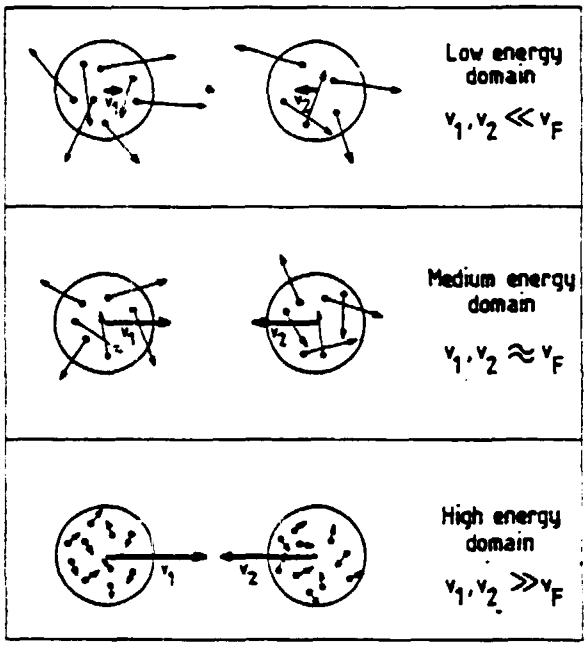


**Fig. - 1 Schematic presentation of the three energy domains. The wide arrows indicate the velocity of the ions and the small ones, distributed randomly the velocity of the nucleons in the frame of reference where the nucleus is at rest.**

1. LINEAR MOMENTUM TRANSFER

When the bombarding energy is smaller than 7-8 MeV/u two heavy ions can fuse together. If the fused system is heavy enough, or has a lot of angular momentum, it will have a large probability to fission. For a given mass ratio and a total kinetic energy of the products, the most probable correlation angle between the two fragments can be easily calculated in the laboratory system by just applying simple kinematics. Indeed the two fission fragments are emitted at 180° from each other in the frame of the fissioning nucleus and one has, to go to the laboratory system, just to add, to their velocity the recoiling velocity of the fused nucleus (see Fig. 2). Nevertheless there will be a distribution around the most probable value of the correlation angle because the fission fragments are excited. Consequently they will de-excite by emitting light particles which will change the orientation, as well as the value of the initial velocity. This distribution will extend both in and out of the reaction plane. If we now remove the condition of a fixed mass ratio, and of a fixed kinetic energy for the fragments, we will create an additional broadening of the correlation angle between the two fragments, but only in the angle oriented along the reaction plane. At low bombarding energies the recoiling velocity of the fused system is equal to the velocity, V, of the center of mass :

$$V = v_1 \frac{A_1}{A_1 + A_2} \quad (1)$$

where $v_1$ is the velocity of the projectile, $A_1$ its mass and $A_2$ the mass of the target. In this case we say that there is full linear momentum transfer.

When the bombarding energy is raised, complete fusion is not the only possible mechanism producing a fissioning nucleus. We can have incomplete fusion where fast light particles are emitted before the remaining nuclei fuse together. The fused system will not recoil with the velocity of the center of mass because these light particles have removed a part of the initial linear momentum of the projectile. Consequently the correlation angle between the two fragments will be larger than in the case discussed above

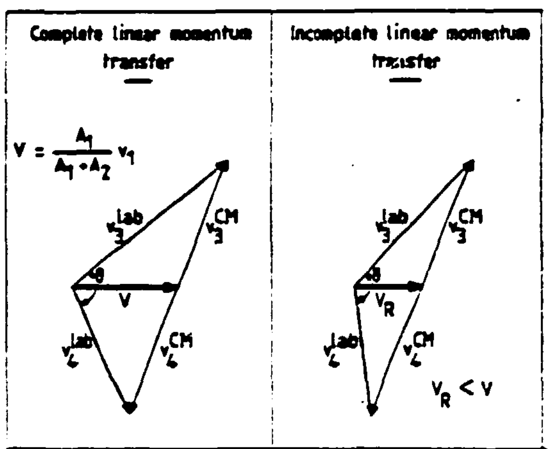


**Fig. 2 - Principle of the measurement of linear momentum transfer using the correlation angle technique : when less and less linear momentum is transferred from the projectile to the fused nucleus the opening angle between the two fission fragments, θ, increases.**

In such a situation we say that we have incomplete linear momentum transfer. The fraction of linear momentum transferred, $\rho$, can be defined as :

$$\rho = \frac{p_3 + p_4}{p_1} \quad (2)$$

where $p_{1//}$, $p_{3//}$ and $p_{4//}$ are respectively the parallel linear momentum components (along the beam axis) of the projectile and of the fission fragments. For complete linear momentum transfer $\rho=1$, whereas, it is zero for non-linear momentum transfer.

When projectiles up to $^{12}C$, $^{16}O$ are accelerated at bombarding energies ranging between 10 and 90 MeV/u, it turns out that the most probable amount of linear momentum transferred from the projectile to the fissioning nucleus represents a larg part of the incident one. This is illustrated in Fig. 3 which shows $\rho$ as a

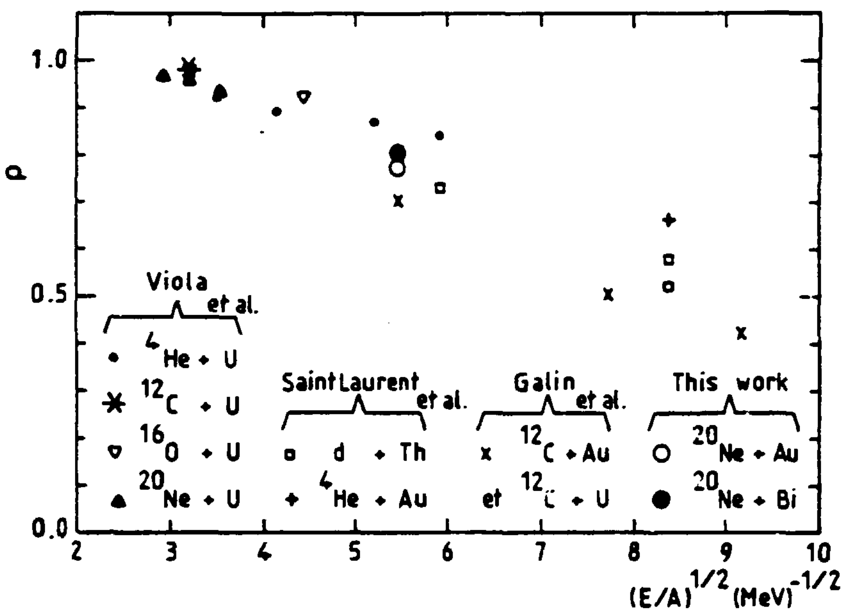


**Fig. 3 - Fraction of full momentum transfer as a function of the square root of the incide t energy per nucleon for different systems [data from refs.[4-7]]. From ref.[7].**

function of the incident velocity for different systems investigated in the literature. We observe that $\rho$ decreases as $\sqrt{E/A}$ increases. This behaviour can be represented, to a good approximation, by the following expression[7] :

$$\rho = -0.092\sqrt{E/A} + 1.273 \quad \text{for} \quad \sqrt{E/A} > 3.2\ [\text{MeV/u}]^{1/2}$$

and (3)

$$\rho = 1 \quad \text{for} \quad \sqrt{E/A} < 3.2\ [\text{MeV/u}]^{1/2}$$

In Fig. 3 we have also plotted the points corresponding to the Ne + Au and Ne + Bi systems which have been investigated at SARA using the 30 MeV/u Ne beam.[7] We however do not know whether these systems will still follow the behaviour given by eq.(3) when the bombarding energy is increased above the Fermi energy (see below).

In order to illustrate how the correlation function of the two fission fragments looks like, we show, in Fig. 4, the result of such a measurement for the Ne + Au system at 30 MeV/u [ref.[7]]. The arrow indicates the position where the most probable value of the correlation angle, $\theta$, should be, assuming full linear momentum transfer. In fact we see that the maximum of the distribution is shifted towards larger values of θ and it corresponds to $\rho \approx 0.8$. Around 160° we have also a contribution of another mechanism : the fission of the quasi Au target resulting from a very peripheral collision where little linear momentum and energy is transferred from the projectile to the target. Such a mechanism is usually called sequential fission. It is easy to deduce a physical information from the most probable values which are observed in the experiment. However for one particular event, one has to be very careful before drawing any conclusion. Indeed the distribution function displayed in Fig. 4 corresponds mostly to the fission products following incomplete fusion plus, for the part close to 160°, a little bit of sequential fission. The large width of the distribution around its most probable value comes mainly from the existence of a mass and kinetic energy distribution for the fission products, and from the evaporation of the excited fission fragments. All these effects induce a broadening around the most probable value. On top of this, we also have a distribution in the linear momentum distribution of the incomplete fusion nucleus. This explains why we observe, for instance, fission fragments with a θ smaller than the one corresponding to full linear momentum

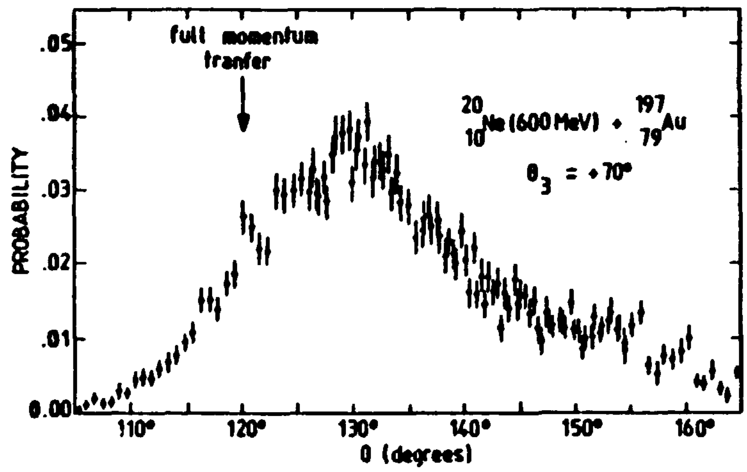


**Fig. 4 - Correlation function of the two fission fragments observed in the reaction Ne + Au at 30 MeV/u. From ref.[7].**

transfer. Of course these products do not correspond to a linear momentum transfer larger than 100 %, but have this value of θ just because of the preceding effects. Since a direct deconvolution of the results is extremely difficult, and perhaps impossible, it seems safer to perform a Monte-Carlo simulation of the data as it has been done in ref.[7].

Eq.(3) seems to give a good representation of the experimental data concerning linear momentum transfer. However, the use of heavier projectiles has shown that this is not the case and ρ depends not only on the bombarding energy but also on the size of the projectile. This has been demonstrated using the 44 MeV/u Ar beam accelerated at Ganil.[8,9] If we apply eq.(3) to the Ar + U system we would get for the most probables values : $\rho \approx 0.66$ and $\theta \approx 105$ for the particular arrangement of the detectors. In Fig. 5 we show the measured correlation function for the Ar + U system[8,9] (similar results have been obtained with Ar + Au)[8] Compared with Fig. 4 we see a very different picture. Indeed the most probable $\theta$ lies close to 170° and corresponds to a sequential fission of the quasi target. The probability of detecting two fission fragments decreases as $\theta$ decreases from the preceding region indicating that there are a small number of events coming from a fission of a fused system. The fact that the Ar + Au, U systems do not follow the systematic given by eq.(3) is very

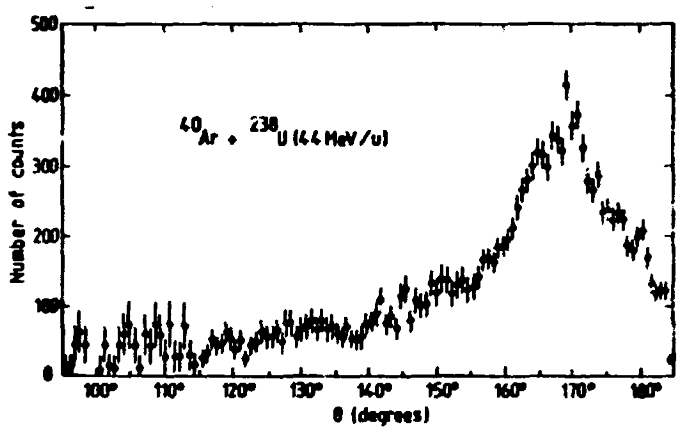


**Fig. 5 - Correlation function of the two fission fragments observ ed in the reaction Ar + U at 44 MeV/u. From ref.[9].**

surprising. It indicates that not only the bombarding energy, but also the mass of the projectile is an important parameter to be considered. Since similar experiments,[10] performed at 27 MeV/u with an Ar beam show a picture similar to the one observed with lighter projectiles (large amount of linear momentum transfer). would be interesting to know if a Ne beam at > 40 MeV would give something similar to Ar or to $^{12}C$. Indeed, the results obtained with the Ar beam seem to indicate that the Fermi energy ($\varepsilon_F \sim 40$ MeV) plays an important role in the process when the size of the projectile is large enough : for bombarding energies below $\varepsilon_F$/u the reaction mechanisms would be close to the one observed at low bombarding energies and, above $\varepsilon_F$/u, the situation would change. Therefore more experiments in this energy region are needed to extract the physical content of what happens.

## 2. VERY INELASTIC FRAGMENTS IN 35 MeV/u Kr INDUCED REACTIONS

In the preceding section we have seen that the amount of linear momentum which can be transferred from the projectile to the fused nucleus, depends not only on the bombarding energy, but also on the mass of the projectile. We may also wonder whether some other mechanism may also depend upon the sizes of the projectile.

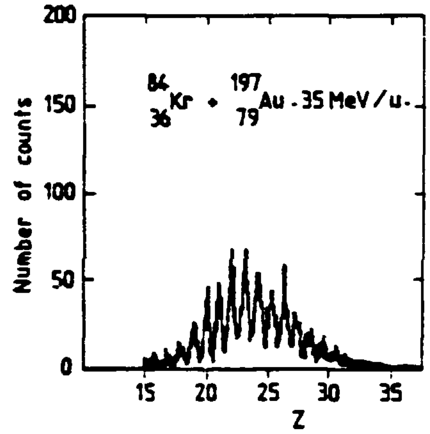


**Fig. 6 - Atomic number distribution of the very inelastic events.**

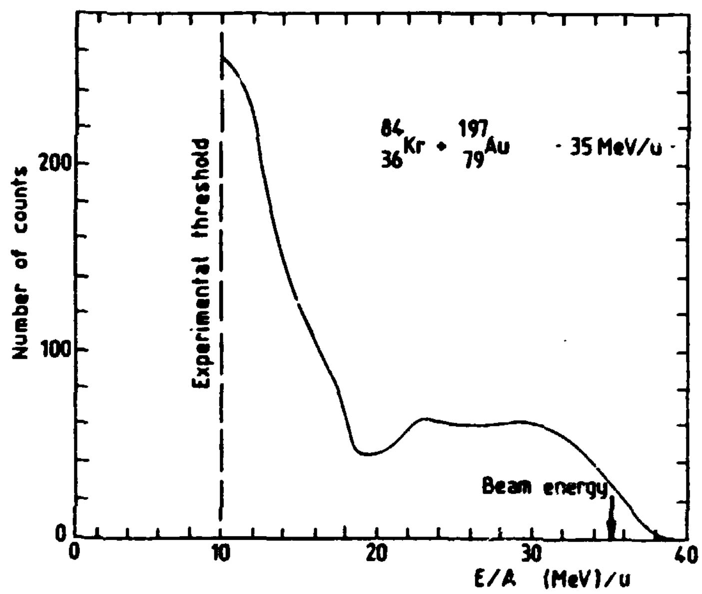


**Fig. 7 - Kinetic energy per nucleon of all the products with a bombarding energy > 10 MeV/u. We see the presence of a lot of events with a kinetic energy < 18 MeV/u. Their atomic number distribution is displayed in Fig. 6.**

which are detected in ref.[13,14] would come from the fusion between the participants and the projectile spectators followed by a fission of this system. Of course it is only speculations about the mechanism and more exclusive experiments are needed to precise the nature of these reactions.

From the two aspects discussed in this lecture it seems that the energy domain between 20 and 100 MeV/u is really a transition region between the two physics which have been extensively investigated at low and high bombarding energies. If it would remain so, the physics would not be so rich as it is just above the Coulomb barrier where many collective phenomena take place.

With Ar projectiles the main mechanisms which are observed are the following (when we restrict to fragments with a mass smaller than half of the total mass) :

- Fragmentation, where we detect products with a mass and a velocity close to the one of the projectile.

- Light products which have a cross section which decreases when the fragment mass increases. These products might be explained by some liquid phase transition mechanism,[2,3] or by a cold fragmentation as in the case of high energy proton induced reactions.[12]

- Depending upon the bombarding energy, and on the target mass, one might also see fission products following incomplete fusion, or associated to the sequential fission of the target-like products.

In the same way as an $^{40}$Ar projectile has revealed different features, compared to $^{12}$C projectile, as far as linear momentum transfer is concerned, it turns out that, with a Kr beam, new features have been observed.[13] In refs.[13,14] the first 35 MeV/u Kr beam provided by the Ganil facility has been used to bombard a $^{197}$Au target. Experimental set-up was such that it was possible to detect several heavy fragments in coincidence. In addition to the usual reactions which are expected in this bombarding region and briefly quoted above, it was found a new kind of events which has not been observed with lighter projectiles. Their atomic number distribution (see Fig. 6) lies between 20 and 28 with a most probable value around Z=24. Their kinetic energy is much smaller than the incident one and lies below ~ 18 MeV/u. In Fig. 7 we show a velocity spectrum of the events detected a little bit backwards the grazing angle. In this region they represent a large part of the differential cross section. Nevertheless they are also present forwards the grazing angle, but they represent only a small part (~ 1 %) of the fragmentation products.

These very inelastic events cannot be understood in terms of the usual pictures used in this energy domain : fragmentation or liquid-gas phase transition. We may think at several origin for them. For example, they could come from a could break-up of the projectile. This would mean that the nuclei behave, under certain circonstances, like a cristal. We can also imagine, and that might be more likely, that we have a kind of participant spectator picture similar to the one used at high energies. However instead of having in the exit channel three components corresponding to the participants, the projectile and target spectators, we would have, due to a reminiscence of the mean field, an interaction between the participants and one of the spectators. This interaction could lead to a fusion between the participants and the spectators of the projectile or of the target. The fused system being highly excited would fission. Therefore we would have a sequential two-step mechanism giving three fragments in the exit channel. Those

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