HEAVY ION REACTIONS BETWEEN 30 AND A FEW HUNDRED MEV/NUCLEON

#### J. P. Bondorf

The Niels Bohr Institute, University of Copenhagen Blegdamsvej 17, 2100 Copenhagen Ø, Denmark

<u>Résumé</u>.- Des prédictions qualitatives des propriétés caractéristiques des réactions entre ions lourds à des énergies dans le système du centre de masse s'échelonnant de l'énergie moyenne par nucléon jusqu'au seuil de production des mésons I sont présentées. La discussion est faite sur la base des lois de conservation, des expériences de réactions très inélastiques (E<sub>lab</sub><10 MeV/nucléon) et des expériences de réactions avec des ions lourds d'énergie supérieure à 200 MeV/A dans le laboratoire.

<u>Abstract.</u> Some qualitative predictions of characteristic properties of heavy ion reactions at CM-energies ranging from around the average binding per nucleon up to about the  $\pi$ -meson threshold are discussed. The discussion is made on the basis of conservation laws, experience from deep inelastic reactions (LAB energy < 10 MeV/nucleon) and experience from hard heavy ion reactions (LAB energy > 200 MeV/nucleon).

#### 1. Introduction.

Most of the development in experimental heavy ion physics has so far been made with beam energies below 10 MeV/nucleon. It is technically possible to accelerate ions with much higher energy, and in the last years a few pioneering experiments with as much as several GeV/nucleon have been made [1]. Also the energy range of the order of 100 - 1000 MeV/nucleon has had its first experiments, and new machines able to make detailed studies in these vastly unexplored fields are being planned or are under construction. The suggestion of a new type of superdense nuclear matter [2] has intensified theoretical and experimental studies of heavy ion reactions in energy regions where the nuclear matter can undergo compression. In this lecture we shall discuss some aspects of heavy ion experiments with beam energies from 30 to about 500 MeV/nucleon. The lower part of this energy region can be studied with the

## GANIL facility.

This energy region is almost new to nuclear physics and most of what can be said about it is based upon inter- or extrapolations from known neighbour-energy regions. I shall try to draw some conclusions based upon the following pieces of information.

a) Expectations from applications of conservation laws, energy, momentum, angular momentum, baryon number, and charge, taking into account some characteristic energies of the nuclei as the nucleon energy corresponding to the speed of sound, the binding energy, etc.

b) Experience from deep inelastic reactions at lower energies (up to about 10 MeV/nucleon) and from  $\alpha$ -particle and proton induced reactions.

c) Experience from hard collisions at energies in the region above 200 MeV/nucleon.  Some expectations from conservation laws.

2.1 Fragmentation.

At low bombarding energy the binary reaction kinematics is usually dominant, and one only needs to worry about multiparticle kinematics for the subsequent decay processes. One can therefore write the primary reaction either as a binary reaction or as a compound reaction:

 $\begin{array}{l} (Z_1A_1) + (Z_2A_2) \longrightarrow \\ \{ (Z_3A_3) + (Z_4A_4) \longrightarrow \text{seq.decay (binary reaction)} \\ (ZA) \longrightarrow \text{seq.decay (compound or complete fusion reaction)} \end{array}$ 

where  $Z = Z_1 + Z_2 = Z_3 + Z_4$  and  $A = A_1 + A_2 = A_3 + A_4$ 

In both cases there can be subsequent decay of the primary products; such as evaporation or fission. For higher bombarding energy, however, it is likely that multifragment events become increasingly important so that we have <u>direct</u>, fast reactions of the type

$$(Z_1 A_1) + (Z_2 A_2) \longrightarrow \sum_i (Z_i A_i) \longrightarrow \text{seq.decay}$$
(2)

where i > 2 at any stage of the reaction. By conservation of charge and mass, we have besides

$$Z_1 + Z_2 = \sum_i Z_i$$
 and  $A_1 + A_2 = \sum_i A_i$ 

The sequential decay processes cause the number of fragments which are simultaneously present at any time to increase after the creation of the primary fragments. The distribution of the primary fragmentation (2) is of considerable interest for the study of heavy ion reactions at higher energy, but also angular and energy correlations between primary reaction products should be given attention if one wants to study the reaction mechanism where (2) plays a role.

The break up process (2) need not be restricted to higher energies. For the lighter projectiles, such as  $^{12}$ C or  $^{16}$ O,

one can think of conventional  $\alpha$ -break up in the Coulomb field or the tail of the nuclear field. This is a rather probable process because the  $\alpha$ -binding energy in the nuclei and the  $\alpha$ -barrier are only a few MeV. In heavier systems, however, the situation is different. The  $\alpha$ -barrier is higher and the most probable small particle which can be emitted is the nucleon.

I shall here draw the attention to a possible mechanism for prompt nucleon emission which can occur in heavy ion induced reactions, but which, as far as I am informed, has not yet been studied very much. Consider a heavy ion reaction with a relative speed  $\vec{V}$  of nucleus 1 at the ion-ion barrier. We now consider a nucleon  $\nu$  moving from nucleus 1 to nucleus 2 (fig.1a). Its velocity in nucleus 1 is  $\vec{V}_1$ . By arrival, its relative velocity in nucleus 2 is

$$\vec{v}_2 = \vec{v}_1 + \vec{V} \tag{3}$$

with a maximum walue

$$\mathcal{V}_{2}(\max) = \mathcal{V}_{F} + |\overline{V}| \tag{4}$$

and the maximum kinetic energy of this nucleon in nucleus 2 is

$$\begin{split} & \mathcal{E}(\text{max}) = \mathcal{E}_F + \mathcal{E}_{rel} + 2\sqrt{\mathcal{E}_F \mathcal{E}_{rel}} \eqno(5) \\ & \text{where } \mathcal{E}_F \text{ is the Fermi energy. This e-} \\ & \text{nergy can easily be so high that the nucle-} \\ & \text{on can escape immediately. This is because} \\ & \text{of the cross term in (5). As an example,} \\ & \text{consider } \mathcal{E}_{rel} = 3 \end{tabular} \quad \end{split}$$



Fig. 1. Two mechanisms of prompt nucleon emission in heavy ion collisions. a) direct escape. b) escape after nucleon-nucleon collision. be obtained in existing accelerators. That gives the kinetic nucleon energy (5) equal to  $\approx$  70 MeV which is much more than necessary for nucleon escape.

Prompt nucleon decay can also happen after one nucleon-nucleon collision just after the ion-ion impact. The nucleon energies obtained in such collisions can also be up to the value (5). This prompt nucleon emission mechanism is illustrated in fig. lb. Also prompt a-emission similar to the nucleon emissions in figs. la and lb can occur, but it is more difficult to estimate the escape energy in this case. Experimental evidence for prompt particle  $\alpha$ -emission is given in [3]. Only a small fraction of the nucleons in the nucleus is so favourably located in phase space that the prompt emission can take place. For heavy projectiles and targets, however, the large number of nucleons causes the probability of prompt nucleon emission drain of the excitation energy to be substantial.

It is evident that if such prompt decay occurs, one should reduce energy and mass of fusion and deep inelastic products before applying evaporation models to them. The characteristics of the pre-equilibrium emitted particles would give experimental insight into the first instances of the close heavy ion processes, where the large energy loss is assumed in order to agree with the phenomenological models. We shall look more at such models in the following section.

2.2 Sharing of energy.

In this discussion we denote <u>ion</u> ener= gies by E and <u>nucleon</u> energies by E.

The incident CM-energy can be shared among the final channel nucleons in many ways depending on how the reaction proceeds. In average there is the following CM-energy per nucleon available in the total system

$$\varepsilon(CM) = E_1 (LAB) \frac{A_2}{(A_1 + A_2)^2}$$
(6)

Only when one is dealing with compound or complete fusion reactions in the strict conventional sense, this energy can be expected to be equally spread (and only as an average) among the nucleons. In other cases there is expected to be strong deviations from such equi-partition. However, also at higher energies, eq. (6) may serve as a guide for expectations. By noticing that the average binding energy per nucleon of the projectile and the target is approximately equal to the average binding per nucleon of the compound nucleus, we see that  $\mathcal{E}(CM)$  is also approximately equal to the average excitation energy per nucleon in the CM system.

It is convenient to look at a diagram, fig. 2, where the nuclear mass A and the excitation energy per nucleon  $\mathcal{E}(CM)$  are



Fig. 2. Regions of nuclear excitation as functions of excitation energy and mass number. The three shaded zones are: the boiling energy  $\mathcal{E}_{\rm b}$ , the nucleon energy  $\mathcal{E}_{\rm c}$ corresponding to the speed of sound, and the  $\P$ -meson threshold. The zones in between are dominated by I) binary reactions and complete fusion II) multifragment reactions without compression, III) multifragment reactions with compression; IV) as III but now including  $\pi$ -meson cooling.

the coordinates. This diagram is equivalent to the diagram which experimentalists draw when trying to compare accelerators. The conventional two body heavy ion reac-

tions are presently made in the region below the energy corresponding to the nuclear binding. Since nuclei are free to separate into smaller fragments above this or a somewhat smaller energy (of the order of 5 MeV/nucleon), we can define a boiling point  $\mathcal{E}_{b}$  of nuclei in this region. Above the boiling point we expect multiparticle events to become increasingly dominant. This energy region is still so low that the compression of the nuclear matter in heavy ion reactions has not yet become important. That happens when half of the ion LABspeed passes the speed of sound (speed of compression waves). The estimate of this speed is that it corresponds to a nucleon energy  $\mathcal{E}_c$  of the order of 15 MeV. The region  $\mathcal{E}_b < \mathcal{E} < \mathcal{E}_c$  is ideal for the GANIL project as can be seen from the curve denoted GANIL-LIMIT (fig. 2). It is seen that for smaller nuclei it is possible that GANIL can also penetrate into the neighbour region, above  $\mathcal{E}_{C}$  , where we also expect multiparticle events but now with compression of the nuclei. At much higher energy threshold extends below the free nucleonnucleon scattering value because of fluctuations in the energies which can be shared by the individual nucleons. The production of free  $\pi$ -mesons which will escape from the outer region of the nucleus causes a certain cooling of the system. Also the share of the intrinsic energy between nucleon and meson degrees of freedom lowers the temperature. These effects influence effectively the equation of state of the nuclear matter and the nuclear compression. In the region considerably below  $\mathcal{E}_{\widehat{\mathcal{H}}}$  there is a possibility of  $\widehat{\mathcal{T}}$ -meson condensates [4] - [5].

In the following section we shall study some experimental and theoretical pieces of information from deep inelastic reactions at  $\mathcal{E}(CM) < \mathcal{E}_b$ , and after that, hard heavy ion reactions at  $\mathcal{E}(CM)$  in the neighbourhood of 100 MeV/nucleon where nuclear compression is certainly a dominant feature of the reactions.

- Reactions of the deep inelastic binary type.
- 3.1 Characteristic experimental signatures.

Since the discovery [6] of a new, highly inelastic type of reaction in heavy ion reactions, the so-called deep inelastic process, there has been made a large number of experimental investigations which confirm that this is a process which exists in certain energy intervals for practically all combinations of projectiles and target. The conventional interpretation [7] of the deep inelastic process is that for a range of impact parameters outside the maximum impact parameter for complete fusion, there occurs a close two body reaction between the ions in which practically all the relative kinetic energy in the radial motion becomes dissipated into heat which is absorbed by the two ions. Because of the intimate contact between the ions, a certain mass transfer occurs. It has the character of a random process so that the mass distribution of the primary reaction products. from the deep inelastic reaction has two peaks, one in the neighbourhood of the projectile and one in the neighbourhood of the target.

The characteristic mass distributions from a reaction of binary type (1) can be seen in fig. 3 (from Ngô et al.) [8]. Because the deep inelastic part of the reaction products is excited, the final (secondary) reaction products of projectile and target-like types do not have identical distributions. In a binary reaction with no seq. decay this would have been the case, but the sequential decay of the primary products occurs before they reach the detector. From the figure it is seen that since the mass distribution for the projectile (Kr) is rather narrow and the distribution for the target (Au) is broader and moved towards lower masses, the big fragment has received most of the lost "dissipated" energy in the reaction. The division of the dissipated energy between the target and the projectile has not yet been experimentally established in a quantitative way. One can make a rough guess of what should be expected in a deep in-



Fig. 3. Deep inelastic cross section as function of angle and mass number of the reaction product for the reaction  $^{63}Cu+197Au$  at  $E_{LAB}$ = 365 MeV. [8]

elastic reaction. By assuming thermal equilibrium between the two fragments and by putting the heat capacities of the fragments proportional to their mass, one gets

$$E_{3/F^{*}}^{n} \approx A_{1/A_{2}} \tag{7}$$

The deep inelastic reactions are in many respects similar to fission, but because of the richness in the possibilities of choosing energies, angular momenta, target and projectile masses in heavy ion reactions, one can vary the experimental conditions for studying the phenomenon much more than it is possible in fission. One of the effects leading to an analogy with fission is the in - out asymmetry of the reaction. This effect can be characterized as a difference between the contact radius at the heavy ion impact and a larger snapping radius when the two ions separate, analyses [9] indicate that for heavy projectiles the data are consistent with a difference in the two radii of as much as

4 fm. Thus, the double nuclear system shows neck formation in the final stages of the deep inelastic process. This is similar to fission. However, one must remember that at the beginning of a collision event, just after contact, a negative (thick) "neck" may be found. This is very different from fission, and the word quasifission, which is also used for deep inelastic reactions, therefore mostly focusses on the final stages of the reaction.

The fissility parameter  $Z^2/A$  plays an important role for the fission probability. Similarly, the charge product  $Z_1Z_2$ is decisive for the ratio between the deep inelastic cross section and the compound or complete fusion cross section. Estimates of the potential between the ions have been given in refs. [10] and [11]. Much attention has been given to the conditions for complete fusion, see f.ex. the review [12]. A simple static model for complete fusion cross sections is given by [13].

#### 3.2 Friction and diffusion.

The large energy loss to intrinsic excitation in deep inelastic heavy ion reactions has been successfully described by means of classical scattering models which include conservative forces and also <u>fric-</u> tion forces [14],[15].

As usual in classical mechanics, the use of dissipative forces requires introduction of phenomenological friction coefficients, f.ex. in the form of a velocity dependent force for the generalized coordinate q

$$F_{frict} = -\hat{Y}\dot{q}$$
 (8)  
The quantity  $\hat{Y}$  is called the friction  
coefficient. The use of the force (8) is  
an oversimplification in most cases. If  
at all, it is only applicable to certain  
dynamical models for systems with well de-  
fined macroscopic degrees of freedom which  
can be clearly separated from the micro-  
scopic degrees of freedom. Nuclei are  
small objects with only few degrees of  
freedom. Consequently, the separation be-  
tween macro- and micro degrees of freedom

is often problematic. It is therefore advantageous to use a more general description of the energy loss from macro degrees of freedom for nuclei. One simply speaks about energy transfer from one part of the phase space  $\{\mathcal{P}\}$  containing the relevant macroscopic degrees of freedom to the complementary part  $\{Q\}$  of the phase space. The latter part contains the remaining degrees of freedom which can be both microscopic and macroscopic. Consider as an example the energy transfer from the relative motion in coordinate  $\mathcal{F} \{\mathcal{P}\}$  to the internal motion defined as the motion of all the other degrees of freedom  $\{Q\}$  . The motion in  $\{Q\}$  need not at all be a thermal chaotic motion but can also be of a collective macroscopic nature. In such a case, it is clear that (8) can only serve as a crude model for the energy loss.

We shall now discuss the magnitude of  $\mathcal{J}$ . The friction force (8) changes the kinetic energy of a particle of mass M from  $E_i$  to  $E_f$  over a distance  $\Delta S$  according to the relation

$$S = \frac{1}{\Delta S} \sqrt{2M} \left( E_{i}^{\frac{1}{2}} - E_{f}^{\frac{1}{2}} \right)$$
(9)

In heavy ion reactions such as Ar + Th [6] the energy loss in the early stages of the relative motion is 100-200 MeV. For geometrical reasons and from analyses of angular distributions using the conservation of angular momentum, one can conclude that the value of  $\Delta S$  is small, maybe  $\sim 1$  fm. By using (9) with the mass corresponding to the reduced mass of Ar + Th, one now gets that the friction coefficient is

$$\gamma \approx 240^3 \text{ MeV/c} \cdot \frac{1}{\Delta S}$$
 (10)

Values of this order of magnitude have been found in many analyses of deep inelastic reaction data.

How can one understand such a large value of  $\gamma$  microscopically? There has so far been several theoretical attempts to calculate  $\gamma$  from microscopic theories [14], [16]. A simple classical approach which uses the picture of the colliding system as shown in fig. 1, but now with no allowance for escape of particles from the ions, leads to rather large values of  $\gamma$ 

in a simple way. The basis of the idea is given by Swiatecki [17]. The nuclei are assumed to be classical gas clouds of density Q and with velocity distribution  $\rho(v)$  which is isotropic in each nucleus. When the two ions make a close collision, there is created a window of area A between them. Now nucleons from nucleus 2 can penetrate through the window to the other nucleus 1 and vice versa (fig. 4). We assume that for the rather low relative velocities between the ions, the nucleon mean free paths remain long so that the transferred nucleons are absorbed inelastically with uniform probability over the whole volume of the receiving nucleus. Effects of the Pauli principle are neglected.



Fig. 4. The "window" A between two touching heavy ions.

For simplicity, let us think of a grazing collision situation. The speed of nucleus 1 relative to 2 is tangential and equal to  $V_{\pm}$ . The rate of nucleon-hits from 2 to 1 through the window is

$$\frac{dn}{dt} = \frac{1}{2} \varphi \, v \, A \cos \theta \, p(v) \tag{11}$$

 $dt^{-2}$ , where  $\theta$  is the inclination of the nucleon speed v. Each nucleon of mass m deposits the excess momentum  $-mV_{t}$  in nucleus 1, relative to this nucleus, and therefore the average force acting on 1 in the tangential direction is

$$F_{\pm} = -\frac{1}{2}mqAV_{\pm}\int_{0}^{\pi/2} \nabla p(v)\cos\theta \frac{dn}{2\pi}dv \qquad (12)$$

$$F_{\pm} = -\frac{1}{4}mqAV_{\pm}\overline{v}$$

By identifying (12) with the friction force (8), one gets the coefficient for tangential friction

$$Y_{4} = \frac{1}{4}m\rho A\overline{v} \tag{13}$$

Also radial friction can be calculated in a similar way. It turns out that the coefficient for radial friction is just twice (13), ref. [18], and we therefore have the radial and tangential components, in the scattering plane, of the friction force

$$\vec{F}_{frict} = \left(-\vec{V}_{r}, -\vec{V}_{t}\right) \qquad (14)$$
where
$$\vec{V} = 2V$$

 $J_{r} = 2 J_{t}$ By assuming the window area, or the contact area between the ions, to be  $A \approx 30 \text{ fm}^2$ , the average nucleon speed  $\overline{v} = 3/_{+} v_{r} \approx 3/_{6} C$ and the nucleon density  $\varphi = 0.17 \text{ fm}^{-3}$ , one gets

$$S_r = 450 \, \frac{\text{MeV}}{\text{fm} \cdot c} \tag{15}$$

This is big but still smaller than the phenomenological experimental values of  $\mathcal{J}_r$ . Other friction mechanisms could therefore be important.

The friction mechanism responsible for (14) is adequate for dissipation of energy in the early stages of the deep inelastic reaction where the window is open. This happens in both early and late stages of the reaction whenever there is solid contact between the ions.

In the later stages of the reaction where the necking happens, the phenomenological analyses show a large friction too. Also here other friction mechanismsmay set in. One such mechanism is the dissipation caused by an energy loss from particle collisions with a moving surface [18] (another kind of "one body friction"). It seems adequate for explaining the friction in fission and vibrations of not too high energy, but the mechanism may also be important for deep inelastic reactions both in the early stages and in the stages of necking. Another possible mechanism is the "two body friction". It is analogous to ordinary viscosity in liquids and it becomes important for high excitation energy where the nucleon mean free path decreases.

In order that (14) is valid, one must

assume that  $|\vec{\nabla}|$  is small compared to  $\vec{v}$ . Otherwise the velocity distribution p(v)can change so much during the collision that the velocity averaging becomes wrong. This condition for the magnitude of the relative velocity can be expressed in terms of a condition for passing times

$$\frac{2R}{\overline{\nu}} < \frac{2R}{|\vec{V}|} \tag{16}$$

There is a number of characteristic times for nuclei which are of importance for the dynamical properties of the colliding system. Some of the times are characteristic for the microscopic structure of the ions and some can be more easily varied from outside by f.ex. changing the bombarding energy. We shall not make a complete list of times here, but only mention a few important ones (Table I).

Table I.

•	Times		can be varied by changing
^	time between two nucleon scatterings	$\tau_{r} = \lambda_{mean} / \overline{v}$ free path	nuclear ex- citation energy
times	time for nu- cleon to pass nucleus	$\tau_2 = 2R/\overline{v}$	nuclear mass number
ernal	time for sound wave to pass nucleus	$T_3 = 2R/c_{sound}$	nuclear mass number
< int	time for one vibrational oscillation	$T_{4} = 1/\omega_{oscill}$	multipolarity and nuclear mass number
times >	passing time for ions	$\mathcal{T}_5 = 2R/ \vec{V} $	bombarding en- ergy and nu- clear mass number
< external	passing the nuclear sur- face of thick- ness b	$\tau_6 = b/ \vec{v} $	bombarding energy

Usually the "internal" times are ordered in the following way

$$\tau_1 \approx \tau_2 < \tau_3 < \tau_4 \tag{17}$$

,

while the "external" times  $au_5$  and  $au_6$ which depend on the bombarding energy, can be anywhere in this range. A slow (gentle) heavy ion reaction has  $\mathcal{T}_5 > \mathcal{T}_4$ while the deep inelastic reactions have  $au_3 < au_5 < au_4$  . Both sets of inequalities are in agreement with (16), i.e.  $au_2 < au_5$  . A fast reaction with nuclear compression . Such reactions are dishas  $T_5 < T_3$ cussed in section 4. The random nature of the nucleon transfer leading to dissipation of energy has one more consequence. It gives rise to diffusion of particles in such a way that the deep inelastic reaction products exhibit broad mass distributions. The diffusion was described by Nörenberg [19] in terms of the Master equation and the Fokker Planck equation. See also [20].

So far, we considered only simple models for energy loss for which the velocity proportional friction (8) is adequate. It is worth noticing that the big dissipation (10) may in fact occur via the macroscopic degrees of freedom in  $\{Q\}$  [21],[22]. In this case, (8) can no longer be used and we have the more complicated situation which was mentioned in the first part of this section.

As it was written in section 2.1, one expects that multiparticle direct reactions become more important as the nuclear excitation energy exceeds the nuclear "boiling" point. This does not mean that binary processes are expected suddenly to disappear at this energy. They will probably remain at much higher bombarding energy, especially for the distant (grazing) collisions. One of the interesting problems at the higher energies is if the still remaining binary deep inelastic processes are also "fully relaxed" at higher energy. Formula (9) makes room for the lack of full damping for big systems at higher energy. There seems to be some evidence af lack of full damping in the reaction Kr + Pb at 718 MeV while Xe + Pb at 1120 MeV still exhibits full damping [23]. This problem requires further investigation.

4. Hard heavy ion reactions.4.1 NucLear compression.

Already as early as in 1959 it was suggested [24] that it might be possible to compress nuclear matter in nuclear reactions of sufficiently high energy. Further theoretical studies of these possibilities were, however, not started until 1973 [25] - [28] and the interest for the compression was greatly increased after Lee and Wick [2] suggested the possible existence of stable highly dense nuclear matter.

So far, there has only been two ways of obtaining nuclear matter at high pressure. One is in neutron stars where the gravitational field compresses the system. The other is in heavy ion reactions at supersonic speeds, called hard heavy ion reactions in this lecture. Both methods are difficult to utilize. The second one, because the high compression requires so high bombarding energy that the compressed system is strongly heated and disintegrates, probably in many fragments, soon after the ion-ion impact. As we shall see later, the compression ratio in the hard heavy ion reaction (ratio between the densities in the compressed matter and the cold matter) is presumably not very high, only of the order of 2 - 4, and all research requiring higher nuclear densities can therefore not be performed in the laboratory, as far as one can see at the moment.

#### 4.2 Experiments.

So far, there have only been made a few H.I. collision experiments at these high speeds. Emulsion experiments [29], fig. 5, show that the events give rise to "stars" of emitted nuclear fragments. Some angular distributions of reaction products are shown in figs. 6 and 7. See also [33]. Presently, it is not possible to conclude from these data how much the nuclear matter has been compressed in the reactions. It has been claimed [32] that the peak at forward angles, fig. 7, could be a specific signal from shock front motion in the colliding system created by a moving local  $\pi$  -meson condensate. Statistical microscopic calculations (see sections 4.3 and 4.4) however, show that sharp shock fronts do not exist and for this reason the shock front interpretation seems problematic.



Fig. 5. A "star" event from an emulsion bombarded with 1.8 GeV/nucleon <sup>40</sup>Ar ions. [29]



Fig. 6. Experimental differential cross section  $d6/d\theta$ , measured by Lexan foil detectors, of <sup>3</sup>He reaction fragments from  $16_0$  + Ag at 1.05 GeV/nucleon LAB-energy. [30]

In the experiments there are observed stars with prongs which by their momentum can be devided in two clearly distinguishable groups, one for target-like products, and one for projectile products. It has been suggested [1] that these events correspond to peripheral collisions where the energy transfer to intrinsic excitation is moderate, but still so big that the fragments can disintegrate in a number of pieces.



Fig. 7. Reaction products for central or almost central collisions of 0.87 GeV/nucleon 160 on AgCl crystals measured by counting tracks in "stars" of more than 3 prongs. The curve is a calculated evaporation distribution. [31]

From the "star" events, one has also identified a number of charged particles from more evaporation-like processes. They may have been produced as secondary products from excited fragments coming from either binary or multi body fragmentation primary processes.

Already from these few remarks it can be seen that the experimental situation is rather chaotic. Whether or not there has been compression in the processes cannot immediately be concluded on the basis of the data. What can be said with confidence is the rather trivial remark that the reactions are to a high degree of the explosion multiparticle type which according to fig. 2 should exist for all energies above the nuclear boiling point.

## 4.3 Hydrodynamic compression.

The experiments are vague with respect to conclusions about compression, but on this point the theories are more specific. Before going into details about the calculations, it is worth pointing out that when one compresses ordinary gases and liquids,

it can be done by means of a piston in a cylinder. In this way one can easily obtain very high densities. It is also easy to deal with the cooling of the compressed matter via heat conduction from the cylinder to a surrounding heat absorbing medium. The situation is much more difficult in nuclei. The only way to compress the matter is via the correlated momenta in the projectile and target in a hard heavy ion collision. The nuclear surface acts only in a very weak way as surrounding walls. This means that the system has practically free surfaces and can easily become disintegrated after a short compression period during the collision, and the cooling is done by emission of particles which causes a large loss of mass from the compressed zone. It is therefore not very probable that the reaction product should finally consist of cold highly compressed nuclear matter even if this phase is a possible phase of nuclear matter.

The first calculations of the compression in heavy ion collisions were made by using hydrodynamics [25] - [28]. In hydrodynamics the Hugoniot theory for strong shock formation can be used. It says that for a gas of point particles obeying Bolzmann statistics (this is also the case for a highly excited Fermi-gas, such as the nuclear system) the maximum unrelativistic compression ratio for the collision of two infinite slabs is

$$\mathcal{V}_{max} = \frac{C_p + C_V}{C_p - C_V} \tag{18}$$

This ratio is obtained when the incident velocity is much larger than the speed of sound in the matter. For a monatonic Bolzmann gas the ratio of specific heats is  $C_p/C_v = 5/3$ , and therefore  $\gamma_{max} = 4$ .

For colliding nuclei one can apply the Hugoniot theory with proper geometrical and dynamical boundary conditions and one obtains in this way compression ratios of same order of magnitude as (18). For energies in the relativistic region the calculated compression ratio may increase, but because of a relatively long nucleon momentum decay length at these energies, the hydrodynamic assumption is bad. Phase changes in the material during the compression could change (18). An endothermic process in the matter, for example, increases  $\gamma_{max}$ .

The condition for the validity of hydrodynamics is that the mean free path of the particles in the fluid can be neglected relative to the overall dimensions of the fluid. This condition is clearly not well fulfilled in nuclei because the mean free path is around 2 fm in the uncompressed matter. All conclusions which rely heavily on the existence of sharp, shock fronts may therefore not be true.

# 4.4 Statistical microscopic theory of compression.

In order to solve the problem of the fluctuations and in order to relate the dynamics of the hard collision directly to the nucleon-nucleon interaction rather than through an equation of state, several groups have recently independently started calculations of hard heavy ion collisions in a statistical microscopic theory. [34]-[38].

The idea of the various models which differ in techniques and sophistication, but not in the basic philosophy, is the following. The nuclei are described as collections of particles which move according to the classical Newtonian laws. The heavy ion collision is simulated by calculation of each nucleon-nucleon collision successively. The distribution of nucleon positions and velocities vary as functions of time and they are averaged according to some ad hoc specifications in order to have smooth functions of densities, spectra, etc.

We shall here report on some calculated results from a model which was set up by the Copenhagen-Oak Ridge group [36]. The cold nuclei are spherical collections of free point-like particles at relative rest. The nucleon-nucleon scattering cross section was chosen as 25 mb and with a spherical symmetric angular distribution (randomly generated) and conservation of energy and momentum microscopically and angular momentum macroscopically.

## C5-204



Fig. 8. Calculated positions of nucleons in a head on U + U collision. Each projection plot is labelled with the number of already occurred nucleon-nucleon scatterings and with the time in units of  $R/v_0$ where  $2v_0$  is the relative speed of the two nuclei.

The result of a U + U collision at four different times is shown in fig. 8, and the resulting central density in fig. 9. Figs. 10 and 11 show mass distributions of the compressed system along the beam direction and along a direction through the center of mass orthogonal to the beam direction. From fig. 10 it is seen that there is no sharp shock front. In fig. 11 there is a small increase of the density at the distance 2-3 fm from the center of mass. This indicates that there is a tendency, in this collision, of a torus-like compressed zone at an intermediate stage of the reaction.

The above mentioned treatment does not apply to energies close to the Fermi energy. In that case the average nuclear potential and the intrinsic kinetic nucleon energy should be included. Also the effect of the Pauli principle cannot be neglected. These effects have been studied [34][35][37]. The conclusions are not very different from the present ones except that the binding of the system makes the explosion effect less dramatic than in our purely repulsive model, because bigger fragments can be created. Because the Broglie wave length in the nucleon-nucleon collision exceeds the inter nucleon distance, coherence effects could also arise, but the coherence is, of course, not possible to study in a classical model.



NUMBER OF ALREADY OCCURRED NUCLEON SCATTERINGS

Fig. 9. Calculated time dependence of the compression ratio  $q/q_o$  near the CM for a head on U + U collision. The four curves differ only in their Monte Carlo numbers. The lower time scale refers to the curve marked with a circled 1.

It is hoped that the microscopic models will eventually be developed so far that signals of specific effects in the nuclear collisions can be identified experimentally. Such specific effects are f.ex. the nuclear compression and possible condensates [2], [4], [5].

5. Light particle induced reactions.

The energy deposit in a heavy ion reaction is of the order of  $(A_1 + A_2) \cdot \mathcal{E}(CM)$ (6) which can easily be some GeV in a hard heavy ion reaction. Reactions with such big energy deposits have for a long time been studied experimentally by high energy proton and  $\alpha$ -particle induced spallation reactions, see f.ex. [39]. One finds that the product masses range over the whole region from A = 1 to  $A = A_t + A_p$ . The mass distributions depend on the bombarding energy and seem to become almost constant above a certain bombarding energy (the plateau value).



Fig. 10. Densities calculated along the collision axis z , at 3 different times during collision. At each time, the circle-diagrams and long-dashed lines describe two colliding non-interacting spheres of density 90 The calculated • densities are averaged within finite volume elements, and then further averaged over 10 collisions differing only in their random numbers. For  $\rho_+(\Delta \tilde{r})$ the volume elements were small cylinders, symmetric around the collision axis z, each of radius  $\Delta \tilde{r}$ , z-span 1.13 fm, and mean z=|z|made a further average over two similar cylinders at z = +|z| and -|z|.



DENSITY IN PLANE HALF-WAY BETWEEN INITIAL NUCLEI IN HEAD-ON U+U COLLISIONS



This is important to notice when one compares the mass distributions from light particle spallations with those of heavy ion reactions, with a similar energy deposit. Although the energy deposit of a light-particle induced reaction could be as high as in some hard heavy ion reactions, the physics of the two types of re-

C5-206

action is expected to be less violent than the heavy ion reaction of the same energy because of the correlated heavy ion momentum. This momentum is a factor  $A_1^{1/2}$ times larger than the momentum for a proton of the same energy as the heavy ion. It is therefore expected that the proton induced reaction will proceed in a way which is very different from the heavy ion reaction. This is well known from classical mechanics. The small bullet just makes a hole in the target but a big slow bullet with the same energy can make a lot of disturbance.

## 6. Conclusions.

An old Danish word says that the most difficult thing to predict is the future. We must face this when we are asked to tell what GANIL can give us. In fact, if we could predict what is going to be observed, there would be no need of building the accelerator. We shall therefore be satisfied with the modest result that the studies below and above the relavant energy range have given some insight into what general type of experimental set-up is needed.

First, I will emphasize that we to a high degree are confronted with multiparticle events and therefore the counter systems should be highly sophisticated with possibilities of various kinds of multiparticle coincidence and correlation measurements, both for larger and smaller fragments from the nuclear boiling or explosion process. Whether the system becomes compressed or not is not easy to establish experimentally, but it seems that only for light projectiles there is a

Bibliography.

- [1] H.H. Heckman, D.E. Greiner, P.J. Lindstrom, F.S. Bieser, Phys. Rev. Lett. <u>28</u>(1972)926. See also refs. [31]-[33].
- [2] T.D. Lee and G.C. Wick, Phys. Rev. <u>D9</u>(1974)2291.
- [3] H.C. Britt and A.R. Quinton, Phys.Rev. <u>124</u>(1961)877.

chance of obtaining compression with GANIL. Unless one gets a direct way of measuring what is going on inside the highly heated central zone, one cannot answer questions about this zone directly. One way of studying early stages of the HI collision is by detecting highly energetic protons or neutrons emitted by the transfer mechanism described in section 2.1. Various ways of loosing energy to intrinsic motion are expected to occur, depending on how fast the projectiles are, relative to the typical nucleon speeds inside the nuclei, and maybe some characteristic changes of the reaction patterns occur when the external passing times coincide with characteristic intrinsic times in the nuclei.

The conventional deep inelastic reactions are expected to occur for the larger impact parameters even at energies above the "boiling" point. In this connection it would be useful to establish if there exist upper limits of full relaxation as function of charge, mass and energy. The GANIL energies seem to be ideal for such studies. Similarly, it would be of interest to find the upper limits for complete fusion. Already now there exists a large amount of data which set angular momentum, charge and mass limits for fusion, but GANIL would be useful to establish how the conventional complete fusion is limited by the excitation energy.

#### Acknowledgements.

The author wants to express his gratitude to S. Garpman, J. Randrup and A. Winther for inspiring discussions and suggestions.

- [4] A.B. Migdal, O.A. Markin, I.I. Mishustin, Sov.Phys. JETP <u>39</u>,212(1974).
- [5] W.Weise and G.E. Brown, Phys. Lett. <u>48B</u>(1974) 297.
- [6] A.G. Artukh, G.F. Gridnev, V.L.Mikheev,
   V.V. Volkov and J. Wilczynski, Nucl.
   Phys. A215(1973)91.

- [7] J. Wilczynski, Phys.Lett. 47B(1973)484.
- [8] J. Péter, C. Ngô, B. Tamain, J. de Phys. <u>36</u>(1975)L23,
  - C. Ngô, thesis, Orsay (1975).
- [9] J.P. Bondorf, J. R. Huizenga, M.I. Sobel,
   D. Sperber, Phys. Rev. C <u>11</u>(1975)1265.
- [10] J. Blocki, J. Randrup, W.J. Swiatecki and C.F. Tsang, LBL-5014 preprint (1976).
- [11] P.R. Christensen and A. Winther, Phys. Lett. to be published.
- [12] M. Lefort, Rep.Prog.Phys. <u>39</u>(1976)129.
- [13] R. Bass, Phys.Lett. <u>47B</u>(1973)139.
- [14] R. Beck and D.H.E. Gross, Phys.Lett.47B. D.H.E. Gross and H. Kalinowski, Phys. Lett. <u>48B</u>(1974)302.
- [15] J.P. Bondorf, M.I. Sobel, D. Sperber, Phys. Rep. <u>150</u>(1974)83.
- [16] H. Hofmann and P.J. Siemens, Nucl. Phys. <u>A257</u>(1976)165.
- [17] W.J. Swiatecki, J. de Phys. Suppl. <u>33</u>(1972) C5 - 45.
  W.J. Swiatecki, Contribution to the International School Seminar on Reactions of Heavy Ions with Nuclei and Synthesis of New Elements, Dubna (1975)
- [18] J. Blocki, Y. Bone, J.R. Nix, J.Randrup, M. Robel, A.J. Sierk, W.J. Swiatecki, to be published.
- [19] W. Nörenberg, Phys.Lett. 53B(1974)289.
   W. Nörenberg, Z. Phyzik, A274(1975)241.
- [20] L.G. Moretto, J.S. Sventek, Phys.Lett. <u>58B</u>(1975)26.
- [21] H.H. Deubler and K. Dietrich, Phys. Lett. 56B(1975)241.
- [22] R.A. Broglia, C.H. Dasso, A. Winther, Phys. Lett. <u>53B</u>(1974)301.
- [23] R. Vandenbosch, M.P. Webb, T.D. Thomas, Phys. Rev. Lett. <u>36</u>(1976)459.
  R. Vandenbosch, M.P. Webb, T.D. Thomas and M.S. Zisman (to be published).

- [24] A.E. Glassgold, W. Heckrotte, K.M. Watson, Ann. Phys. 6(1959)1.
- [25] G. Chapline, M. Johnson, E. Teller, M. Weiss, Phys.Rev. <u>D8</u>(1973)4302.
- [26] C.Y. Wong, T.A. Welton, Phys. Lett. <u>49B</u>(1974)243.
- [27] W. Scheid, H. Müller, W. Greiner, Phys. Rev. Lett. <u>32B</u>(1974)741.
- [28] M.I. Sobel, P.J. Siemens, J.P. Bondorf, H.A. Bethe, Nucl. Phys. <u>A251</u>(1975)502.
- [29] H.H. Heckman (1974), reported by R.Stock in "Heavy Ion Collisions", R. Bock Ed., North Holland Publishers, to be published.
- [30] A.M. Poskanzer, R.G. Sextro, A.M. Zebelman, H.H. Gutbrod, A. Sandoval, R. Stock, Phys. Rev. Lett. <u>35</u>(1975)1701.
- [31] H.G. Baumgart, J.U. Schott, Y.Sakamoto,
  E. Schopper, H. Stocker, J. Hofman, W. Scheid
  W. Greiner, Z. Physik <u>A273</u>(1975)359.
- [32] J. Hofman, H. Stöcker, U. Heinz,
   W. Scheid, W. Greiner, Phys.Rev.Lett.
   <u>36</u>(1976)88.
- [33] R. Kullberg and I. Otterlund, Z. Physik <u>259</u>(1973)245.
- [34] A.D. McKellar, L.Wilets, (to be published).
- [35] A.R. Bodmer and C.N. Panos, (to be published).
- [36] J.P. Bondorf, P.J. Siemens, H. Feldmeier, S. Garpman, E.C. Halbert, (to be published).
- [37] A.I. Baz, S.M. Kiseljev, J.E. Pokrovskij, L.V. Chulkov (to be published).
- [38] K.K. Gudima, V.D. Toneev, abstract194, this conference.
- [39] G. Rudstam, Nucl. Phys. <u>A126</u>(1969)401, Z. Naturforsch. <u>21a</u>(1966)1027.

C5-208