NUCLEAR-PHYSICS RESEARCH WITH HEAVY IONS IN THE 10 TO 30 MEV/NUCLEON RANGE: BIRTH AND DEATH OF HOT NUCLEI

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ABSTRACT

The physics of collisions between complex nuclei at intermediate energies, 10 to 30 MeV/nucleon, is treated as a special case within the general and actively investigated field of many-body physics. This special case presents an extreme diversity of phenomena, and the related questions, for the major part, can be grouped into three complexes of questions, the first concerning the transition from ordered to statistical (thermal) motion, the second the response of nuclei to increasing heat, and third the response of nuclei to increasing angular momentum at low temperature. Examples of questions belonging to complex 1 and 2 are discussed: How can one produce hot nuclei? And how do they decay?

INTRODUCTION: WHY THE FIELD IS SO RICH

This contribution has the task to represent, on the user side, amongst various disciplines, the field of nuclear physics, historically the first and longtimes the most important user of accelerators. Within this field I restrict myself to the physics of collisions between complex nuclei ($A \geqq 10$), and furthermore to collisions at intermediate bombarding energies, between 10 and 30 (or somewhat more) MeV/nucleon. This field is extremely rich and presents an astonishing variety of phenomena. In order to indicate the reasons of this richness and to make you feel the flavor of the field I have to recall the characteristics of its two neighbouring and more simply structured fields, those of low-energy and high-energy collisions, the properties of which intermerge here to produce the full complexity of the observable phenomena.

A low-energy reaction typically is performed with projectiles of 5 MeV/nucleon energy, or below. In such a case the velocity of the nucleons inside the nuclei due to the Fermi motion, which implies a mean kinetic energy of 25 MeV per nucleon, is large against the velocity of the relative motion between the colliding nuclei - this is the decisive criterion. Thus, while the internuclear distance changes by 1 fm, compared to about 10 fm nuclear diameter, the fastest nucleons traverse their respective nucleus and adjust their orbits to the changed field of forces, the message of the field change due to the collision is transmitted over the whole nucleus, and the nucleus consequently reacts as a whole. In other words, the whole process can be described by a few macroscopic or collective variables: the internuclear distance, the quadrupole deformation of the two nuclei or the total complex, one or two higher deformations or a neck variable, the mass asymmetry of the two nuclei. In short, we deal with the physics of nuclear "liquid drops", the single nucleons do not play an explicit role, the smooth "mean field" constituted by the superposition of all nucleon-nucleon forces dominates the scene.

The opposite scenario is encountered at high energy, say 1000 MeV/nucleon. Now the Fermi motion of the nucleons is negligible, compared to the fast relative motion of the nuclei, and the mutual binding between the nucleons inside a nucleus, resulting in about 8 MeV binding energy per nucleon, is irrelevant, too. One may visualize the two nuclei as two clouds of independent bullets which encounter each other. Where the two clouds overlap, individual nucleons of the one collide with individual nucleons of the other, both being kicked out of their respective mother cloud. The non-overlapping remainder of each cloud continues its way and for quite some distance it will not even have taken notice of the fact that a part of it has been cut out - one speaks of the projectile or target "spectator", respectively. The kicked-out-nucleons are found inbetween the two spectators, both in ordinary as in velocity space, and form a sort of rapidly expanding dilute gas, often called "fireball".

At intermediate collision energies, now, the velocity due to Fermi motion is comparable to the common velocity of the projectile nucleons (or bombarding velocity), and the former, being isotropically distributed, may have components perpendicular to the projectile velocity also comparable in size to the latter. Hence, if the two colliding nuclei touch laterally, while passing each other, part of their nucleons will penetrate into the respective other nucleus and traverse it and partly be contained and bent around by the mean field of that nucleus. These nucleons constitute a collective lateral flow not developped in the high-energy limit. On the other hand, since Pauli blocking is not as effective as at very low energies, these traversing nucleons may scatter at the encountered nucleons of the nucleus entered, one, two or more times, in a manner that is necessarily statistical. Thus their collective, ordered motion gradually is transformed into disordered, statistic motion - the kinetic projectile energy becomes thermalized. Both mechanisms together make that potentially all nucleons of the binuclear complex become involved in the process, and we have a complicated interplay between ordered collective motion and statistical single-nucleon motion. These conditions make the study of intermediate-energy nucleus-nucleus collision require the full aparatus of MANY-BODY physics. Within the general frame of many-body physics, the nuclear collision complexes constitute objects of particular interest because of some special features which are not found elsewhere in physics (for instance small and well controllable particle number, combination of short-range and long-range forces, interplay between classical deterministic, classical statistic and quantum-mechanical dynamics, etc.).

The major part of questions to be studied in the field may be grouped into three complexes:

1. Questions concerning the transition from ordered states over chaotic to statistical equilibrium states.

2. Questions concerning the response of nuclei to increasing values of some macroscopic variables, notably heat (temperature).

3. Questions concerning the response of nuclei to increasing rotation velocity, at low temperature (in principle a subcomplex of 2, developped into a field of its own).

In the following I will discuss two intensively studied problems out of complex 1 and 2.

HOW MUCH OF THE PROJECTILES KINETIC ENERGY CAN BE CONVERTED TO THERMAL MOTION?

As indicated, this question belongs to complex 1. In principle there are several variables which may undergo a transition from an ordered to a statistical distribution, notably

kinetic energy,
angular momentum,
neutron excess,
mass asymmetry, ...

And there are several questions concerning each transition, e.g.:

What is the relaxation time?
Do partial equilibria exist?
Do local equilibria exist?
Is there a limiting value of that variable in equilibrium?

This constitutes a quadratic matrix of problems, complicated further by the anticipated coupling between variables. In this section I treat the example of the kinetic-energy variable, asking whether there exists a maximum value of it which may be converted into heat via dissipation in the nuclear collision.

To investigate this one has to measure the "heat" or excitation energy contained in the nucleus/nuclei after the collision. Alternatively, if the two nuclei essentially merge into one "fused" nucleus one may look for its momentum, since all projectile nucleons which equilibrate their kinetic energy also impart their momentum to the final nucleus. So one has to measure the velocity of the latter, and this is done most effectively for fissioning (i.e. heavy) final nuclei. In the system of a fissioning nucleus, the two fragments after fission fly, of course, apart back to back, with 180° rel. angle. If the system moves, then the two fragment velocity vectors in the laboratory are bent forward and together. The deviation from 180° is a measure of the systems velocity.

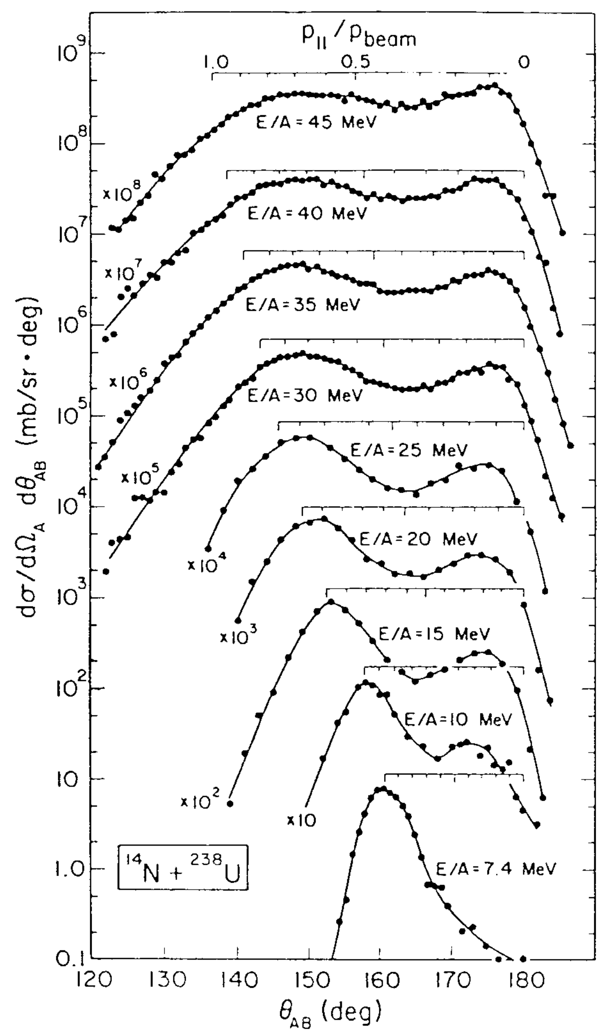

Fig. 1: Folding angle distributions for fission fragments from collisions of ^{14}N projectiles with a ^{238}U target at different projectile energies E/A. (From Fatyga et al. 1).

Fig. 1 shows some measured distributions of the folding angle between the fission fragment directions. Most distributions have a maximum at the right side due to a concentration of events at angles close to 180°, indicating small momentum transfer: here the

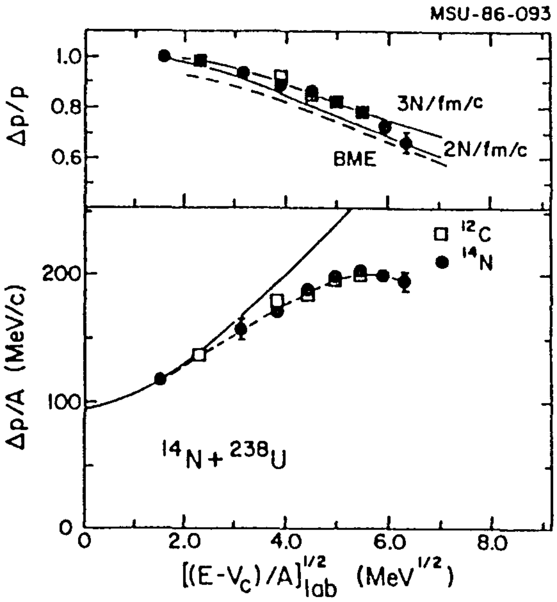

Fig. 2: Most probable momentum transfer extracted from fig. 1 for the fusionlike reactions, as function of the projectile velocity (measured by the square root of the kinetic energy above the barrier B). (From ref. 1).

target nucleus ^{238}U is just knocked a bit in a grazing collision and then fissions. More relevant for our case is the other maximum on the left side indicating collisions with high-momentum transfer: here the ^{14}N projectile with its entire mass and momentum is absorbed by the target, at least at lower projectile energies, as may be red off from the $p_{\|}/p_{beam}$ scales: for $p_{\|}/p_{beam} = 1$ the total projectile momentum p_{beam} is found in the beam axis component of the residue nucleus momentum, $p_{\|}$. (The broadening of this peak is partly caused by neutron evaporation changing the recoil direction.) One notes also, however, that starting with projectile energies of 20 MeV/nucleon the most probably transferred momentum falls more and more behind the full projectile momentum and from 35 MeV/nucleon on stays at a constant value.

Fig. 2 shows the most probable momentum transfer of the fusionlike peak as function of the projectile velocity; one sees clearly the saturation or even a tendency of decrease on the high-energy side. This all seems to indicate that the mechanism of energy/momentum dissipation becomes less effective at higher relative velocity.

However, these results could find a different and rather exciting interpretation, promoted essentially because of a similar experiment performed with ^{40}Ar projectiles. Fig. 3 shows on the right the obtained fission folding-angle distributions. Again the position of the fusionlike peak stays at about the same angle (110°) when the energy rises above 30 MeV/nucleon.

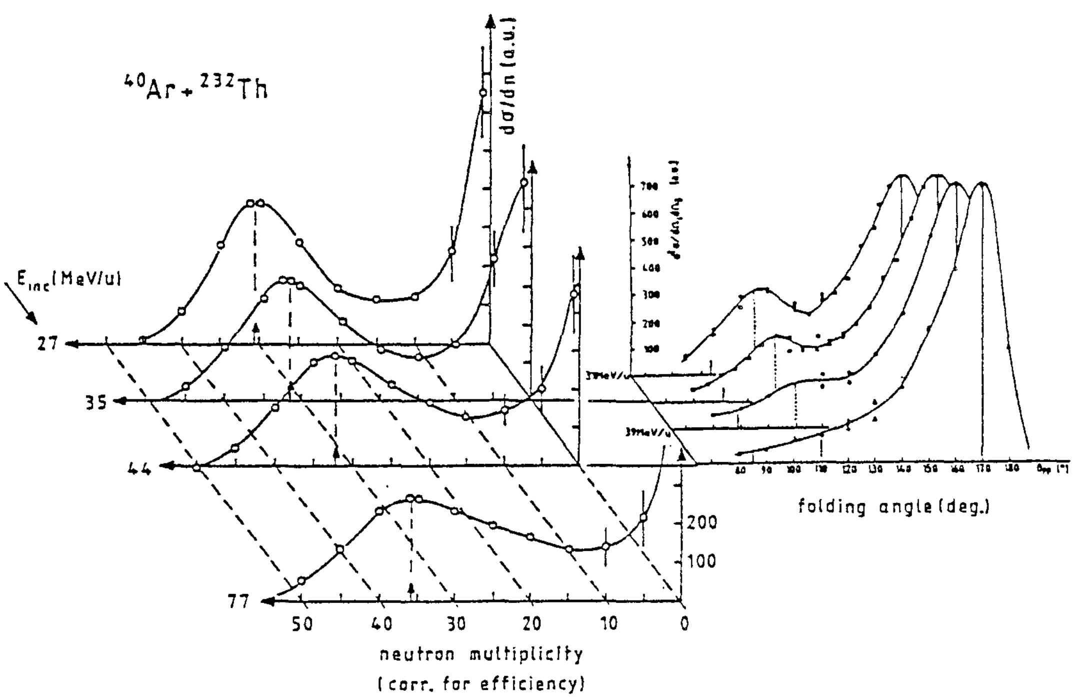

Fig. 3: Neutron number distributions (left, ref. 2) in comparison with fission fragment folding angle distributions (right, ref. 3), both for the ^{40}Ar + Th system at various projectile energies between 27 and 77 MeV/nucleon.

But in addition the cross section in this peak dies out gradually, at the highest energy the probability for observation of a fusionlike process just disappears. This result, too, could imply that the mechanism of energy/momentum dissipation becomes less and less effective and only reactions with low energy conversion survive. But equally well, the dissipation could stay effective, the excitation energy would continue to rise with increasing bombarding energy, yielding hotter and hotter nuclei - only that these, from a certain excitation energy on, would not decay any more by binary fission and thus dissappear from the fission correlation as in fig. 3 (right). Now the speculation was that the decay mode to replace binary fission at high temperature should be the famous "multifragmentation"; the hot nucleus explodes instantaneously into many (more than two) pieces. The controversy between the contradictory interpretations sketched was quite vehement and lasted for some years.

Meanwhile, this controversy has found at least a partial solution. This was achieved by measuring the excitation energy deposited directly without relying on the fission decay. I take this occasion to mention a very effective experimental method to measure the excitation energy. It was promoted for the physics of nuclear collisions by U. Jahnke at the Hahn-Meitner-Institute Berlin, and it exploits the "neutron ball", a 4π detector for neutrons of close to 100% efficiency. It is able to determine the number of neutrons emitted in each single reaction event. Since in heavy nuclei (like those found in the collisions of figs. 1-3) the overwhelming part of the excitation energy is consumed by the evaporation of neutrons, the number of these ejectiles constitutes a direct measure of the quantity in question. Fig. 3 displays in its left half, for the same combination of colliding nuclei, $^{40}Ar+^{232}Th$, the distribution of the neutron number, with the ordinate axis pointing to the left side in order to have a parallel representation in both halves of the figure, the large momentum/energy deposit always being to the left. One immediately recognizes in the neutron number distribution, too, the peak representing fusionlike reactions with large excitation energy release, and, in contrast to the fission angle distributions, this peak stays with effectively unchanged intensity up to the highest projectile energy studied, 77 MeV/nucleon.

So apparently energy dissipation continues to be effective and to produce hot nuclear systems. There are two further important messages in these data. The first one is expressed by fig. 4 which shows the evolution of the excitation energy produced in the fusionlike reactions (the most probable exitation energy) with increasing bombarding energy. One notes a monotoneous rise of the excitation energy, but there is a distinct flattening of this curve beyond ~ 25 MeV/nucleon projectile energy, corresponding to the saturation of momentum transfer discussed above. As a consequence, if one wants to sample nuclei and their behaviour over a large range of excitation energy, an accelerator with 25 MeV/nucleon maximum projectile energy is very effective yielding up to 650 MeV excitation in the present case. To further increase the excitation by some 20 percent requires an additional order of magnitude in beam energy.

The second consequence: Since the hot nuclei formed do not appear in the binary-fission channel, evidently they decay in a different mode. Is this then really the anticipated multifragmentation? Or could it be that

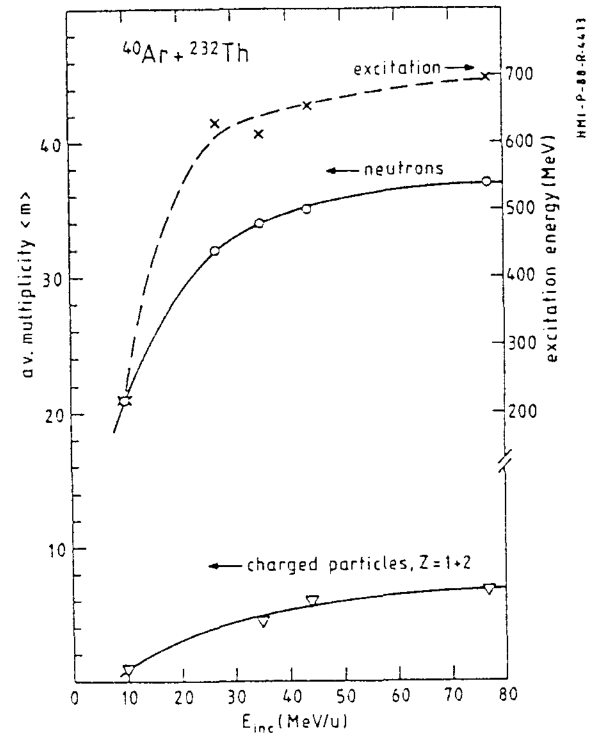

Fig. 4: Most probable or mean neutron multiplicity (circles) and corresponding excitation energy (crosses) for the fusionlike component in fig. 3 (left) as a function of incident energy (from ref. 2).

the nucleus is so hot and evaporates light particles so rapidly that it, before being sufficiently elongated on its way to fission, has already become too small to fission at all and ends as an evaporation residue? Here we are already right in the middle of the second question I wanted to address.

HOW DOES THE DECAY MODE CHANGE WITH INCREASING HEAT (EXCITATION ENERGY)?

This is one of the questions belonging to complex 2 mentioned in the introduction and concerning the response of nuclei to increasing values of macroscopic variables like mass, neutron excess, angular momentum and, notably, excitation energy. One may inquire about changes of static and dynamic nuclear properties and of decay modes, limiting values of the macroscopic variables the nuclei can withstand without instantaneous decomposition, the occurence of phase transitions etc. In particular the interesting problem of phase transitions is intimately related to changes of the decay mode. This is demonstrated by theoretical calculations of D.H.E. Gross and coworkers (4) from the Hahn-Meitner-Institute, the results of which are displayed in fig. 5. For the example of a medium heavy nucleus, ^{131}Xe, it gives the correlation between excitation energy E* and temperature T, obtained by a microcanonical statistical calculation. The phase space used in this calculation contains all possible partitions of the nucleus into all possible fragments.

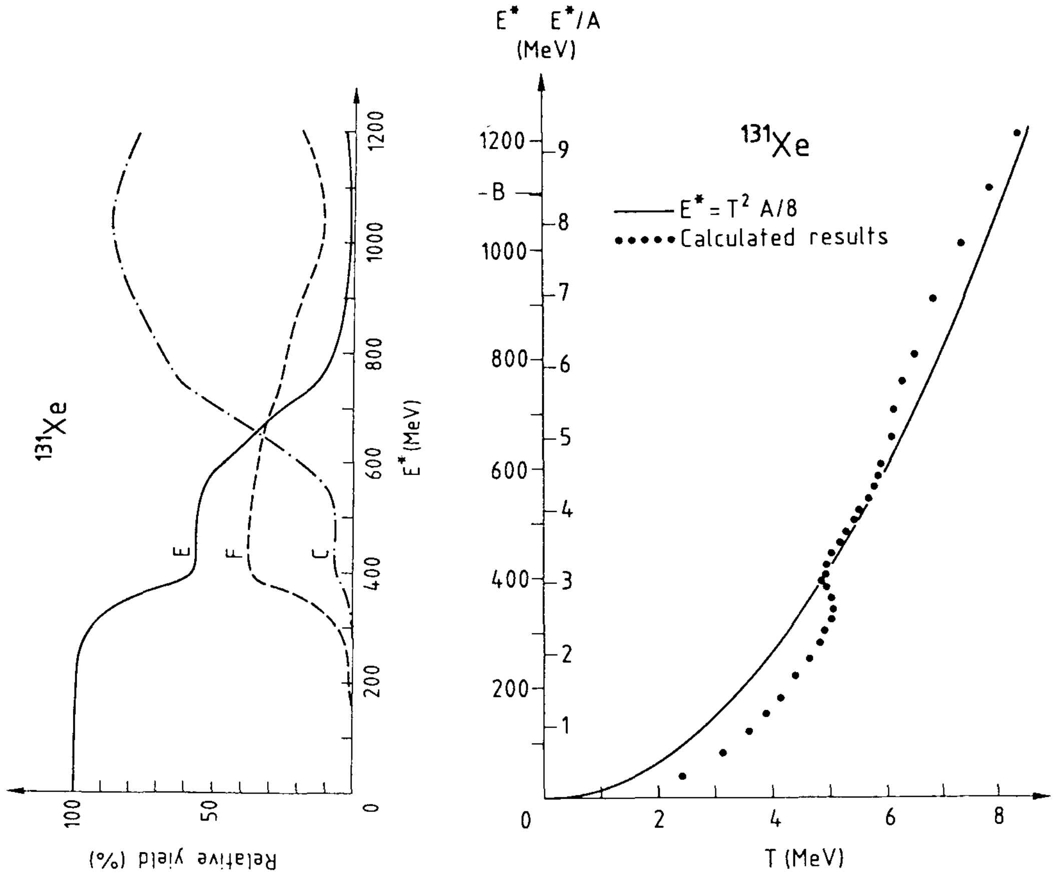

Fig. 5: Correlation between temperature and excitation energy (right part) and relative probability of partitions with one major fragment (E), two (F) or more (C) major fragments as function of excitation energy (left part). These are results of microcanonical statistical calculations (4) for the nucleus ^{131}Xe.

The correlation exhibits a pronounced step at 5 MeV temperature, typical of a phase transition. There one may increase the heat/excitation energy of the nucleus without further rise of temperature, quite as in the case of water at the boiling point at which, by additional heat, it is in corresponding proportion transformed into vapor, the whole staying at the same temperature. Now what is the character of the phase transition in our nuclear case? This may be recognized from the left part of the figure showing on the same excitation energy scale the evolution of the probability to find partitions with one big fragment besides several small ones (curve E, reminding of "evaporation"). Precisely at the phase transition step between 300 and 400 MeV excitation this probability drops drastically, giving way to a corresponding rise of probability for two major fragments (curve F, reminding of "fission"). Evidently the added excitation energy is consumed to create new surfaces inside the nucleus, instead of raising the temperature. The surface tension, consequence of the short-range nucleon-nucleon attraction, is overcome by the Coulomb repulsion. Thus the obtained nuclear phase transition is possible only because of and a demonstration of the particular role played by the long-range Coulomb force. The long range of this force implies that the potential energy is not proportional to the system volume (at constant density). Technically speaking, the thermo-dynamical potentials are "not extensive", a particular case in statistical mechanics, which makes nuclei specially interesting objects within many-body physics.

Incidentally, a second, somewhat less pronounced phase transition is indicated at 6 MeV temperature in fig. 5. It is connected with the onset of fragmentation into three or more major pieces (curve C, for "cracking"). It is tempting to associate this with the "multifragmentation" repeatedly entering our discussion. Many experimenters all over the world are searching for such a decay. One obvious thing to do is to look for the number of (bigger) fragments going out after a nuclear collision. As an example, fig. 6 displays the results of Jin et al. (5) for collisions between ^{40}Ar and ^{27}Al nuclei. They find that the probability for emission of 3, 4 or 5 not too small fragments (Li or heavier) increases strongly between 25 and 35 MeV/nucleon projectile energy - so apparently there is a fragmentation into many pieces, and this is connected with high excitation energy of the nuclear collision complex.

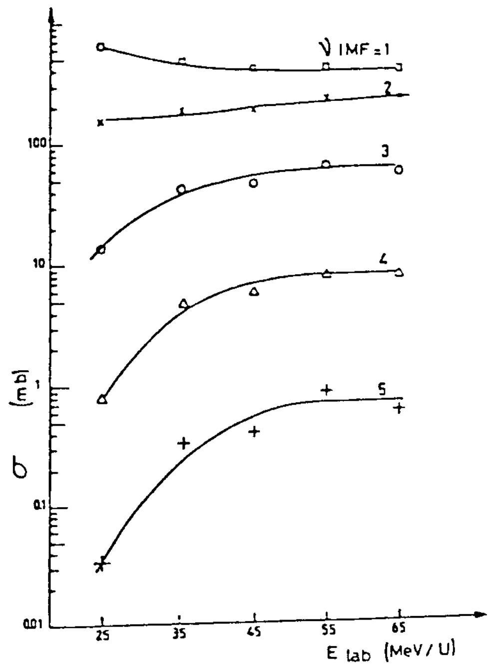

Fig. 6: Cross section for observation of a number ν of intermediate-mass fragments (IMF, with $Z \geq 3$) as function of bombarding energy E_{lab}, for collisions of ^{40}Ar with ^{27}Al (from ref. 5).

However, one must be cautious. Multifragmentation in the sense of the phase transition picture is understood to be an instantaneous decomposition of a hot nucleus. But we have to anticipate also the possibility that such a nucleus undergoes a binary decay (fission or evaporation) with one or both fragments being sufficiently excited to decay again, after some time, into two fragments, and so on. Such a series of sequential, binary decays leads to many final fragments, too, but is nothing else than an extension of the normal fission/evaporation decay modes. The difference between multifragmentation and sequential binary decays lies in the temporal ordering of emission acts. Thus experimentalists have to get a measure of the emission times.

Very little information of this type is presently available. A first approach was made in the experiments of Trockel et al. (6). They measured for two coincident not too small fragments ($Z \geq 8$) the probability for emission as function of the relative velocity v_{rel} between the two.

In fig. 7 such functions are plotted, divided by the product of probabilities to find the fragments individually at velocities v_1, v_2 such that the relative velocity is v_{rel}. This function $R(v_{rel})$ apparently is constructed in a way that it is identical to 1 if the two coincident fragments are emitted so that they do not take notice from each other. If, however, they are emitted close in space and time, they feel their mutual Coulomb repulsion and are pushed apart. They would not fly with the same velocity, and the correlation function will be depleted around zero relative velocity. This is clearly shown by calculated curves in fig. 7 and of course, the depletion around $v_{rel} = 0$ is the more pronounced, the shorter the time between the emission of the two fragments. The experiment, too, shows a depletion, but the quantitative comparison with the calculations suggests rather a relative emission time of about 1000 fm/c. Expressed, via typical velocities, as a distance: the first fragment is already about 100 fm apart when the second is emitted. This is a rather large distance compared to a typical nuclear diameter of 10 fm. The conclusion is that, in the case studied, the nucleus decays rather in a sequential way. Instantaneous multifragmentation still is to be discovered, a task occupying presently many groups of experimentalists.

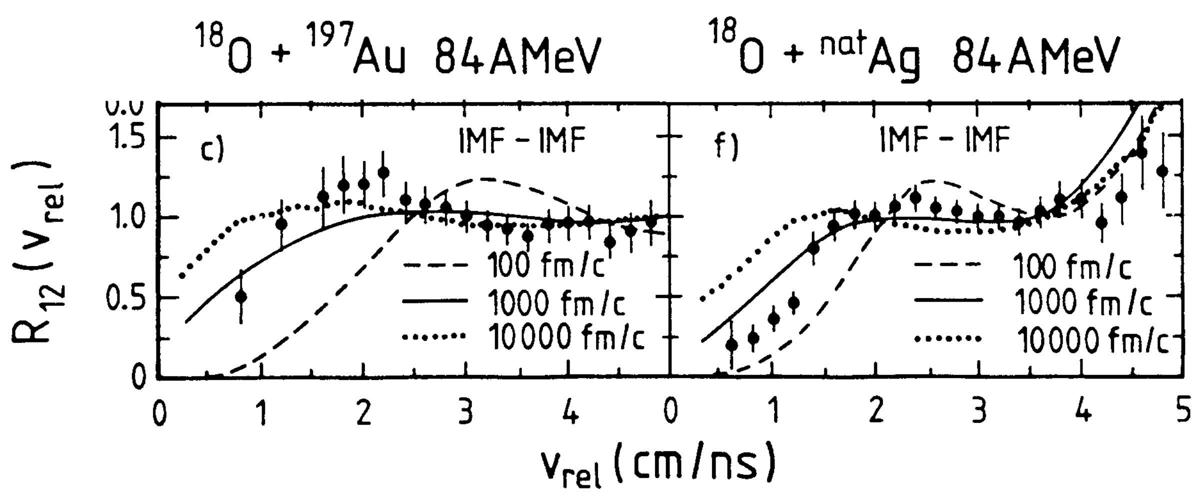

Fig. 7: Correlation function $R_{12}(v_{rel})$ for two coincident fragments of intermediate mass (IMF, $Z \geq 8$) in dependence on their relative velocity v_{rel}. The value $R = 1$ signifies uncorrelated emission. Points: experimental results, curves: calculations for relative time T_{rel} (fm/c) between the emission as indicated. (From ref. 6).

CONCLUDING REMARKS

I have tried to describe, in an extremely selective way, the type of problems presently in the centre of interest in the physics of nucleus-nucleus collisions. These problems and their treatment reveal this field as a sector of the general and actively investigated field of many-body physics and give rise to the hope for an intensive mutual stimulation.

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