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NEW ASPECTS OF NUCLEAR PHYSICS WITH HEAVY ION BEAMS DELIVERED BY CYCLOTRONS

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Abstract.- Cyclotrons are very well adapted for accelerating heavy ion beams in the range 5 to 100 MeV per nucleon. This allows the possibility of very large energy deposits in nuclear matter when medium mass projectiles collide with heavy targets, and then new aspects of nuclear physics studies have been open by such massive probes.

They consist either in a better knowledge of collective properties of nuclear matter, like compressibility, viscosity, shape deformation or in the discovery of the nuclear structure of special forms of rotating nucleides (nuclear states of high angular momentum - so called "dizzy" nucleides).

At the same time, important strides have been made in detection technics and identification processes.

This renewal of nuclear physics due to heavy ions is briefly described, as well as prospects for the near future when the region 20 - 100 MeV/n becomes available. There are three sections :

a. Very dissipative phenomena observed in collision between nuclei. Fusion, incomplete fusion, quasi-fission, deep inelastic transfer reactions. Their studies are made in order to understand how the nucleus behaves as a micro-ensemble of condensed matter, heated at various temperatures.

b. Spectroscopy of rotating dizzy nuclei.

Because of high angular momenta brought by the projectiles, one can produce excited nuclei sharing a very great rotational energy. These objects show very interesting structure which is revealed by on-line gamma spectroscopy.

c. Production of exotic nuclei.

Because cyclotrons can deliver beams for all the elements of the periodic table, many combinations of projectiles and targets are possible and result in the production of isotopes very far from the stability. These nucleides show many properties from which one learns fundamental data concerning the binding of nucleons in nucleides.

I should like to take the opportunity of this 9th Cyclotron Conference to show the new lease of life which has been given by heavy ion beams to the study of nuclear structure and nuclear matter. Large limitations in the methods of approach to nuclear physics were due, during 50 years to the fact that the only available projectiles were neutrons, protons, alpha particles and to a minor extent deuterons and tritons.

Essentially two main classes of reaction mechanisms were originated by nucleonic projectiles, i.e., the compound nucleus process described by N. Bohr, Weisskopf, Feschbach and others, and the direct reactions where the incident proton (or neutron) interacts with a single nucleon of the target. Collective aspects of nuclear matter in the nucleus were entirely neglected and the concept of nuclear fluid was mentionned in rare occasions (giant resonance, fission) so that these aspects were not considered with great interest, as compared with nuclear structure studies in the frame of the shell model theoretical basis.

It is around 1960 that it was realised that cyclotrons could accelerate very efficiently ions heavier that $^{4}_{2}He^{++}$, as far as they could be produced with a charge state as high as possible, and progress were made specially at Dubna on Pig ion sources . The first intense beams of ^{12}C, ^{16}O and ^{20}Ne were produced in Dubna , Stockholm , and Orsay [1] between 1960 and 1966. In the same time, double linear accelerators were adapted to heavy ions in Yale and Berkeley [2] (Hilac machine). The stripping of low charge state ions produced by a first stage of acceleration into high charge ions introduced into the second stage became a general method for delivering energetic heavy ions. It was applied first to a pair of linear accelerators. (Berkeley, Yale, Manchester) and later on to a linear accelerator injecting into a cyclotron, the ion source of the later being replaced by the stripping foil. (Alice-Orsay, 1969 [3]). Finally, the stripping system was adopted for many tandem electrostatic machines.

Nevertheless, at least at the second stage, cyclotrons have the great advantage to deliver an energy proportionnal to the square of the ion charge, whereas other machines produce and energy proportionnal to the charge. This advantage is particularly interesting for medium mass projectiles, because the beam kinetic energy permits to induce into the collision a very large excitation energy. This is illustrated in figure 1, where, for example, the domain of available center-of-mass energies $\overline{E}$, i.e. of energy depositions, is indicated for our cyclotron system, GANIL, as well as for the linear accelerators systems UNILAC and BEVALAC. The maximum laboratory energy per nucleon varies for Ganil between 96 MeV/n for $A < 20$ and 11 MeV/n for $A = 238$, whereas it is constant and equal to 12.5 MeV/n for Unilac.

Moreover, this conference as well as several workshops on ion sources has shown that there are indeed promising prospects of high charge state sources, which will be very well adapted to cyclotron acceleration. It means that you may be able in the future to deliver intense beams of energetic heavy ions with a single cyclotron provided that external sources like E.C.R. [4] or Ebis [5] devices could be installed.

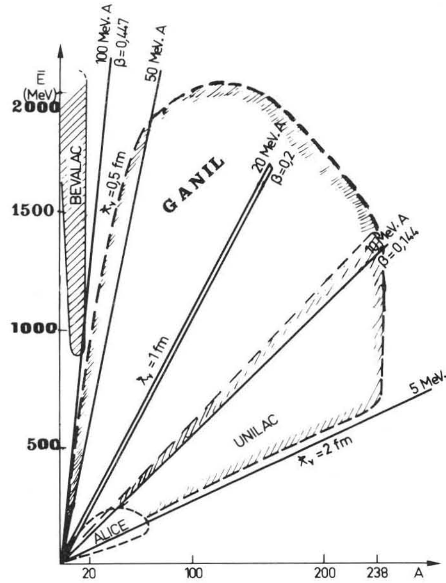

Fig. 1 : Comparison of the possibilities for large energy deposits in heavy ion collisions. The center of mass energy, $\bar{E}$, is taken for a target of the same mass as the projectile. The ranges of available energies is shown for Ganil, Unilac, Alice (Orsay) and Bevalac. Also for several values of velocities, expressed as $\beta = v/c$, the associated wave-length of travelling nucleons is indicated. For 20 MeV per nucleon, it corresponds to 1 Fermi.

1. Development of Detection Technics.- The important progress in construction of cyclotrons would have result into rather limited consequences for nuclear studies without the large development of particle identification. When the available projectiles are protons, neutrons, deuterons, tritons and alpha particles, the reaction process consisted mainly in the formation of a residual nucleus escorted by a few nucleons (neutrons or protons) and γ radiations. The main purpose for experimenters was to measure accuratly the kinetic energy and the angular distribution of these emitted particles. Even when eventually deuterons, tritons or alpha particles are produced, it was rather easy to obtain a good identification since the products mz^2 of their mass by the square of the charge were so different that a rather simple E-ΔE product could make the separation.

But, as far as complex projectile nuclei collide with complex target nuclei, the exit channels are quite numerous and the variety of emitted particles is rather broad. Therefore, two experimental challenges occured. First, identify correctly both mass and Z of the products, second, collect at once all the products in coincidence for each event, so that one may restore the complete process induced by the collision.

i) For the first goal, the mass identification has been improved by measuring much more accurately the velocity and the kinetic energy of the fast particles. The main progress was made on the precision of times of flight, due to channel plates and fast electronics. When one plots the kinetic energy versus the time of flight, it is now possible to obtain a distinct mass separation [6]. at least until atomic masses around A = 100, with a time resolution of 10^{-10} sec. Such performances were totally unrealistic 3 years ago. For heavier masses, one has to use magnetic spectrometers so that the magnetic rigidity proportionnal to the momentum gives an additionnal information.

The Z identification is obtained quite currently by ΔE and E measurements in ionization chambers or solid state detectors. Again, great improvements have been worked out on ionization chambers so that energy resolutions of the order of 5/1000 are reached and atomic numbers can be separated at the present time until Z around 50. Fig. 2 shows for example how various products ejected in the reaction ^{27}Al + ^{32}S are identified from carbon to titanium [7].

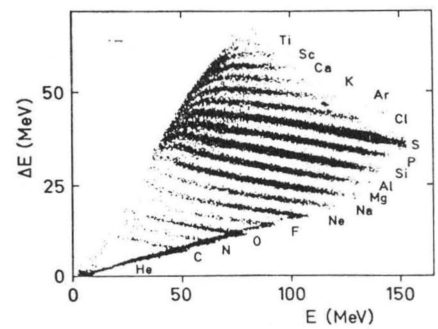

Fig. 2 : Z identification with a ΔE-E telescope. Each element is indicated.

ii) Another aspect corresponds to the fact that the observation of a single reaction product is not a sufficient data for a good understanding of the reaction mechanism. In the simplest cases, two fragments are emitted and the knowledge of their angular correlation as well as their kinetic energy is necessary for obtaining the kinematics of the reaction. Therefore, the role of coincidence technics is essential. In a first stage, inclusive experiments might give a general description of the occuring phenomena, but later on, exclusive experiments become necessary. There are two possibilities. One is to set up many detectors, each having a reduced solid angle, and to organize the soft ware in the data acquisition so that a number of chosen coincidences are trigged. A typical experiment [8] of this kind was made recently at CERN with a ^{12}C beam of 86 MeV/n where the number of parameters was equal to 32.

Another choice is to install a single detector with a large aperture, so that it can recognize many particles, but of course, the position of the particle should be also obtained as accuratly as possible. Even more, it could be interesting to follow the trajectory and to measure as well the time of flight along this path. This has lead to a new generation of complex detecting devices, using the principles of parallel plate avalanche counters (time sensitive and position sensitive detectors). Such a construction is made in Orsay [9] on the basis of the scheme of figure 3 and it will be available for the work at Ganil.

For bombarding velocities reaching 100 MeV per nucleon, the number of particles emitted in a single collision might be as large as 20 to 30 and quite sophisticated multi-detectors are constructed. An example the plastic ball made in Berkeley, consists [10] of many plastic scintillators with their photomultipliers for light particles, associated with heavy fragment silicon detectors (figure 4).

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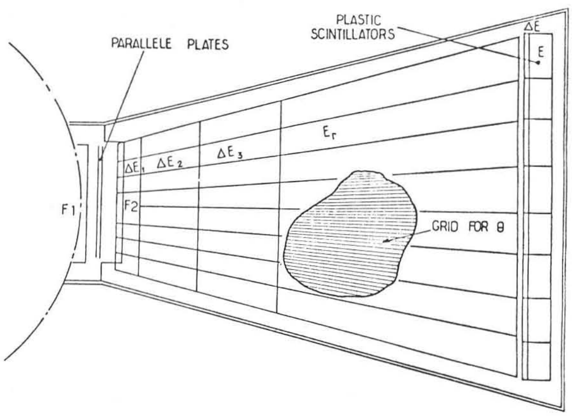

Fig. 3 : Schematic view of an arrangment made of parallele plates, ionisation chambers and plastic scintillators (or detecting several events at once) (project MEΩ, Gardès et al. - IPN-Orsay)

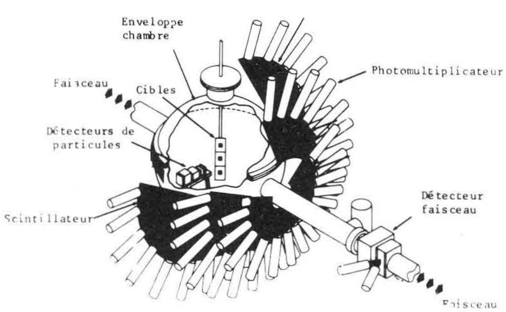

Fig. 4 : An artist view of a large multidetector apparatus made of plastic scintillators around a spherical ball prepared by Lawrence Berkeley Laboratory.

Another aspect of the consequences of heavy ion projectiles is the great variety of nuclear species which are synthetized inside the target or collected outside of it because of the recoil momentum. Once more, the fast collection of these exotic nuclei which have short half-lives has been a challenge and new procedures have been invented : helium jet, mass spectrometers with special ion sources, precise mass determinations using time of flight technique, velocity filters, etc...

2. New Aspects of Nuclear Properties Open by Heavy Ion Probes.- Let us come now to the aspects of nuclear studies which have been open by massive probes. In a few words, they may be classifed into three classes.

i) Macroscopic aspects : they consist in a better knowledge of collective properties of nuclear matter, like viscosity, shape deformation, compressibility. Can we understand how the nucleus behaves as a micro-ensemble of condensed matter heated at various tempe-ratures ?

ii) New aspects of nuclear structure and research in the field of rotational states. Because of high angular momenta brought by the projectiles, excited nuclei are produced which share a very great rotational energy. Their deexcitation by gamma rays reveals how nucleons are organized in the more or less deformed shapes of these "dizzy" species.

iii) Production of exotic nuclei. Because cyclotrons can deliver beams of all the elements of the periodic table, many combinations of projectiles and targets are possible and result in the production of isotopes very far from the stability. These nucleides show properties from which one learns fundamental data concerning the binding of nucleons in nuclear matter.

2.1. Collective properties. Nuclear "macrophysics".- The shell model describes nuclear matter in a microscopic fashion as a quantal fluid at low temperature. The ground state of a double magic nucleus is considered as the reference like the noble gas atom for atomic structure (closed shell). Nevertheless, collective states were observed in γ spectroscopy and their origin was attributed to rotation and vibration bands adapted from the well known descriptions of molecular physics and condensed matter physics (phonons). Therefore "rotational" and vibrational models (cranking model) were developed on the "macroscopic" frame of the Bohr and Wheeler's liquid drop, with the well known parameters : surface energy, electrostatic pressure, moment of inertia, etc...

The detailed study of nuclear structure was developed with the help of very mono-energetic beams of protons and deuterons or by the γ spectroscopy of radioactive decays. This was done in the frame of the shell model. Now, the necessity for learning a very different but complementary aspect of the nuclear behaviour, the collective one, forces us to come back to the liquid drop and to use violent collisions with other nuclei in order to induce surface vibrations, volume vibrations, fast collective rotations, prompt or delayed disruptions into fragments, jets of nucleons, etc...

In order to clarify a little how these questions can be approached, let us consider what are the main classes of collisions when a nucleus A_1 encounters another nucleus A_2 with enough kinetic energy, depending on the magnitude of the impact parameter, b. The scheme of figure 5 presents three main features depending on the deflection functions $\theta = f(b)$. For trajectory n° 1,

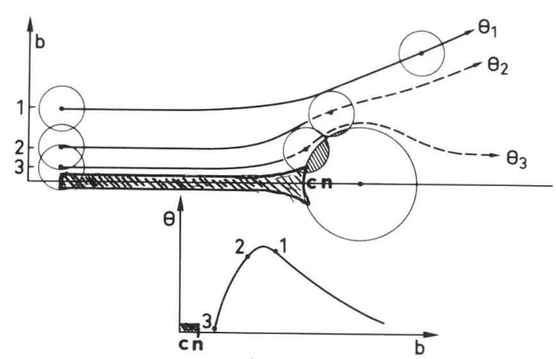

Fig. 5 : Deflection functions for three typical classes of interaction in addition to the compound nucleus formation (cn), for which the projectile is absorbed by the target and the deflection function disappears. b is the impact parameter. θ is the angle of emission for the modified projectile.

only Coulomb interaction is exerted. However, the very high charge of the projectile induces excitation energies in the target which are not accessible by light particle bombardments. The excitation might even be so high that large oscillations of nuclear matter occur and a new kind of so called "coulomb induced" fission is produced. Such a phenomenon has been observed indeed by Specht et al. [11], by bombarding uranium with a tungsten beam accelerated just below the coulomb barrier.

Trajectory n° 2 corresponds to a grazing collision, where only one or two nucleons are exchanged between the two nuclei. A very large set of data was obtained from these quasi-elastic scatterings, since they are very strickly controlled by quantal selectivity rules. Therefore, one can learn something about the characteristics of the states of the peripherical nucleons concerned by this soft interaction.

The 3rd trajectory was not considered as possible before 1969. At that time, it was generally assumed that either the nuclear perturbation during the grazing collision was weak and ended into a direct exchange of nucleons, or a more or less head-on collision would induce the formation of a compound system made of $A_1 + A_2$ nucleons, which, later on, decays by various exit channels. Therefore, the deflection function would disappear as shown by the shaded area noted c.n. However, an intermediate type of reaction occurs, which was discovered in Dubna and Orsay [12] about at the same time, with very similar AVF cyclotrons. This discovery called Deep Inelastic Collisions of Dissipative Transfer Reactions, or Quasi-Fissions for very heavy systems, is of great importance because it is at the origine of the present study of many new collective aspects of nuclei. Let us summarize briefly their main characteristics :

When attractive nuclear forces exerted because of the deep interpenetration of the two nuclei are strong enough as compared to coulomb and centrifugal forces, then the two systems are clutched and a unique body rotates with an angular velocity $\omega = \frac{d\theta}{dt} = \frac{\ell\hbar}{\mathfrak{J}}$. Where $\mathfrak{J}$, the moment of inertia, depends on the shape deformation as well as the relative rigidity. The model of two rigid spheres connected by a neck may be a rough picture of what happens. All the available initial kinetic energy of the entrance channel is transformed into internal and rotational energies, and, finally, the two fragments reseparate and share a kinetic energy only due to the charge repulsion, like in nuclear fission. This is the important feature, because one can handle a system in which the entrance conditions are well defined, and the exit channels can be examined in details, since one can measure not only the kinematics but also the actual behaviour of the two fragments and eventually of the nucleons emitted during this process. Since we have to conserve the energy, the fragments share an excitation energy corresponding to the kinetic energy loss and to the Q value. The deexcitation can be observed through the emission of neutrons, protons, alpha particles and γ rays. The γ multiplicity and various characteristics of the particle emission give information on the rotational energy.

Figure 6 is extracted from one of the earliest publication [12] on the subject which tried to give qualitatively a schematic picture of what was believed of the process occuring with the help of macroscopic concepts like hydrodynamics and transport theory. It is indeed interesting to compare it to a real calculation made recently [13] for the collision of ^{16}O on a calcium nucleus using the time dependent Hartree-Foch method. In figure 7, the nuclear matter densities are obtained starting with a microscopic description of the effective nucleon-nucleon interaction placed in a self consistent medium field.

The time evolved between the close approach and the scission is long enough for the exchange of many

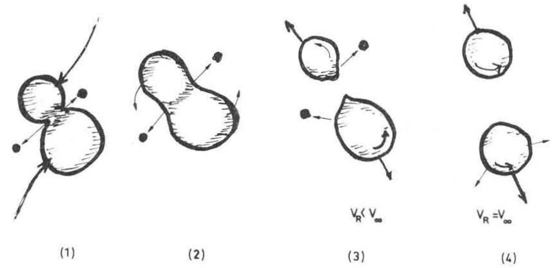

Fig. 6 : Sequences of a deep inelastic collision as it was presented in 1970. 1. is the clutching of projectile and target ; 2. is the rotating composite system ; 3. is the separation ; 4. corresponds to the two fragments recoiling from the coulomb repulsion and being deexcited. At stages 1 and 2, fast particles may be emitted by friction forces. At stage 3, pre-evaporation and evaporation occur from excited fragments.

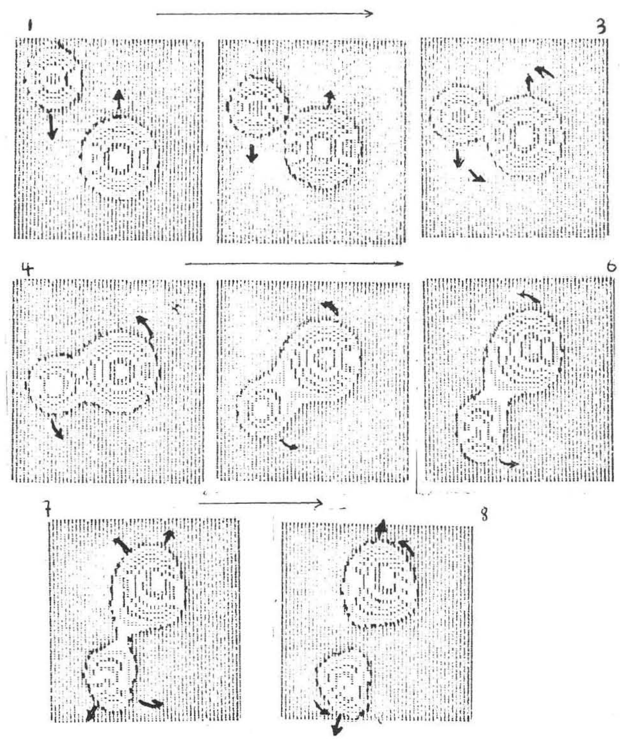

Fig. 7 : Hartree-Fock calculations of a deep inelastic reaction $^{16}O + ^{40}Ar$. Contour lines represent the nuclear density. The reaction follows the sequence from the left to the right and from the top to the bottom.

nucleons through the connection window between the two nuclei. Also collective vibrations have time to occur through the all composite system. Therefore, instead of finding two fragments very similar to the entrance partners, one observes a broad distribution of various masses and atomic numbers.

When projectiles and targets are very heavy, i.e. for example A_1 around 80 and A_2 larger than 160 mass units, even the smallest impact parameters (so called low ℓ-partial waves) correspond to this type of reaction, and head-on collisions cannot produce complete fusion. This was a great surprise [14] around 1974, when it was expected that complete fusion of heavy systems could lead to compound nuclei and then, the decay products could be superheavy elements . As a matter fact, we understand now rather well why, even for those cases where the angular momentum introduced in the entrance channel is small, the system cannot end up as a unique equilibrated compound nucleus and then follows another way which was called at that time "quasi-fission".

Let us consider for a moment how we can estimate the time scale for these phenomena and particularly for the drastic energy loss which occurs when two nuclei collide in a dissipative process as described above. At velocities around 10 MeV per nucleon, the duration of an elastic collision is of the order of 10^{-23} sec. We shall take this time unit. The associated wave-length, $\lambdabar = \frac{\hbar}{mv}$, for such a velocity and for A = 50 is close to 0.1 fm. When this kind of nucleus rotates, the time necessary for an entire rotation, $\tau_R = (\frac{\theta}{\omega})2\pi$, can be calculated from the angular momentum $\ell\hbar$: $\tau_R = \frac{2\pi}{\ell\hbar}$. This is 10^{-20} sec = 10^3 units for ℓ = 50. It gives the idea for using the angular evolution as a clock. Then, let us try to estimate the time necessary for full energy relaxation. Experimentally the data is the angular distribution of the emitted fragments. By looking at the sketch of fig. 8, it is possible to see above which angle the fragment kinetic energy becomes constant and equal to a pure coulomb repulsion. It means that the kinetic energy loss has been achieved and the relaxation is complete.

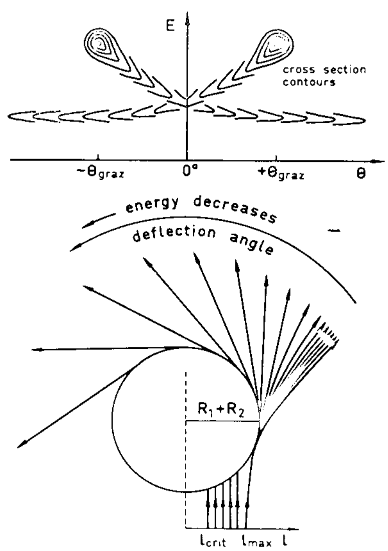

Fig. 8 : Evolution of the kinetic energy of emitted fragments as a function of the angle. At the grazing angle, the reaction is quasi-elastic and the projectile, very slightly modified, keeps nearly all the kinetic energy. When the system has lasted for a while, it has turned around of a certain deflection angle and energy loss has occured. It can rotate on the other side of the beam (negative angle) and reach a stage where all the initial kinetic energy has been lost.

Considering a uniform rotation, the time evolved between the grazing angle, θ_z, and the angle where the separation is observed is given : $\frac{\theta_r - \theta}{\tau} = \frac{\ell\hbar}{\mathcal{J}}$, where $\mathcal{J}$ is the moment of inertia of the relative motion and $\ell\hbar$ the angular momentum of the system after sticking. These values can be estimated at least as averages. Typically, for a medium mass system, the system has rotated of an angle around 50 degrees before the disruption with an energy loss of 100 MeV leading to complete relaxation. This gives some 10^{-21} sec for τ, i.e. 100 units. We notice that what is generally called a direct interaction, for example, the creation of a pair particle-hole in a fermi gas, lasts only around 10 units.

There are others collective variables which are attainable :

i) the loss of orbital angular momentum. This can be done by measuring respectively the multiplicity of the gamma rays emitted by the fragments ;

ii) the mass asymmetry obtained by the mass identification ;

iii) the degree of deformation by measuring an energy loss corresponding to a limit greater than that obtained from the coulomb repulsion energy of two spheres ;

iv) the neutron to proton ratio related to isospin, which is deduced from accurate measurements of the A distribution for each Z. After a considerable accumulation of experiments, there is now a rather good knowledge of the time necessary for equilibrating all these degrees of freedom. Using the 10^{-23} sec units, it takes only 10 units for the neutron to proton ratio, 50 to 100 for the radial relaxation of energy and 100 to 200 for the tangential relaxation. The slowest equilibration is the mass asymmetry corresponding to nucleon transfer. It is of the order of 500 units, the same as for the time for deformation. This is to be compared with the life time of a compound nucleus excited at 100 MeV which is of the order of 1000 or 10.000 units.

Since a microscopic approach with a very large number of interactions between nucleons seems for the moment unrealistic, the most general tool for describing relaxation phenomena has been taken from the transport theory. The transport equation written by Pauli in 1928 [15] gives the normalized probability (P(x,t) to find at time t the system at the position x :

$$\frac{\partial}{\partial t} P(x,) = -\frac{\partial}{\partial x} (v.P(x,t) + \frac{1}{2}\frac{\partial^2}{\partial x^2} (D_x.P(x,t))$$

When the drift coefficient v, and the diffusion coefficient D_x are independent on x and t, the solution is a Gaussian :

$$P(x,t) = (2\pi D_x t)^{1/2} \exp\left(-\frac{(x - vt)^2}{2D_x t}\right)$$

where the average <v>, related to the first moment, expresses the direction of the random walk, and D_x, related to the second moment, describes the stochastic aspects of the random walk.

This type of equation was applied [16] for different variables x - kinetic energy of the relative motion, angular momentum transfer, mass asymmetry, ratio N/Z - which correspond to the quantities which were experimentally measured at various angles, i.e. at various periods of time after the starting collision. Several review papers have been published on this new field of nuclear physics which, in ten years, has broaden considerably [17,18,19,20].

We have spent sometime considering the duration of these phenomena in order to emphasize that through the experimental study of this new type of reaction, one has access to something which, before, seemed to be quite impossible to reach, i.e. the behaviour of nuclear matter in a range of times between 10^{-20} and 10^{-23} sec, that is a very crucial period for understanding the organisation of nucleons in a nuclear system. In other words, these are the necessary conditions for learning something about nuclear viscosity and friction forces. Then, one may understand how the coupling of individual particle states can result into a collective dissipative process. The situation is rather unique, because a nucleus, as a system of about 100 nucleons is a small micro-ensemble where statistical mechanics is difficult to apply directly, but also holds already too many particles for an exact microscopic calculation (N. body problem in quantum mechanics).

Before closing this paragraph, let us say a word of what is expected when the beam energy is increased from 10 to 30 or 100 MeV per nucleon, since this is now the range of energies attainable by the new generation of cyclotrons. As this is clearly demonstrated in fig. 1, the energy deposit can be increased up to several GeV. In other words, the internal temperature is higher and higher. There is certainly an important transition corresponding to a temperature of the order of 8 MeV, which is the average nucleon binding energy [21]. These very hot nuclei are going to explode. For the moment, there are very few experiments in this range. The Vicksi machine, in Berlin, reaches 25 MeV per nucleon for light projectiles. Also some compact cyclotrons deliver Neon beams at 20 MeV/n. The ^{12}C beam at CERN is the only facility for the moment which allows studies between 30 MeV/n and 86 MeV/n. It is probably too early to draw conclusions from the work done there by four teams during the last couple of years, but new mechanisms have appeared like incomplete fusion, fast fission, fragmentation...

2.2. Spectroscopy of rotating "dizzy" nuclei. Nuclei at high spins. Rotational states.- The use of heavy ions has made possible the investigation of high-spin states. When 100 units of angular momenta are added to a nucleus, a new regime occurs in which the rotational energy approaches the order of magnitude of the coulomb and surface energies, and is much larger than shell effects.

Nuclei are not totally rigid bodies. Some of them are particularly soft objects. As a result, the nuclear shape and consequently the moment of inertia are affected by the rotational energy.

Nuclei, even at low excitation or at ground states, display both collective and single-particle features. For example, the low lying rotational bands represent an almost pure collective motion in the rare earth region. It means that, like for molecules, the energy gaps between states follows the I(I+1) rotor formula and the gamma rays correspond to E_2 transition (ℓ=2). Near the close shells, on the contrary, the energy levels are almost completely determined by the motion of a single nucleon (for example in the tin or lead regions). Between these extreme cases, most nuclear levels display both collective and non collective features at low energies. High-spin states behave the same and one observes the coupling of single particle motion with collective properties derived from the classical rotor. When a large increase of the coriolis and centrifugal fields is induced by high angular momenta brought by heavy energetic projectiles, the motion of individual nucleon is affected, and the intrinsic structure like the shell effect will be affected. Moreover, collective characteristics like equilibrium deformations and even fission paths will change.

Let us schematically describe what has been learned for a nucleus like ^{160}Er when it is formed in the complete fusion of ^{124}Sn and ^{40}Ar followed by the evaporation of 4 neutrons. Figure 9 shows the excitation energy versus the spin shared by the compound nucleus. At low energies and low spins, one observes the deexcitation by a sequence of γ rays corresponding mainly to

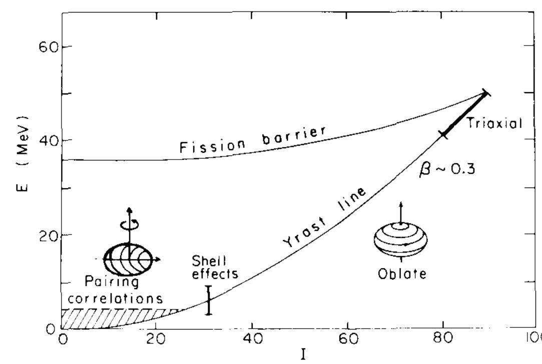

Fig. 9 : Plot of excitation energy versus spin for a nucleus like ^{160}Er. At low energies and spins the shape is prolate. At higher spins the nucleus prefers the oblate shape and perhaps the triaxial configuration.

the ground band and a few vibrational bands. There are not many levels. Then the number of levels increases exponentially. At the same time, the pairing correlation weakens with increasing spin. Shell effects disappear also when spin reaches 20 - 30 $\hbar$. The Yrast line in figure 9 represents the locus of the lowest lying states of each spin. Schematically, all excitation energy on this line correspond to rotation, i.e. $E^* = \frac{I(I+1)\hbar^2}{2\mathfrak{J}}$, where $\mathfrak{J}$ is the moment of inertia. But this quantity depends on the shape.

Most deformed nuclei at low excitation are prolate. But as the angular momentum increases, pairs of nucleons may decouple from the deformation axis and align their spin with the axis of collective rotation which is perpendicular to the axis of symmetry of a prolate body. When more and more pairs align with the rotation axis, an increasing fraction of the total angular momentum will be carried by aligned particles rather than by the collective rotation of the core. If all the particles become aligned, the nucleus becomes oblate and the symmetry axis is now the rotation axis.

At still higher spins, the nucleus stretches more and more and may become triaxal. And, at last, the deformation is so strong that fission occurs. Whereas the fission barrier for zero spin is around 40 MeV for this kind of nucleus, it becomes almost zero about I = 90.

Since a decade of years, heavy ion facilities, and particularly ^{40}Ar beams delivered by cyclotrons, have open a very intense exploration of the properties of nuclei sharing high spin states. In April 1980, an international Conference was held in Strasbourg on the subject [22]. In order to describe the behaviour of these nuclei sharing high spins (called sometime "dizzy" nuclei), the first generation of experiments measured γ energy spectra and γ multipolarities of the residual nuclei resulting from the compound nuclei decays. The important discovery [23] of the years 70 was the anomaly of the moment of inertia called "backbending". This was obtained through the following procedure. Continuum γ ray spectra were measured for a given residual excited nucleus. The effective moment of inertia, $\mathfrak{J}$, can be determined from the expression :

$$E_\gamma = \frac{\hbar^2}{2\mathfrak{J}}\ (4I-2)$$

if one associates the measured γ energy, E_γ, at the bump edge of the spectrum with the highest spin I, in a true rotor. Now, this transition energy, E_γ, can also be expressed as 2hν or $2\hbar\omega$ where ω is the rotation velocity. Assuming $\mathcal{J}$ constant, for example equal to the moment of inertia of a rigid sphere, E_γ increases linearly with I. In a number of cases this was not found. For example, for nuclei like ^{162}Y or ^{160}Er, the transition gamma energy did not increase anymore, for I values higher than 10. Plotting $2\mathcal{J}/\hbar^2$, determined through $(4I-2)E_\gamma$, versus $(\hbar\omega)^2$ deduced from $(E_\gamma/2)^2$ shows a back-bending behaviour which reveals a drastic change in the effective moment of inertia as shown in fig. 10.

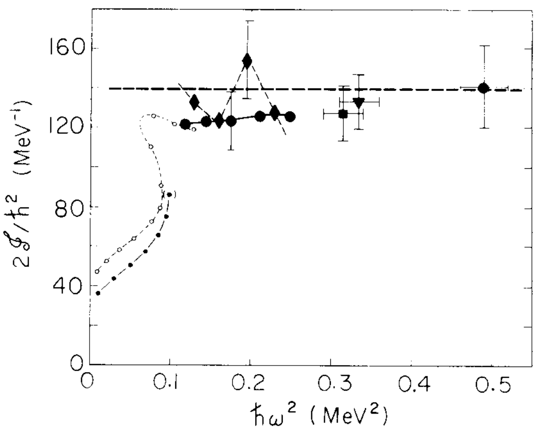

Fig. 10 : Plot of $2\mathcal{J}/\hbar^2$ versus $\hbar\omega$ for ^{162}Y. Filled dots are the known low-spin states, open dots are states of ^{160}Er. The large dots, triangles and diamonds correspond to various entrance channels. The horizontal line is the moment of inertia of a rigid sphere with A = 162. From ref. [25].

Stephens and Simon [24] have suggested that this large increase of $\mathcal{J}$ is due to the alignment by Coriolis forces of single particles. This corresponds to the easiest way for the nucleus for sharing large angular momenta without too much energy. So far for the back-bending discovery in soft deformed nuclei.

After this first generation of experiments, progresses in the construction of big INa detectors have open the possibility for studying continuum γ rays, and E_γ correlation between two γ-rays have permitted to isolate transitions in the very high spin region. If a γ-ray from a particular cascade is observed in a detector, then it is possible to have coincidence events in another detector for all other transitions in this cascade. One obtains a typical E_γ-E_γ pattern of coincidences for a constant moment of inertia as shown in fig. 11. The effect of the variation in the moment of inertia is to wash out the ridge structure for coincidences between distant transitions in the cascade. This technique has been used for a couple of years and new properties of higher spin states have been discovered, as it was reviewed by Garrett and Herskind [26]. For example, a second back-bending occurs at higher spins.

A third generation of experiments will start very soon, with the help of a much more sophisticated apparatus, the so-called "crystal-ball", made of more than 162 INa detectors with close to 4 π geometry. With this apparatus, high γ-ray multiplicity and total energy can be measured in the same time, and therefore, in such "crystal balls" it will be possible for the first time to observe both transition energy correlations and the complete spatial correlations for a specific cascade without no loss of efficiency.

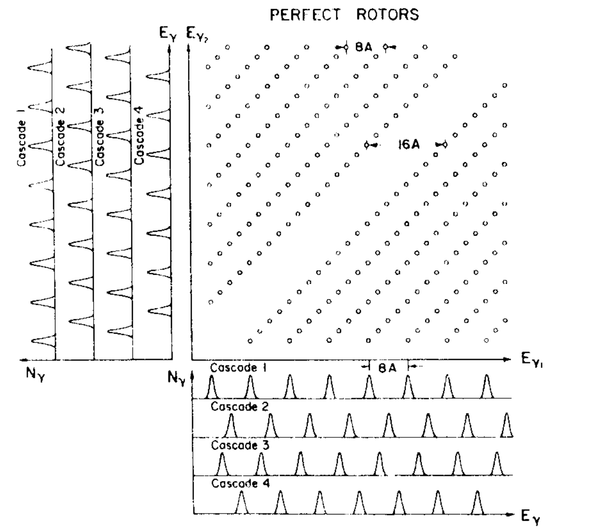

Fig. 11 : Coincidence pattern for the four bands of constant $\mathcal{J}_{coll}$. The spacing of the adjacent ridges and the ridges bordering the equal energy valley are equal to 8 A and 16 A respectively when $A = \hbar^2/2\mathcal{J}_{coll}$. From ref. [26].

In conclusion of this section, I should like to make the following remark.

Spectroscopic studies, which accumulate many data for the knowledge of nuclear structure, have started with the observation of the γ decay of radioactive nuclei in the earliest days of nuclear science. Later on, excited states at higher energies were mostly studied with the help of nuclear reactions using monoenergetic light projectiles. It was very important to work with a very good energy resolution performed by electrostatic machines, since the levels were displayed by measured differences in kinetic energies of the out-going particles reponsible for having excited the levels.

The new aspects of high-spin state spectroscopy comes back to the first approach, so that the energy resolution of the beam is not so important, but the performance of the γ detectors and of the coincidence technics is crucial.

Also, the great versatility of available beams which can be furnished by cyclotrons is of great importance. The main quality of these beams is the good emittence since many detectors are put along the beam as close as possible from it without being touched even by a very small fraction of current.

2.3 Production of exotic nuclei.-"In the development of physics, there has been a general tendency and perhaps sometimes even a sport to search for new objects belonging to a certain group. The history of physics has convinced us that frequently the discoveries and studies of these rare objects in unexpected ways have added considerably to our knowledge of the laws of Nature". This was the opening of Prof. Bergström at the Conference on New Isotopes in 1966 [27]. The search for exotic nuclei is indeed connected to the knowledge of nuclear matter.

Heavy ions have contributed very strongly to the large broadening of the knowledge of many isotopes on both sides of the stability line. Since new nucleides have shorter life-times, it has been necessary to develop fast collection methods. In this respect one advantage of heavy projectiles is the large momentum which they bring into the reaction so that the products are generally projected out of the target and can be collected separatly. A disadvantage is the high stopping power in matter of heavy ions as compared with protons, so that the integrated cross section along the efficient depth in the target , $\int_0^R \sigma_x\, dx$, is rather small, even when cross sections are larger than for reactions induced by protons.

a) Neutron rich isotopes.- In the region from Boron to Titanium, more than 50 new isotopes have been discovered during the two last years at Berkeley and Orsay. The production is based on the following reaction mechanism which has been found in 1975. When a projectile undergoes a deep inelastic reaction, its ratio N/Z is modified very rapidly so that the ejectile takes the N/Z ratio of the composite system. This fast equilibration of the isospin parameter was one of the most interesting result obtained in the study of this type of reaction [28]. Therefore, since heavy targets hold a much greater excess of neutrons than light nuclei at their stability line, the resulting composite system will be strongly affected by this excess and the light fragment emitted will share a greater N/Z ratio than the projectile itself. A theoretical model explains this effect and it is now possible to predict what range of neutron rich isotopes can be produced. This was done by Chiang et al. [29]. Figure 12 shows for example how the production rate is maximum for ^{32}S which is neutron rich by an increase of 6 as compared to the stable ^{32}S.

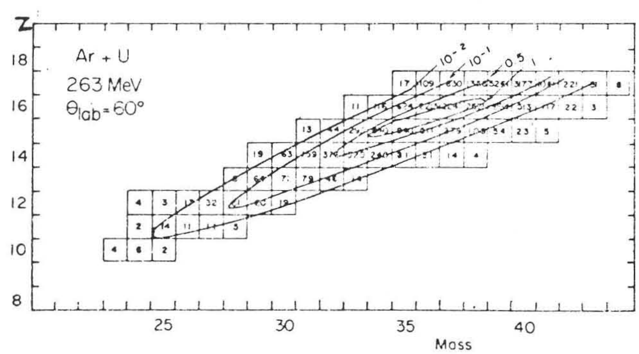

Fig. 12 : Experimental nuclide distribution in deep inelastic collisions induced by the reaction $^{40}Ar(263\ MeV) + {}^{238}U$ (in number of events). These results are compared to the calculation represented by contour plots of isoprobability. From ref. [29].

At higher energies above 50 MeV per nucleon, a new reaction mechanism occurs, the fragmentation, which is responsible also for the production of a large set of new isotopes. For the moment, there are not enough data for estimating how efficient will be the 50 - 100 MeV/n beams, although the results obtained at CERN with 86 MeV/n seem quite promising.

b) Neutron deficient isotopes.- The main reaction mechanism is, of course, the fusion-evaporation process, which has been extensively studied. Because of the locus of the stability line in the Z, N plane , any combination of a projectile with Z = N, and of a medium mass target, where N > Z, will end up into a neutron deficient compound nucleus. This situation was already described in 1972 at the Conference of Aix-en-Provence [30] where we could predict how efficient could be heavy ions for populating the neutron deficient rare earth nuclides. Around 500 new isotopes have been synthetized since that time. Also, it is well known that all the new elements from Z = 98 to Z = 107 have been created with heavy ion reactions in Berkeley, Dubna and for the last one in Darmstadt [31].

In this section, I should like to show only one recent example of the exploration in a particular region around N = Z = 40. It is quite an interesting locus of the nuclear chart because these nuclei should be particularly soft nuclei and should exhibit particular characteristics. Figure 13 indicates all the new isotopes of the elements Sr, Y, Zr, Nb which were

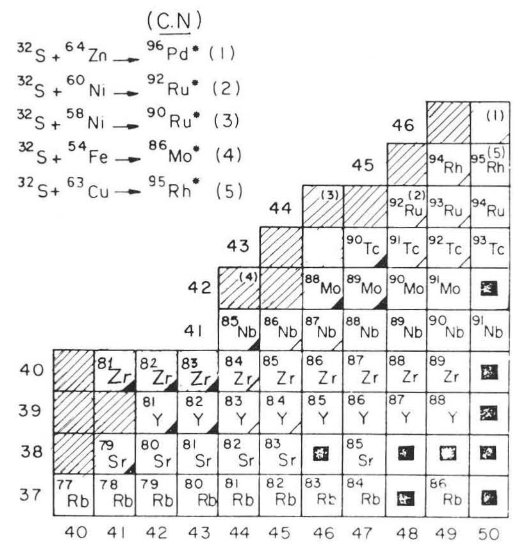

Fig. 13 : Chart of the isotopes around N = Z = 40. Stable isotopes are indicated by a black corner.

identified recently [32]. Their masses could be measured accurately and a new zone of deformation was found. The technique used was to bombard Ni and Fe targets with sulfur projectiles and to collect the product with the helium jet transport system. Moreover, these nuclides, after deposition on a thin foil, decay by β^+ desintegrations. The recoiling daughter is generally ionised, so that it can be accelerated by a negative electrode and the time of flight is measured between the start given by the detector of the positive electron and the stop on a channel plate located at around 50 cm.

A typical mass spectrum is shown in figure 14. The helium jet transportation is a very promising technique, since in a few millisecondes it can take the products far away from the beam. On a collection foil or on a tape, there are possibilities for masses determinations, for studying the radioactive decays, the X-γ coincidences and eventually for doing γ spectroscopy.

c) Exotic beams.- A very new proposal seems to me very interesting as far as high intensity beams will be delivered in the range 20 to 100 MeV per nucleon : when a beam of ^{12}C encounters a thick target (a few mg.cm^{-2}), at energies around 1 GeV, transfer reactions occur at full energy and because of neutron loss or neutron gain, ^{11}C or ^{14}C are produced with a kinetic energy not very different from the main beam energy. The straggling is not very important and therefore, one may expect [34] as already observed at CERN [35] that secondary beams of these unstable species can be easily transported after separation from the main beam. One may expect, for example, a loss of intensity of the

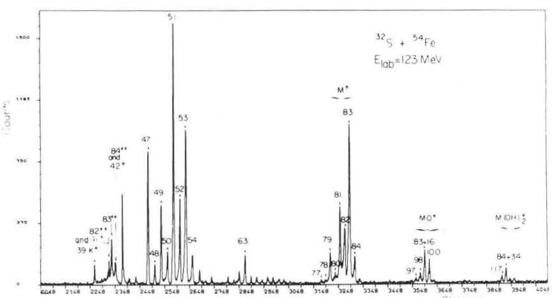

Fig. 14 : Mass spectrum 33) after collecting nuclei in the reaction ^{32}S + ^{54}Fe. Also the ion MO^+ is produced with a lower rate which depends very much of the element. This has even been used for Z identification since it has been observed that MO^+ exists for Zr ions and is absent for Yttrium.

order of 10^{-3} between a primary ^{12}C beam and a secondary ^{11}C beam, and perhaps a factor 10^{-4} for ^{14}C.

It is clear that with 10^{13} ions per second, for the main beam, secondary beams with 10^9 to 10^{10} particles per second become very interesting facilities and because the entrance channel itself consists of unstable species, this might be a great advantage for producting nuclei further away from the stability line and also for studying new reaction mechanisms. For example, there are only a few number of target elements where one can use various stable isotopes, like ^{58}Ni, ^{60}Ni, ^{62}Ni and it is known how useful is the comparison between these various neutron numbers. The possibility to deliver nearly for any element different isotopic compositions in the beam itself extends very much the field. This is why at Ganil, there is a project for a magnetic separation of different mass-to-charge ratios in the complex beam resulting from the passage through a thick target. It will be used also for charge separation after a stripper, in order to deliver beams of highly charged ions for atomic physics.

3. Conclusion.- Such a large portion of nuclear physics is now taken by heavy ion reactions and their consequences that it was impossible to cover all the field. However, I hope that these few examples have shown that heavy ion cyclotrons built during the last ten years, or under completion at the present time, are useful tools for nuclear physics. This does not mean at all that light ion beams are not any more interesting. There are still important spectroscopic studies to be made with protons, deuterons and tritons between 20 and 50 MeV, as far as the energy resolution permits to identify levels which are separated by a few keV. The recent theoretical developments due to Arima and Iachello[36] has given support for trying new experiments. They should test the validity of the Interacting boson approximation, which simplify the shell model so that the N body problem could be approached more realistically.

However, this domain still remains the field of nuclear physics of the electrostatic machines, with their continuous current and very good energy resolution.

On the other hand, good light particle beams at energies around 100 MeV seem to be useful probes for the renewed study of giant resonances and more generally new degrees of freedom.

The last word concerns the prospect for new accelerators. During the last decade, there has been in nuclear physics as well as in all other domains of physics, a tremendous blossom of instrumental improvements. The result has been a huge accumulation of informations, sometime still enclosed in pile of magnetic tapes. The second aspect of the general trends in physics during the seventies was the approach of complex problems like for example, order-disorder problems, spin glasses, amorphous condensed matter, turbulence phenomena. This was also observed in nuclear physics with the macroscopic approach of nuclear matter properties and again the N body problem. In several fields of physics the very great variety and complexity of results has been transformed in a progress of our knowledge because very strong and powerful theoretical concepts have been raised : this is particularly true in high energy physics with the attempt of a unified theory of interactions, the new quantum numbers of "chromodynamics" and all the construction around quarks and gluons. It gave a thread for displaying the great quantity of available informations into the right direction, and it makes possible for prospecting the future in a given frame.

Such a situation has occured, I believe, in nuclear physics when all experiments could be thought in terms of the shell model. However, this is not any more the case and we feel a lack of directing ideas. Therefore, it is certainly difficult to predict what sort of facility we should need in 1990, as far as for the moment we know that the eighties will be devoted mainly to the full operation of a number of new heavy ion machines. In my opinion, during a couple of years we should require a deep consideration of the field, and perhaps wait for what will emerge from the results raising from the operation of these new cyclotrons and tandem of the beginning eighties.

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