GANIL

THE DEVELOPMENT OF HEAVY-ION RESEARCH AT GANIL

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1. INTRODUCTION

Two scientific domains have been explored very actively at GANIL : the thermodynamic behaviour of nuclear systems with high internal energy, and the properties of light nuclei far from stability. These are fundamental aspects of nuclear physics that beams at energies close to the Fermi energy can most efficiently explore. The aim of GANIL in the coming years is to develop and further improve its research programs in these two areas.

The fact that new machines are now providing physicists elsewhere with beams somewhat similar to those from GANIL will contribute to even more fruitful investigations.

The current prospects at GANIL aim at better conditions to produce and study rare exotic nuclear species, and to characterize the behaviour of hot excited nuclear matter.

In sections 2 and 3, the general objectives of these improvements will be described, while the specific projecs, which concern either the accelerator itself or the experimental equipement, will be adressed in section 4 through 7. Broader and longer-term perspectives will be described in section 8.

2. PROSPECTS FOR THE STUDY OF EXOTIC NUCLEI

Some ten years ago, a pioneering experiment [1] was performed at Bevalac to observe exotic nuclei from the fragmentation of ^{48}Ca projectiles at 212 MeV per nucleon. As compared to the yields obtained at Bevalac; those anticipated at GANIL were lower, in part because the angular distribution is broader at low energy so that the analyzing achromatic spectrometer cannot collect all the fragments. This deficit in detection efficiency at GANIL as compared to Bevalac energies reaches two to three orders of magnitude. Yet this disadvantage was more than compensated by the much higher beam intensity available at GANIL. Altogether it appears that the present possibilities of GANIL are some two orders of magnitude above those of the experiments performed at Bevalac at the time. How they will compare with those opened by the upcoming SIS/ESR at GSI is still an open question.

Improvements are made and planned for the efficiency of the study of exotic nuclei at GANIL. Their relevance can be illustrated on one particular example. Absolute mass measurements have been obtained from precise determination of two independent parameters of the fragments. The method has been described elsewhere [2]

The magnetic rigidity is measured by the SPEG spectrometer with a FWHM of 10^{-4} and its time of flight is determined along a flight path some 100 meters long. New mass values, with accuracies better than 500 keV and reaching sometimes 200 keV, are obtained in that way.

The accuracy of the measurement directly depends upon the number N of collected nuclei of a given species, roughly as $\sqrt{N}$. Thus gains in beam intensity foreseen from the development described in § 4 and 7 will be of great importance.

Obviously, the observation of new isotopes, the study of rare new decay modes, a major field of research at GANIL which is reported elsewhere |[3]| in this school-seminar, can also benefit from intensity gains.

A first improvement along this line has recently been obtained through the successful completion of the Operation Augmentation d'Energie (OAE), or Increased Energy Operation|[4]|.

GANIL was designed to accelerate beams of heavy ions produced by a PIG ion source to an energy ranging from 95 MeV per nucleon for Carbon to 8 MeV per nucleon for Uranium. The main parameters of the accelerator were finalized in 1975 on these bases. It now appears that ECR ion sources are operational. They exhibit important advantages over the PIG sources, including the reliability of their operation. Actually, GANIL has been operated since 1986 with an external ECR source and an axial injection.

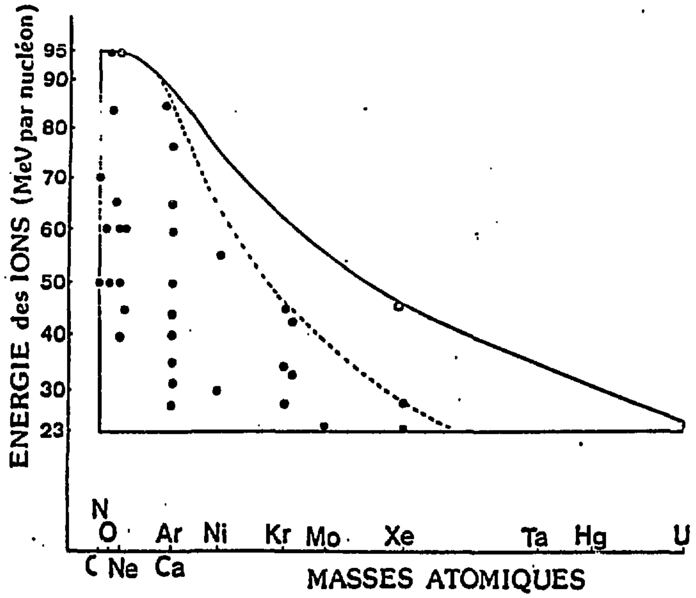
The good characteristics in intensity obtained by higher-charge states have opened the possibility of accelerating ions at higher energies. However, the initial injection radius of CSS2 required that their charge be increased by a factor of 3.5 in the stripper foil, which becomes impossible with incident ions in a higher-charge state.

Thus the modification of GANIL has consisted in increasing the injection radius of CSS2 so that it accomodates ions which have undergone a charge increase by a factor 2.5 only in the stripper foil. In this way higher energies are indeed obtained for the heavier elements (fig. 1). Several other changes were operated all over the accelerating system to adapt to this new mode of operation. CSS1 operates with harmonic 5 instead of 7. The injector cyclotron Co was modified accordingly. It was decided to operate it with harmonic 3, which minimizes the variation of its ejection radius which was increased by 23mm only. These and other less important modifications were realized during a six-month period starting December 1, 1988, that interrupted the normal operation of GANIL for the furst time after 6 years of beam production.

One obvious benefit of this operation is that higher energies for heavier ions open new possibilities for the production of medium-mass exotic nuclei, while reducing the number of partially stripped fragments which make identification through magnetic spectrometers sometimes uncertain.

A second benefit is that the continuous development of ECR ion sources at GANIL |5| has resulted in improved intensities. For instance not only has the energy of

Fig. 1 Energies (in MeV per Nucleon) of the beams accelerated at GANIL. Black dots correspond to beam operation from 1983 through 1988, and open dots to the first new beams accelerated after the recent energy upgrade (operation OAE, see text). The maximum beam energy now available is represented by the full curve, to be compared to the previous upper limit (dotted curve).



Xe ions be brought from 27 to 44 MeV per nucleon, but their intensity has increased typically from 50 nA to 800 nA.

Another improvement to the study of exotic nuclei has come from the use of beams of neutron-rich isotopes which lead to neutron-richer exotic fragments. The acceleration of ^{48}Ca ions by a Dubna-Ganil collaboration |6| has been remarkably fruitful. Other possibilities, such as the acceleration of ^{76}Ge, are being actively studied.

3. PROSPECTS IN THE STUDY OF HOT NUCLEAR SYSTEMS

Some important features have emerged in the study of nuclei at high excitation energy over the last few years.

First, in the initial steps of the collision, nuclei span a broad range of temperature and compression. As a result the excitation energy is shared among these two degrees of freedom in a way which actually varies with time. The increased awareness of the role of compression energy might help explain the limiting temperature (about T = 5 MeV for heavy systems) which appears to be found independently by several experimental studies. That would mean that the system, on its way back to a low-excitation state, would explore a broad range of the nuclear equation of state which would therefore fall within reach of experiment.

Second, under certain conditions, this dynamical evolution can bring the system into a region of so-called "spinodal" instability. Calculations predict that, at this point, multifragmentation is expected to occur within a short time, leading to a characteristic distribution of heavy fragments. Such a process is expected to occur through a critical regime, quite similar to the phase transition process observed in many instances of physics [7].

Further progress in these two fondamental problems requires major experimental developments.

For instance, the investigation of the sharing of energy between the thermal and compression modes requires to observe in detail the de-excitation of hot nuclei. Yet a large number of light particles and heavy fragments are emitted during the de-excitation process. Therefore an ability to measure high multiplicies over a 4π solid angle is necessary. The quantities to be measured for each fragment, in an event-by-event account of the nuclear collisions, are the velocities, angles and for the lighter fragments, Z and N values. Very low energy thereseholds are quite necessary, as discussed in section 6.

As for the study of multifragmentation, the analysis methods recently developped point to the necessity of measuring the moments of the distribution in size (or A, or Z) of the fragments. Through the critical regime, the mass distribution follows a power law ($A^{-\tau}$) while it is exponential ($e^{-\alpha A}$)on either sides of the critical regime. Along the same line, the moments of the size distribution should exhibit a characteristic dependance upon the fragment multiplicity around the critical regime.

From an experimental point of view, this requires that each event be characterized by its multiplicity up to values where 30 or 40 light particles and 10 fragments with $Z > 4$ are emitted, and that the A and Z values be, if not measured, at least estimated.

These experimental requirements were not fully satisfied by available equipments since either the energy threshold was too high or the multiplicity measurement insufficient. Therefore going further than the results obtained so far requires to develop a new kind of detector as described in section 6.

One more prospect must be underlined. With the new heavy beams now available through the OAE operation (see section 2 and fig. 1), collisions around the Fermi energy involving more than 400 nucleons can now be studied at Ganil. Progress on the difficult yet fundamental problems discussed in this section will greatly benefit from it since up to now the limited size of the system studied and the strong consequences of surface effects could interfere with the study of hot nuclear matter. The availability of more extended systems should make the processes under study clearer.

4. INTENSITY INCREASE OPERATION (OAI)

In order to increase the beam intensities delivered by the GANIL injectors, which are presently limited either by space charge effects (light ions) or by low source currents (heavy ions), a new high-efficiency injection system[8] has been designed for optimal matching of the beam in the six-dimensional phase space between the ECR ion source installed on a 100 kV platform and the first accelerating gap of the injector cyclotron Co1.

The new injection system includes a spiral inflector associated with a small electrostatic quadrupole located immediately after. Operation of this system is planned for the end of 1990.

Indeed, over the past years, the operation of the accelerator showed clearly that, due to space charge effects, the transmission between the source and the injector outputs decreases rapidly from 25 to 3.5 % when the source intensity raises (from 10 to 100 eμA for a 1.3 keV/A O^{2+} beam). If the ion source voltage is raised to 100 kV (maximum value imposed by voltage breakdowns in the inflector) instead of the present 15-20kV, this efficiency should increase to 40 %, due to both the velocity increase and the lengthening of the bunches. Thus, an intensity of 100eμA for the reference beam of 15 keV/A Ar^{6+} can be accelerated in the injector. On the other hand, the beam line between the source and the cyclotron has not only to transport the beam without losses but must also provide the matching in the six-dimensional phase space into the cyclotron, through the inflector.

Taking into account the total phase space volume makes it possible to handle 300 to 400 eμA beams in the injection line and to accelerate 100 to 150 eμA intensity in the injector. A factor of three to five is expected from this operation with respect to the currents obtained after the recent upgrade (OAE) discussed in section 2, in particular through the use of a new ECR ion source of the Caprice type operating at 14 GHz, presently under construction.

5. THE TAPS PHOTON MULTIDETECTOR

In the first six years of research performed with the beams of GANIL, it has become clear that some specific and very fruitful problems of nuclear physics at the Fermi energy could definitely be best studied by detecting high energy photons. Such are the study of the first stage of the collision, subthreshold production of π°, γ decay and micro-structure of giant resonnances.

It is worth detailing shortly these three topics.

It is observed that high energy γ emission in heavy-ion collisions exceeds what would be expected from free nucleon-nucleon collision.This is due to the extra energy available from nucleonic Fermi motion within nuclei. All analyses indicate that the probability of hard proton emission is highest at the first stages of the collision before the energy has been shared and thermalized. One sees how the detection of hard photons can shed light on a particular phase of the dynamical evolution induced by the collision.

In a rather similar way, subthreshold π° production is made possible by nucleonic Fermi motion. It can at the same time benefit from collective effects, several nucleons pooling their energy to make the emission of π° possible, which is detected through the two hard photons emitted when it decays. This gives probably a unique access to a specific aspect of the pionic field in nuclear matter.

Although giant resonnances have been known for quite a while to result from major collective excitations of nuclei, much remains to be learnt. First, not all modes have been observed, and for instance a study of the isovector quadrupole giant resonnance is of great importance. And second, their microscopic studies, the damping of the oscillations, allow to address fundamental properties of nuclear matter. This calls for a precise study of their γdecay.

All these reasons have led Ganil to look for a high efficiency γ detector to be used in connection with the high resolution SPEG spectrometer which can select a specific nuclear reaction.

It was found that the two-arms photon spectrometer (TAPS) designed for use at the upcoming SIS/ESR facility at GSI would be best suited. Therefore a very remarkable collaboration has been set up between GSI, GANIL and the laboratories of Giessen (a major potential user of that detector) and KVI Gröningen (site of the future AGOR accelerator) to build TAPS which will be used alternatively at the various sites quoted.

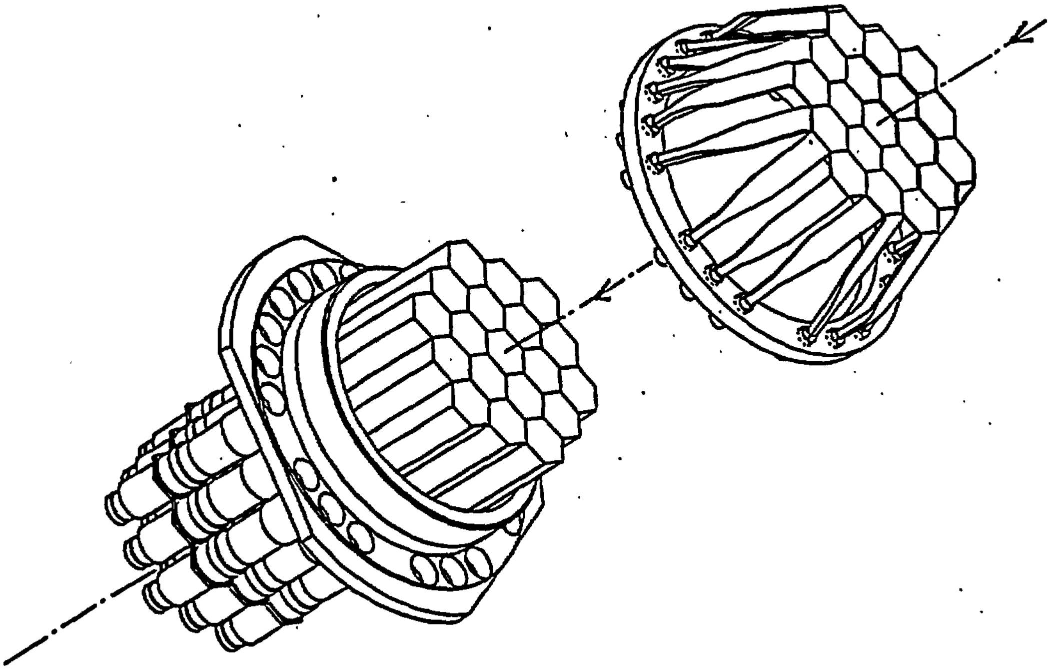


Fig. 2 : The veto detector (upper right) and the associated module of 19 BaF_2 detectors (lower left) will be used to record γ signals and to discriminate against charged particules. The TAPS multidetector consists of 14 such modules.

The system consists of 14 modules (fig. 2) of 19 BaF_2 detectors. the discrimination between γ particles and charged particles is accomplished in two ways. On line, a veto detector made of plastic scintillators will be positionned in front of each module. It will be supplemented by the off-line time analysis of the BaF_2 output signal. It is known indeed that this signal has a fast and a slow components and that γ particles give a stronger fast component than the charged particles.

The TAPS multidetector will be used starting in December 1989 at Ganil, mostly in association with the SPEG spectrometer, as represented in fig. 3. The abilities of SPEG for particle identification and energy measurement will be used as a trigger for TAPS.

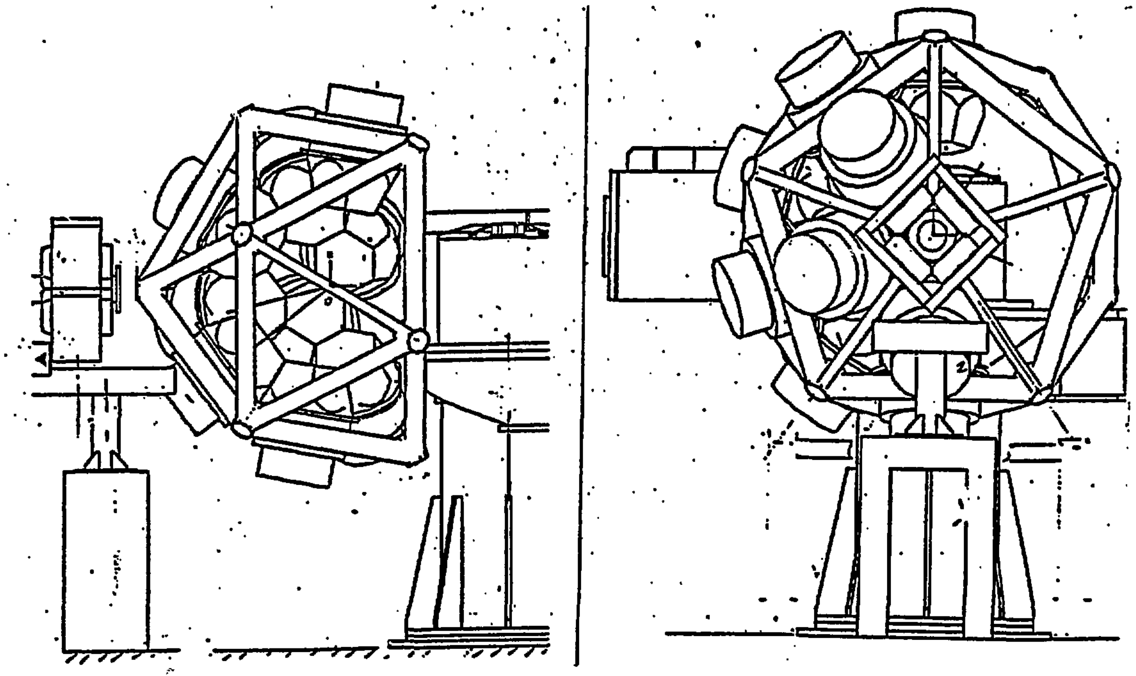


Fig. 3 : For most of its operation at GANIL, the γ multidetector TAPS will be mounted on a spherical mechanical support in connexion with the SPEG spectometer as represented by these two views, from the side (left) and along the beam axis (right).

6. A CHARGED PARTICLE MULTIDETECTOR, INDRA

It was argued above (section 3) that a multidetector with low threshold and high granularity is essential to study, without damaging experimental biases, the thermodynamic evolution created in the nuclear collisions induced by the heavy-ion beams of GANIL.

Up to now, the experiments performed never were truly exclusive, and assumptions had to be made to relate the results to a detailed nuclear process. It would probably have been unreasonable to request that experiments, in the difficult and intricate domain of the thermodynamic evolution of nuclear systems, start by being exclusive. Very little sense might have been extracted from the hundreds of parameters simultaneously recorded. Yet, now that the major trends have been observed through experiments which deliberately focused on some of the parameters only, it is timely to design a detector which is as free as technically possible from experimental biases.

It is expected to significantly improve upon the performances of the multidetectors which have been installed over the years inside the large scattering chamber Nautilus.

This detector (fig. 4) which is called INDRA is a 4π device with an ability

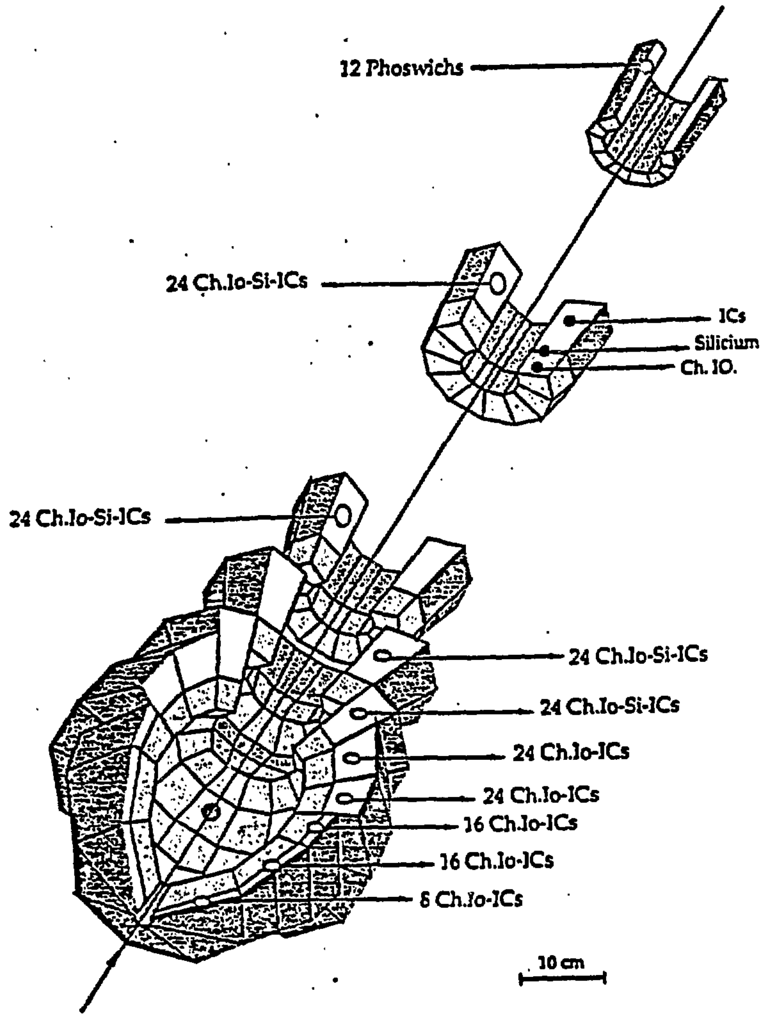


Fig. 4 : A schematic view of the INDRA multidetector

to detect both light charged particles and heavy ions. It will be built by a collaboration between GANIL (Caen), DPhN/BE (Saclay), IPN (Orsay) and LPC (Caen) laboratories. It has been optimized to study specifically the formation of hot nuclei between 20 and 100 MeV per nucleon at GANIL.

The geometry of the detector is decomposed into a series of rings with their axis along the beam direction. The rings cover a given polar angular range whose granularity increases as the polar angle decreases. Each ring is divided into 24 azimuthal cells.

At forward angle the cells are made of three detection layers ($\theta < 45°$: axial ionisation chambers (5cm ; 50mbar ; CF4), Silicon detectors (300 μm), and CsI). At backward angles two detection layers are present ($\theta > 45°$: axial ionisation chambers (5cm ; 50mbar ; CF4), and CsI). These combinations of detectors should allow for the identification of light particles and heavy ion ($Z<30$) over a large dynamical range ($2<E<100$ A.MeV). The geometrical efficiency will be close to 90 % of 4π.

At the most forward angles ($\theta < 3°$) a ring of 12 phoswich detectors (NE102-NE115) will have Z identification capabilities ($Z<20$) even for high counting rates.

The total number of detectors consists of 96 ionisation chambers, 180 Si detectors, 324 CsI and 12 phoswich detectors.

Alltogether, it is a high-resolution device, versatile and easy to operate. It can be used alone, or in association with other detectors for specific research purposes. For instance, its association with TAPS for additional detection of γ or π° particles or with ORION for neutron coincidences are taken into account for the design of INDRA.

It might be worth mentionning that both computerized electronics and triggering procedures have been made as user-friendly as possible, as must be expected from a detector meant to be a major common tool at a national laboratory.

7. A BEAM TRANSPORT DEVICE FOR SECONDARY BEAMS : SISSI

At GANIL energies, beams of radioactive isotopes are produced by fragmentation-like processes of intense primary beams. A limitation to the yield of secondary beams comes from the inability of present beam transport systems, including the LISE spectrometer,[9] to accept the broad distribution in angle and momentum of the fragmentation products. In this respect, higher incident energies such as those available at Bevalac, and soon at SIS/ESR, are much more favorable since the relative spreading is smaller.

If a beam transport system can be designed at GANIL to accept all or most of the fragments, full use could then be made of the high intensity of the incident beams (10^{12} to 10^{13} pps), soon to be even higher (see section 4) to produce the most intense secondary beams available. This would open new opportunities both for inducing nuclear reactions with radioactive isotopes at a reasonable rate,and to develop the study of exotic nuclei to hitherto unobservable species.

A system of two superconducting solenoids, on either side of the target, is being studied which might be able to improve the rate of collection of secondary fragments by a factor of typically 20 over the present situation. Fig 5 shows the angular distribution $d\sigma/d\theta$ of fragments of various mass value when a 35 MeV per nucleon ^{84}Kr beam is fragmented on an ^{27}Al or ^{12}C target. It is clear that the present angular acceptance of detecting devices, around 1°, hinders the collection of the fragments. An increase of this acceptance up to around 5° would multiply the yield by a factor of about 20.

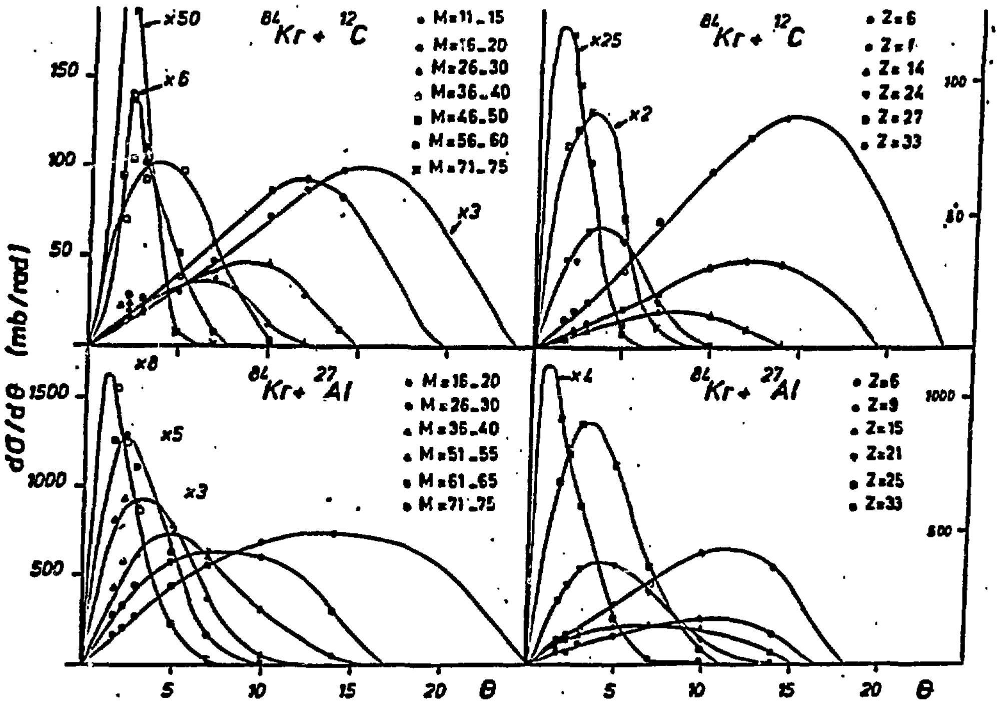


Fig. 5 : Laboratory angular distributions from ref. |10| of some products from both the $^{84}Kr+^{12}C$ and $^{84}Kr+^{27}Al$ collisions at 35MeV/A as a function of mass (left-hand side) and of atomic number (right-hand side). The symbols represent the experimental data, while the smooth curves have been used to extract the angle integrated cross section. It is immediately obvious that SISSI, which will allow to transport all fragments emitted in the 0°-5° angular range, will provide for a strong yield increase over the present facilities which have only a 0°-1° angular acceptance.

This can be achieved in the following way. The transport lines of GANIL have an acceptance of up to 35π mm.mrad. For the secondary beam to be transported, its size

Δx and its angular aperture must at all points, according to the Lionville theorem, be such that $\pi \quad \Delta x \quad \Delta\theta \; < \; 35\,\pi$

If $\Delta\theta$ has to be as large as wished, i.e. 5°, then Δx must be smaller than 0.35mm. In other words, the incident beam must be concentrated on the target within a 0.35mm diameter.

This requires that, upstream from the anticipated target location, after the extraction from the second cyclotron CSS2, a very strong focalising solenoïd be installed. In the same way, a second solenoïd, downstream from the target, should reduce the angular aperture $\Delta\theta$ of the secondary beam (initially 5°) to make it acceptable for the first optical elements of the transport beam line, i.e. with an angular acceptance of about 85 mrad.

The limited space available implies that the high magnetic rigidity necessary, 2.8 T.m., result in magnetic fields of up to 10 T in the superconducting solenoïds. At the present stage, a detailed design study is in progress.

The advantages of such a development are obvious. The production rate of exotic nuclei would be increased by more than one order of magnitude over the present situation. Separated secondary beams with intensities of 10^7 to 10^8pps would become available, and they could be directed towards any of the experimental equipment of GANIL.

This development, together with the planned increase in intensity, would represent a major advance in the study of nuclei far from stability.

CONCLUSIONS

There is a growing interest in the study of collisions around the Fermi energy. The occurence of new mechanisms such a multifragmentation, the derivation of the nuclear equation of state far from the usual equilibrium situation open perspectives of fundamental importance. An increased ability, by orders of magnitude, to study nuclei far from stability will further add to the usefulness of GANIL beams. The number of accelerators in the same energy range is increasing with the operation of the K=1200 superconducting cyclotron at MSU, the RIKEN and the Lanzhou sector-separated cyclotrons, the prospects of new accelerators at Catania and Gröningen , and other projects such as studied at Dubna.

Therefore, the longer-terms developments envisionned at GANIL quite naturally call for keeping at the forefront on this exciting field through continuous improvements of the accelerator and experimental equipment.

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