GANIL

Lecture given at the International School of Heavy Ions Physics
ERICE (Italy), October 6-16, 1993

NUCLEAR PHYSICS AT GANIL - TRENDS

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The purpose of this lecture is to give an overview of recent nuclear physics experiments performed at Ganil and to point out some trends for the next future. I will focus mainly on studies of nuclei under extreme conditions, and on progresses achieved with radioactive beams. Many interesting contributions achieved at Ganil on nuclear physics, solide state and atomic physics and biophysics have not been covered within the scope of this presentation.

1. Thermal and mechanical properties of nuclear matter.

One of the most fascinating domain of nuclear research is the behaviour of nuclear matter which undergoes heating and compession induced by heavy ion collisions. There is a long list of research topics concerning this field achieved at Ganil these last ten years which has made our understanding of some aspects of this complicated problem named the equation of state of nuclear matter.
One of the key question relates to the maximum thermal energy, a nucleus can sustain without breaking. Finite temperature Hartree-Fock calculations peformed by Levitt and Bonche have predicted that nuclei become unstable when reaching a critical temperature. These limits which depend of masses of composite systems have been actively studied in a wide range of dynamical conditions. An example of the data obtained few years ago is given in the fig. 1. In these experiments, one observed the disappearance of the fusion-fission bump corresponding to central collisions, at around 3-4 MeV excitation energy per nucleon of the composite systems. This feature was puzzling since the neutron multiplicity spectra which sign the formation of hot nuclei dit not follow the same trend. In fact, we understood recently that the binary fission channel is not anymore an intense decay process for nuclei exceeding 3-4 Mev excitation energies as illustrated in fig. 2. A careful analysis of different decay modes has been achieved using the detector set-up installed in Nautilus for charge particle detection and identification. A transition is observed from binary fission towards multifragment emission around this excitation energy independently of the considered system. The multifragmentation process (more than two heavy fragments) is an increasing function of excitation energy and is in competition with particle evaporation leading to heavy residues. This balance with masses and energies of composite system have not be so far established experimentally while predicted theoretically by E. Gross.

Now, a question to adress, concerns properties of multifragmentation decay channels open above 4 MeV/u excitation energy. Is it a sequential emission of intermediate mass fragments or a simultaneous disassembly process ? After a careful selection of central collisions leading to thermal equilibrated nuclei, these events are compared to predictions of two extreme hypothesis : one assuming sequential fragment emission and the second prompt fragmentation. The experimental relative velocity between two fragments as well as their relative angle distributions are nicely fitted with the model

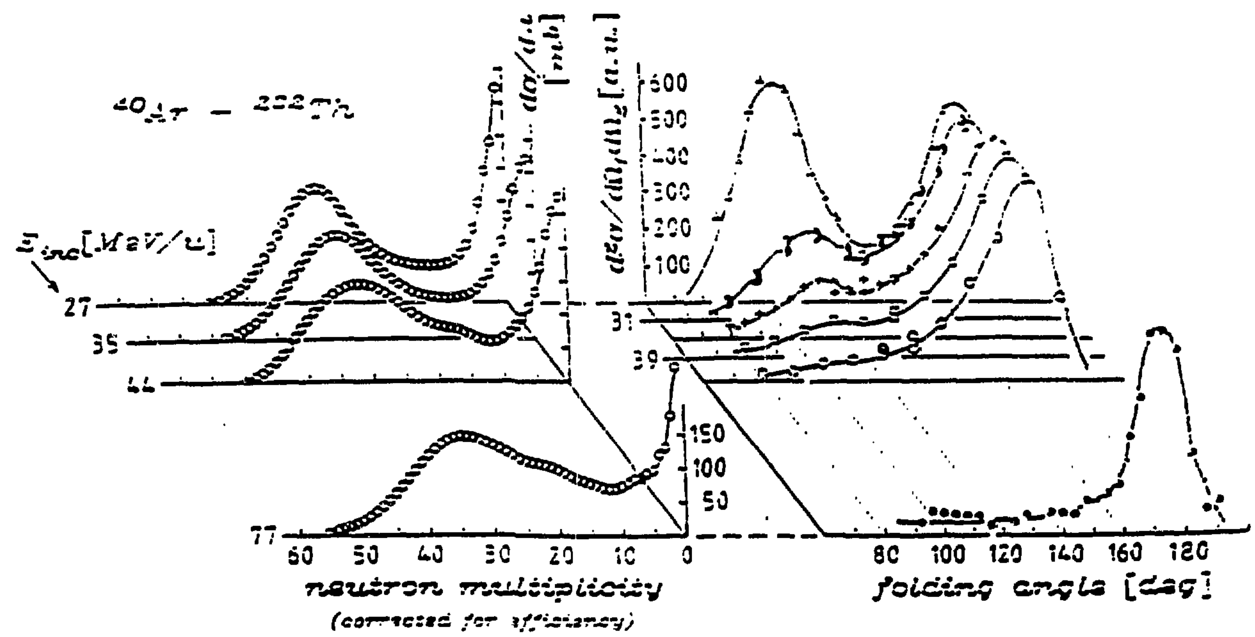

Fig 1 : Comparison of neutron multiplicity spectra and fission folding angle distributions for the reaction Ar + Th over the whole range of incident energy from 27 to 77 MeV/u.

simultaneous character of the disassembly process has been established, at least for this specific reaction, the authors search for possible signature of compressional effects. The basic idea is that the average kinetic energies of emitted fragments keep the memory of the compressional energy which is not transformed in thermal energy during the expansion stage. In this framework deviations from a pure coulomb repulsion are expected for fragment kinetic energies. This assumption is checked in fig. 4 ; data are fairly well filled with no expansion energy contributions for most of the fragment charge distribution. Nevertheless light charge fragment detected at the forward hemisphere are better filled by calculation predictions including radial expansion. This important aspect has to be studied in future to disentangle possible preequilibrium emission effect from compression effect.

The multifragmentation of nuclei opens a window on the behaviour of the equation of state of nuclear matter in a region where new phases might exist. INDRA is a new generation detector (fig. 5), which was designed to study high order correlations between heavy fragments to sign new trend of nuclei. The technical challenge was to construct a 4 π solid angle coverage of detectors with a low energy threshold and a high dynamic range. In spring 1993, a first body of data acquisition was successfully achieved and the first results are very promising.

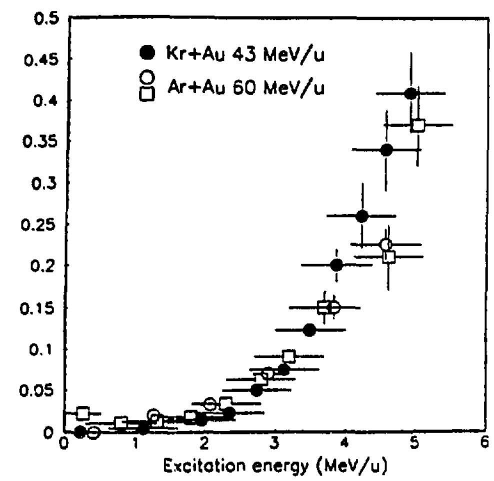

Fig 2 : Evolution of the two-fold versus three-fold fragment production as a function of the excitation energy per nucleon for two systems. The mass number of the composite is around 200-220. Black points : Kr + Au at 43 MeV/u using the recoil velocity method ; open points : Ar + Au at 60 MeV/u with the same method and open squares : Ar + Au at 60 MeV/u using the elasticity method. From G. Bizard et al, Phys. Lett. B 302 (1993)162

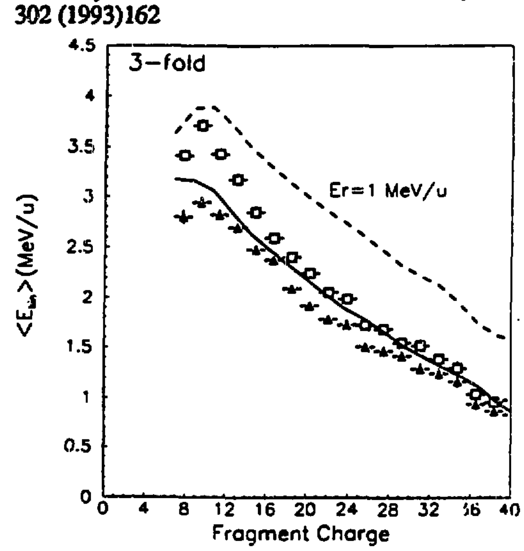

Fig 4 : Average kinetic energy calculated in the "event" frame as a function of the atomic number for 3-fold events. The open squares and the black triangles are respectively the data when all the fragments in each event are considered and when only the fragments emitted in the backward hemisphere are considered. The curves are the results of the "simultaneous" model calculations (solid line) with no expansion energy and with a 1 MeV/u radial expansion energy (dashed line). From O. Lopez et al, Phys. Lett. B 315 (1993) 34

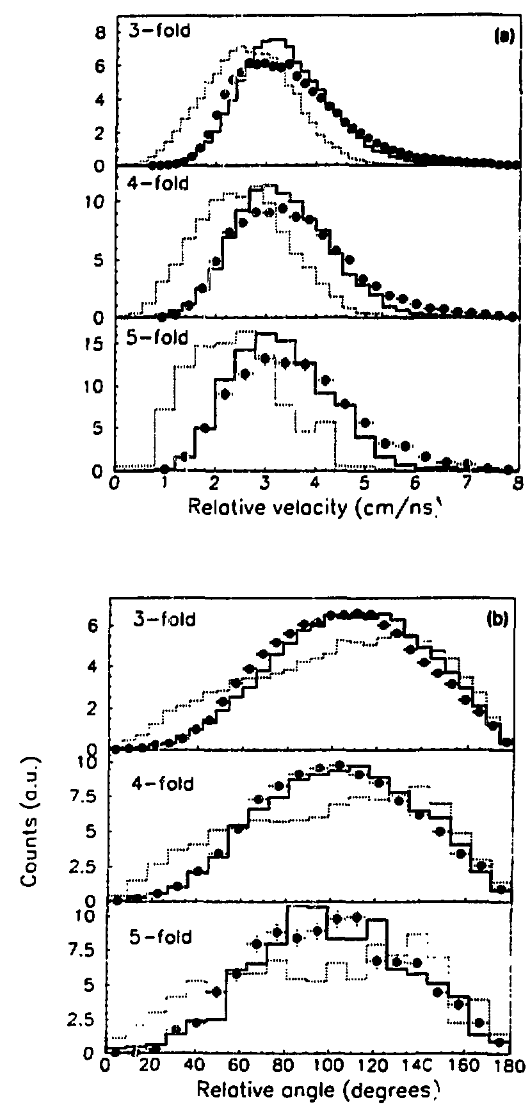

Fig 3 : (a) Relative velocity distributions between fragments taken two-by-two for three different fragment multiplicities (indicated in the left corner of each panel). Black points correspond to data, the dotted line to the results of the "sequential" model calculations and the solid line to those of the "simultaneous" model. (b) Same as (a) but for relative angles. From O. Lopez et al, Phys. Lett. B315 (1993) 34

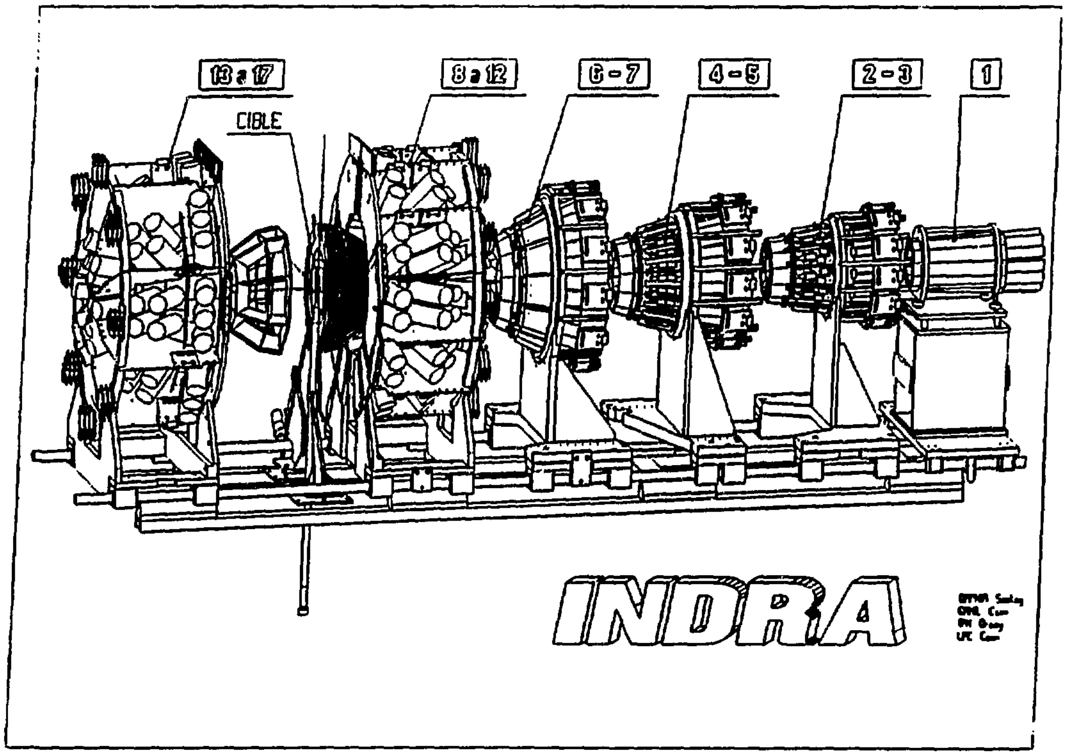

Fig 5 : The INDRA detector - Ensemble of 336 cells arranged according 17 rings centered with the beam axis. Charge identification (up to Z = 50) is achieved by two or three detection layers : low pressure gas-ionization chamber, 300 μm silicon detector and Cesium iodiode scintillators.

2. Nuclei far from stability

2.1 Limits of nuclear stability

The exploration of the isospin degree of freedom is also a very important aspect of the research performed at Ganil since 10 years. Two magnetic spectrometers (SPEG and LISE) with complementary properties have been built to identify new exotic nuclei and to study their properties. The proton drip-line (zero binding for protons) has been probably mapped up to $Z \cong 30$ and few tenths of neutron-rich-nuclei have been identified for masses lower than 100 (fig 6). Limits of nuclear stability and properties of the p and n drip lines have been intensively studied by the projectile fragmentation method using ^{58}Ni, ^{48}Ca... Ganil beams with high intensity (~ 2 μA).

Mass measurements are of crucial importance to test the validity of nuclear structure theories especially, values near the drip lines. Then this goal has been actively pursued at GANIL using the alpha and SPEG spectrometers and a precision of 310^{-4} has

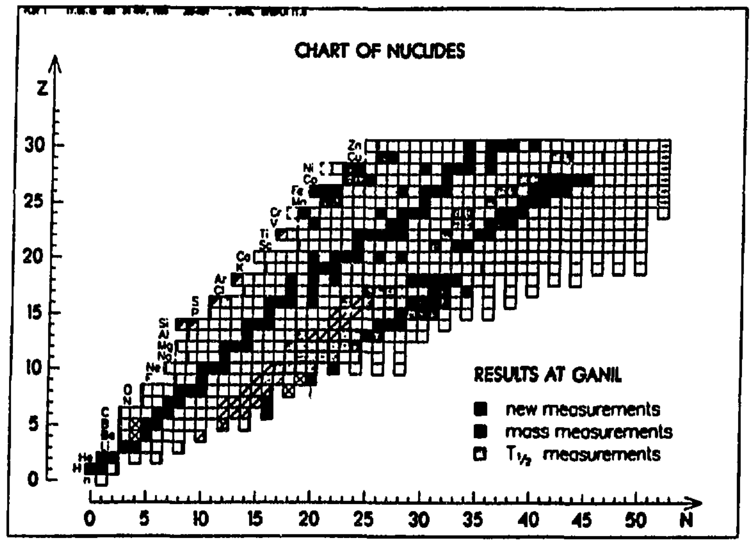

Fig 6 : Chart of nuclei which are either stable (black squares) or are radioactive (grey squares). Those plotted are results obtained at GANIL)

been reach with a flight path of about 100 meters. To improve the precision by an order of magnitude, an original method has been tempted : the beam accelerated by first CSS cyclotron of GANIL hits a target and reaction fragments are injected in the second CSS cyclotron used as a mass spectrometer with a flight path of few kilometers. The method has been checked successfully on well known nuclei as ^{15}N and ^{6}He and a precision of 5.10^{-5}be obtained. It has been deduced from these studies that in case for which it is possible to accelerate simultaneously both known and unknown mass nuclei, then a precision of 6.10^{-7} can be derived. This method open an important field of investigation for heavy nuclei for which mass differences are less than 10^{-4}.

2.2 Radioactive beams

2.2.1 Nuclear structure studies

By improving both primary beam intensities and the purity of selected fragments reactions, it becomes possible to use exotic nuclei as new beams with intensities sufficient to induce reactions and study their properties. This new trend was started with the discovery of Tanihata relative the ^{11}Li halo nucleus.

In this talk, I present a result obtained for the first time, mainly the coulomb excitation of bound excited states of ^{11}Be which is a one neutron halo nucleus (fig 7). Comparison between experimental and theoretical cross section is underway. This experiment is considered as a test of the method for further nuclear structure studies induced by ^{12}Be, ^{14}Be, ^{8}He, ^{13}B, ^{19}B,^{19}C, ^{22}C...halo nuclei

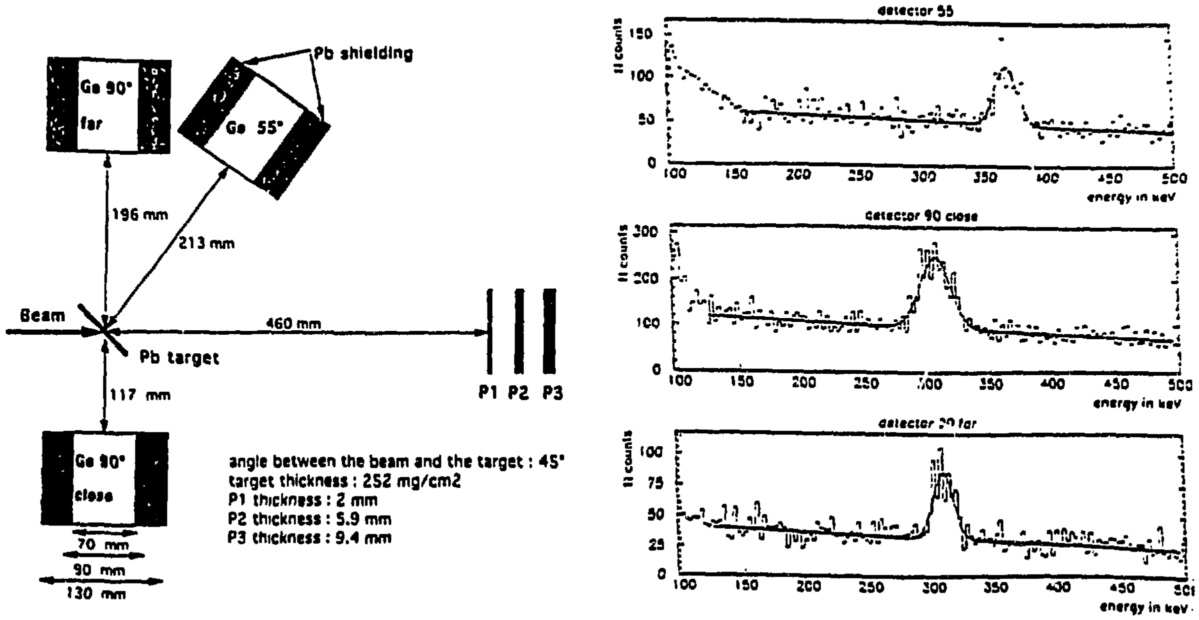

Fig 7 : shows the experimental set-up. The radioactive beam impinges onto a lead target chosen for its high atomic number, which strongly enhances Coulomb excitation. We used plastic scintillators (NE 102) for particle identification in order to accept high count rates. Three large-volume germanium counters are used for the detection of in-flight γ de-excitation. The Doppler shift of these rays will be sensitive to the angle of detection. The distances from the target indicated on left side part result from a compromise between Doppler broadening and solid angle efficiencies. Right side part shows the dependance of these two quantities with the distance to the target for the 55° oriented germanium detector. From R. Anne et al, Nouvelles du GANIL n°45 April 1993

2.2.2.Nuclear Astrophysics

Another research field open by radioactive beams concerns nuclear reactions of astrophysic interest as $^{13}N + p \rightarrow {}^{14}O + \gamma$ or $^{11}C + p \rightarrow {}^{12}N + \gamma$ which plays an important role in the hot CNO cycle. The reaction rate is believed to be dominated by resonant E1 capture via a low lying excited state in the compound nucleus. These reactions have been studied at the Louvain-La-Neuve laboratory. At GANIL, P. Aguer et coworkers developp an alternative access to radiative capture in studying the dissociation of fast nuclear projectiles in the coulomb field of a heavy target nucleus. Then ^{14}O and ^{12}N radioactive beams are produced via ^{18}O projectile fragmentation and after a 100 meters flight path hit a ^{208}Pb target where the coulomb break up reaction takes place. ^{13}N and ^{11}C reactions products are detected by the SPEG spectrometer and the associated protons by a CsI hodoscope located around 0°. The determination of the radiative width leads directly to the radiative capture cross section. These data associated to precise knowledge of lifetimes and masses of unstable nuclei are of most importance in the description of the r- process and for synthesis of nucleides.

2.2.3 Isomeric beams

Isomeric beams could open fascinating fields of investigations in nuclear structure since it becomes possible to study at low excitation energies, excited states constructed in a structure quite different of the ground state configuration (fig 8).
Recently at GANIL a ^{42}Sc (6^{+}) isomeric beam has been produced by the ^{12}C (^{40}Ca, ^{10}B) transfer-reaction at 30 Mev/u. The ^{42}Sc nuclei were transmitted by the Lise spectrometer and collected at the rate of 164 pps and 76 % purity. A program to improve these characteristics is underway and ,elastic and inelastic scatterings as well as cross section measurements are planned in next future.

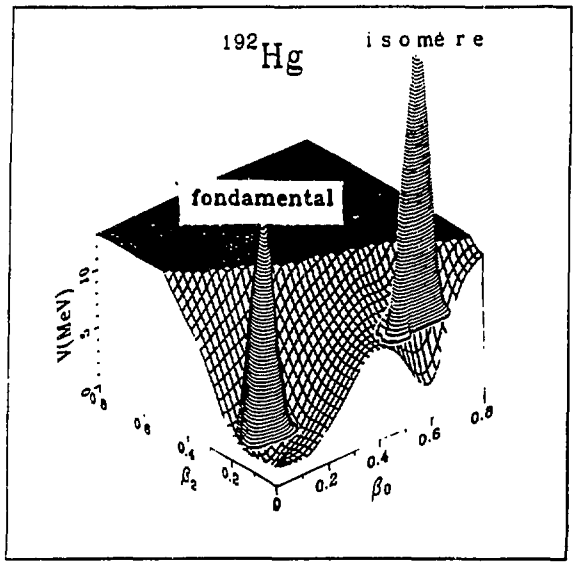

Fig 8 : Potential energy surface versus deformation parameters. The representation of square modules of ground date and isomeric state waves functions, show their location in the main and secondary wells.
From M. Girod et al, CEA, Chocs n° 4 may 1992

2.2.4 Technical improvement

These few examples show the variety of research fields underway at GANIL with high energy radioactive beams. Of course experiments become possible or easier with higher beam intensities. In the very near future, two major improvements will be achieved in order to get a significant increase of radioactive beam intensities. The first one, named OAI (Opération Augmentation d'Intensité) concerns modifications of the ECR source and the injector cyclotron, then primary beam intensities close to 5.10^{13} p.p.sec on target will be available for nuclei up to Ar. The second improvement is connected with a high gain in the transmission of the secondary products. This is the SISSI project (to be operated beginning 1994) which uses two lenses (superconducting solenoids) and which improve the transmission or radioactive beams by a 20-50 factor with respect to the present possibility ; together with the increase of the primary beam, two orders of magnitude will be thus gained for the secondary beam intensities. Examples of beam intensities which will be available and delivered in the whole experimental area of Ganil are indicated :

^{11}li	:	$3\,10^4$ ions/sec	^{26}Na	:	10^6 ions/sec
^{13}O	:	10^6ions/sec	^{36}Si	:	10^6 ions/sec
^{20}O	:	$5\,10^7$ ions/sec	^{38}Si	:	$6\,10^7$ ions/sec

Unfortunately secondary beams produced by projectile fragmentation have energy and angular spreads larger than a standard beam and furthermore energy lower than 40 MeV/u cannot be reach with a degrader without a strong reduction of the intensity ; The GANIL Plus project will overcome these difficulties by using another production method.

3. High resolution experiments

The possible existence of long range force between hadrons has been considered by theorists in the QCD framework. Thus exchange of two gluons at distance far from nuclear force range can give rise to a colour Van der Waals force. An experiment has been achieved at GANIL to check this assumption . The method consist in studying the Mott scattering of the ^{208}Pb + ^{208}Pb system since this approach was found to be especially sensitive to detect small effects via the angular shifts in the oscillatory pattern. The theory predicts an angular shift of 0° 06 in the Mott distribution as a signature of this effect. But in the present conditions, the angular distribution of ^{208}Pb +^{208}Pb at 1129 Mev has a period of 0° 18 ; then to get a significant signal, it was necessary to measure scattering angle with a precision of 0°003 and to determine the beam energy at 10^{-4}. These technical challenges have been reach as illustrated in fig 9. The coulomb angular shift due

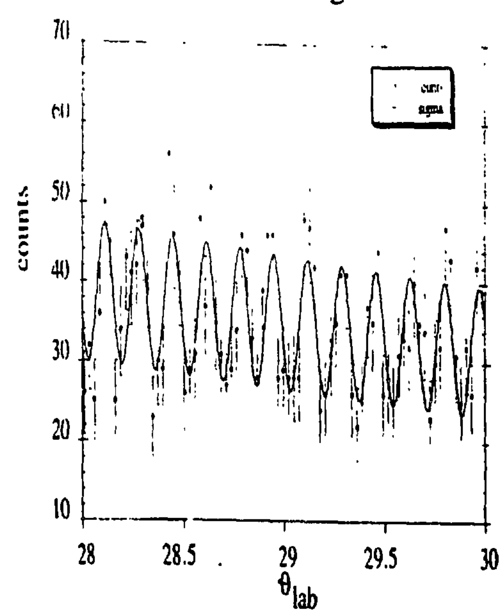

Fig 9 : Mott scattering angular distribution at 1129.74 MeV. Solid line is the best fit to experimental measurement.

relativistic effects, nuclear polarizability, electron screwing and vacuum polarisation are evaluated to be of the order of 0° 06 at θ lab = 30°. The experimental shift obtained with the data presented in fig 9 is (0.088 ± 0.003)°.An analysis is underway for results obtained at different incident energies. Whatever the conclusions concerning the primary goal of the experiment, it is clear already that such small effects have been precisely measured for the first time and open new research studies based on small angular shift (like resonant transfer reaction of pair of nucleons,...).

4. The GANIL Plus project

The study of nuclei far from stability has already greatly increased our knowledge of nuclear properties in the past few years. The availability of high intensity secondary beams issued from fragmentation process has largely contributed to this. However, the use of secondary beams produced by isotope separation on line methode (ISOL) and further post-accelerated will improve these possibilities by a factor that will permit a qualitative difference due to an increase of intensity by several orders of magnitude and the existence of high optical quality beams. This emergence of a "new" physics has been presented in different workshop and reports (see references).

As described briefly in section 2, GANIL already delivers competitive medium energy secondary beams using mainly projectiles fragmentation. A further step in the direction of both higher intensities, and better optical qualities at lower energy for radioactive nuclear beams has been investigated. It deals with the production of these radioactive species in a thick target through spallation and fragmentation processes. In this case, the reaction products are stopped in the target. They may then diffuse out as atoms and be ionized in an ion source. This promising method, which is opening very new perspectives in physics has been actually studied at GANIL since two years and a project named Ganil Plus has been recently accepted for realization in the next five years. A lay-out of the project is presented in fig 10.

<u>Basic features</u>

- Use of heavy ion beam from the GANIL facility (~5 x 10^{13}light ions/s at 95 MeV/u) as a primary beam to produce radioactive atoms, from the interaction of this beam on a thick target.
- An ECR source as an ionizer, produces multicharged ions with a high yield (ratio between the number of extracted ions with the required charge state and the number of atoms injected into the source). The ionization efficiency for the most probable charge states are the following, 60 % for Li, 25 % for Ar and 15 % for Pb. The highly radioactive environment in the vicinity of the target implies the design of a coil-free ion source (only permanent magnets) : GANIL handles this technique fairly well since few years.
- Previous to injection into a post-accelerator, an efficient selection spectrometer of ions is required. An additional selection can be provided by another analyzer located after the accelerating system.
- Our choice of a compact cyclotron as post accelerator is based on the following main reasons : first of all, using a high charge state ion source allows us to consider a cyclotron and second, the energy range to be covered (fig 11) (≅ 2 to 20 MeV/u) for the charge over mass ratio as given by the ECRIS (≅ 0.1 to 0.35) are typical of a compact cyclotron whose beam characteristics satisfy rather well requirements of physicists.

GANIL-PLUS

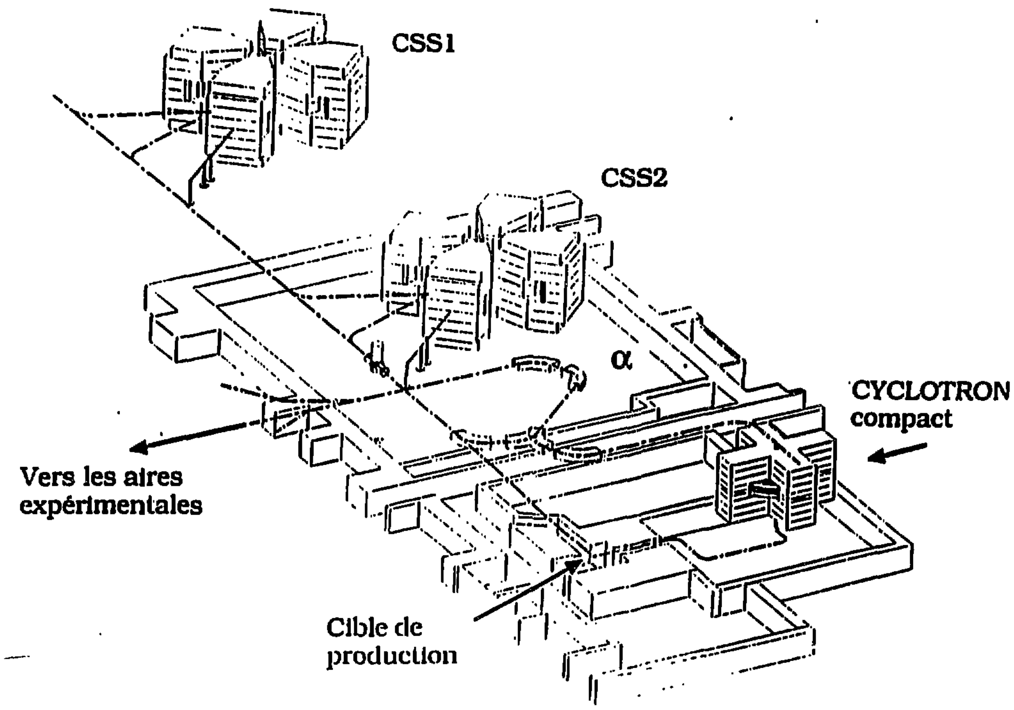

Fig 10 : Layout of the GANIL Plus project

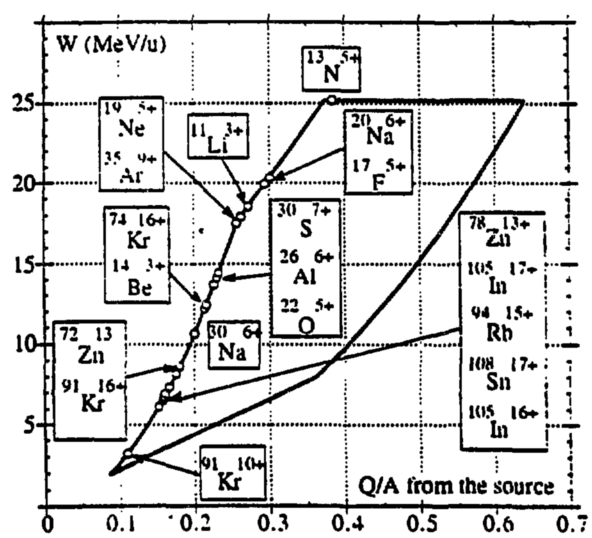

Fig 11 : Energy range of radioactive beams

Moreover, a cyclotron is by itself a powerful mass analyser and will deliver rather pure beams,which is a prime quality in RIB physics. Third, GANIL has a good knowledge of cyclotrons and a long experience in their design and operation . Moreover, this new facility will fit in the loose end of the existing building still lowering the cost of an already rather cheap solution.

First beams are expected in currently 1998. An International Scientific Committee has been installed to pilot the project and also to organize a new european user laboratory for radioactive beams at GANIL.

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