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PROSPECTS FOR THE STUDY OF EXOTIC NUCLEI AT GANIL

C. DETRAZ
GANIL - BP 5027 - 14021 CAEN Cédex - FRANCE

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C. Dētraz
GANIL, Caen, France

1. Introduction

Projectile fragmentation in nuclear collisions at a few tens of MeV per nucleon is now well established as a powerful tool for the production of nuclei far from stability[1]. Projectiles with low relative number of neutrons, such as ^{36}Ar or ^{40}Ca were used at GANIL to produce very neutron-deficient isotopes, such as ^{22}Si (ref.[2]), and to study their properties. For instance, the β-delayed proton emission of the light Tz = -5/2 nuclei, such as ^{31}Ar (ref.[2]) has been investigated. Neutron rich projectiles such as ^{40}Ar, but mainly ^{48}Ca have allowed the observation of a wide series of very neutron-rich nuclei[4-5] One major characteristics of the latter is that they exhibit large probabilities for β-delayed neutron emission. Far from being a marginal channel for their decay, this mode becomes rapidly predominant, as was shown in the study of a long series of Na isotopes[6]. The increasing distance of these nuclei to the valley of β-stability translates into increasing values of $Q_β$, the energy available for their β-decay which evenutally opens the window for decay into particle-unstable states of the daughter nuclei. The coincidence between the delayed neutrons from such a decay with the electrons provides a valuable experimental tool for measuring β-decay half-lives at very low counting rates. Recent experiments[7] at GANIL have studied β-delayed neutron-emitting nuclei such as ^{18}C or ^{29}P. The fragmentation of a ^{48}Ca projectile has allowed the study of nuclei even further away from stability . For instance, the β-delayed neutron emission of nuclei around ^{44}S has been studied. Their half lives were measured. These nuclei, and especially ^{44}S, are of interest for the understanding of the nucleosynthesis in the universe[8]. This represents a major step in improving the quality of the input of nuclear physics properties into astrophysical nucleosynthesis calculations. Most of the time, one had to rely on extrapolations or models to estimate the half lives and branching ratios of nuclei located on the r-process path. It now appears that laboratory experiments can produce these much needed values. That, together with the current progress in the measurements of mass values of exotic nuclei [9-10], i.e. of binding improve the accuracy of astrophysical calculations.

2. Experimental improvements for exotic fragment collection planned at GANIL

Some ten years ago, a pioneering experiment[11] 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 are lower, in part because of the thinner targets one can use at lower energies, 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 is 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.

Yet improvements can be made, and are actually planned, for the efficiency of the study of exotic nuclei at GANIL in two domains, mass measurements and spectrocopic studies.

2.1 Mass measurements at GANIL

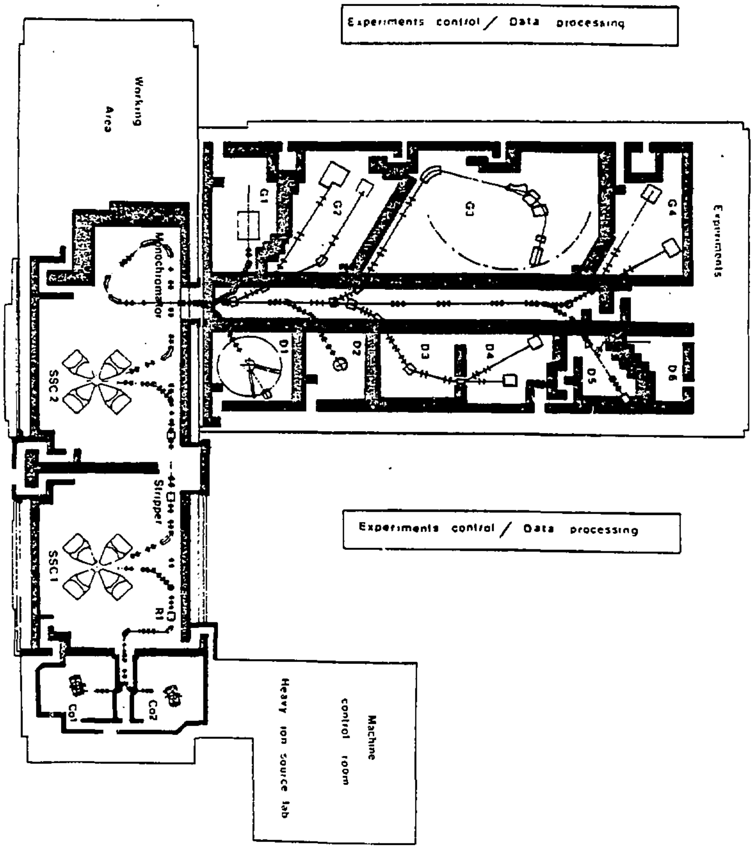
Absolute mass measurements have been obtained from precise determination of two independent parameters of the fragments. The method has been described elsewhere [9]. The magnetic rigidity is measured by the SPEG spectrometer with a FWHM of 10^{-4}. Its time of flight is determined along a flight path some 100 meters long, since the target is exceptionally located near the exit of the second and last sector separated cyclotron of GANIL, while the fragment is detected in the focal plane of SPEG (fig. 1). New mass values, with accuracies better than 500 keV and reaching sometimes 200 keV, were obtained.

The accuracy of the measurement directly depends upon the number N of collected nuclei of a given species, roughly as $\sqrt{N}$. An important improvement will then come from a modification of the beam lines between CSS2 and SPEG (see fig. 1) which will increase their momentum acceptance by a factor of about 10. During the normal operation of GANIL, the beam itself has a narrow momentum distribution and is adequatly transported. But fragmentation products have a much broader distribution, which is due, to first order, to the Fermi momentum distribution of the abraded nucleons. Thus the narrow acceptance of the beam lines drastically limits the transmission of the fragments. The use of two new quadrupoles will bring, at a low cost, a very valuable increase in that respect. This modification will be in effect in the Fall of 1988.

Furthermore the statistical agreement which relates the mass accuracy to $\sqrt{N}$ implies that gains in beam intensity foreseen from the development described in § 2.3 will also be of great importance.

2.2 Spectroscopic studies of exotic nuclei.

The ß-delayed emission of γ-particles, protons and neutrons has been observed from nuclei brought to rest. The basic equipment for these studies is the LISE spectrometer[12] (fig. 2), which selects the fragments emitted from the target according to their A/Z values and collects them in a low-background area through a triple-focusing magnetic system within a 5 % momentum acceptance. Further selection has been successfully accomplished by inserting an energy degrader[13] at the intermediate focal



<u>Fig. 1</u> : This map of GANIL and its experimental areas shows the two injector cyclotrons CO_1 and CO_2 and the two successive sector-separated cyclotrons CSS1 and CSS2. The SPEG spectrometer is located in Hall G3 and the LISE spectrometer in halls D3 and D4.

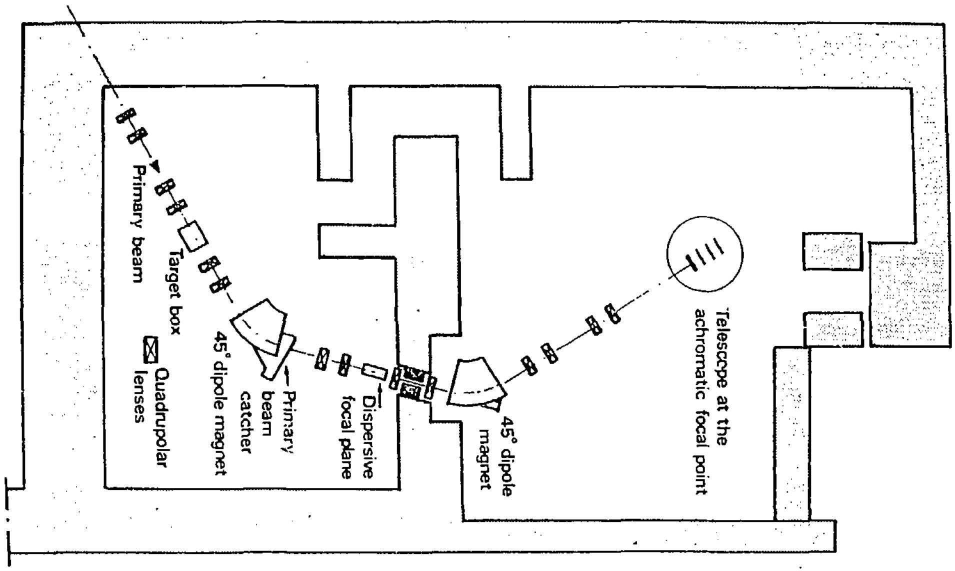


Fig. 2 : General layout of the LISE spectrometer. Note the two meters concrete shielding between the first and second sections of analysis.

point between the two dipoles of LISE. Indeed, for the nuclei of interest, the energy-loss selection operates according to a $A^{2.5}/Z^{1.5}$ law. This, when combined with the magnetic selection which follows the A/Z law, drastically restricts the number of nuclear species collected at the focal plane of LISE. Although simple in its principles, this method requires considerable care to conserve the achromaticity properties of the instrument. Furthermore, changing charge states in the energy degrader might reduce its efficiency and considerably complicate its use for high-Z fragments. Yet, for nuclei up to about Z = 20, it has brought excellent results.

Different devices have been used to observe and measure the decay properties of the exotic nuclei selected. Germanium detectors in coincidence with a plastic scintillator were used to record $\beta\gamma$ decays[14]. The β-delayed charged particle emission has been observed in the decay of new neutron-deficient nuclei such as ^{31}Ar (ref. [3]). Many results have also been obtained by detecting the β-delayed neutron emission from new neutron-rich isotopes by use of a nearly 4π detector filled with liquid scintillator located around the telescope which stops the fragments[7].

Obviously the production and study of exotic nuclei selected by LISE can directly benefit from an increase of the beam intensity.

It can also benefit from an increase in the incident energy of the heavier isotopes in three ways. First higher energy means a higher cross section for fragmentation. Second, at higher energy, fully stripped ions are obtained up to higher Z-values of the elements produced, which results in the disappearance of ambiguities due to different charge states. Third, an increased incident energy leads to more forward-peaked emission, hence to a more efficient collection of the fragments by the spectrometer within its limited angular acceptance. At last, it will be shown, in § 2.5, how these studies will benefit from further selection in LISE.

2.3 The planned increase in incident energy

GANIL was designed to accelerate beams of heavy ions produced by a PIG 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. At that time new types of sources were already being developed, but it was observed that no substantial gain in energy would be expected from their use, since they aimed mainly at the production of higher charge states.

It now appears that ECR ion sources are operational. They exhibit important advantages over the PIG sources, such as the reliability of their operation. Actually, for the last two years, GANIL has been operated with an external ECR source and an axial injection. The good characteristics in intensity obtained by higher charge states opens the possibility of accelerating ions at higher energies. Indeed the ions will reach higher velocities at the exit of CSS1 (see fig. 1). However the injection radius of CSS2 requires that their charge be increased by a factor of 3.5 in the stripper foil. This becomes impossible with incident ions in a higher charge state.

Thus the planned modification of GANIL consists in increasing the injection radius of CSS2 so that it accommodates ions which have undergone a charge increase by a factor 2.5 only in the stripper foil. In this way higher energies can indeed be obtained for the heavier elements (fig. 3). Several other changes must be operated all over the accelerating system to adapt to this new mode of operation. CSS1 will operate with harmonic 5 instead of 7. The injector cyclotron Co must be modified accordingly. It was decided to operate it with harmonic 3, which minimizes the variation of its ejection radius which must be increased by 23 mm only. These and other less important modifications have been studied[15]. They will be realized during a six-month period starting December 1, 1988, that will interrupt the normal operation of GANIL.

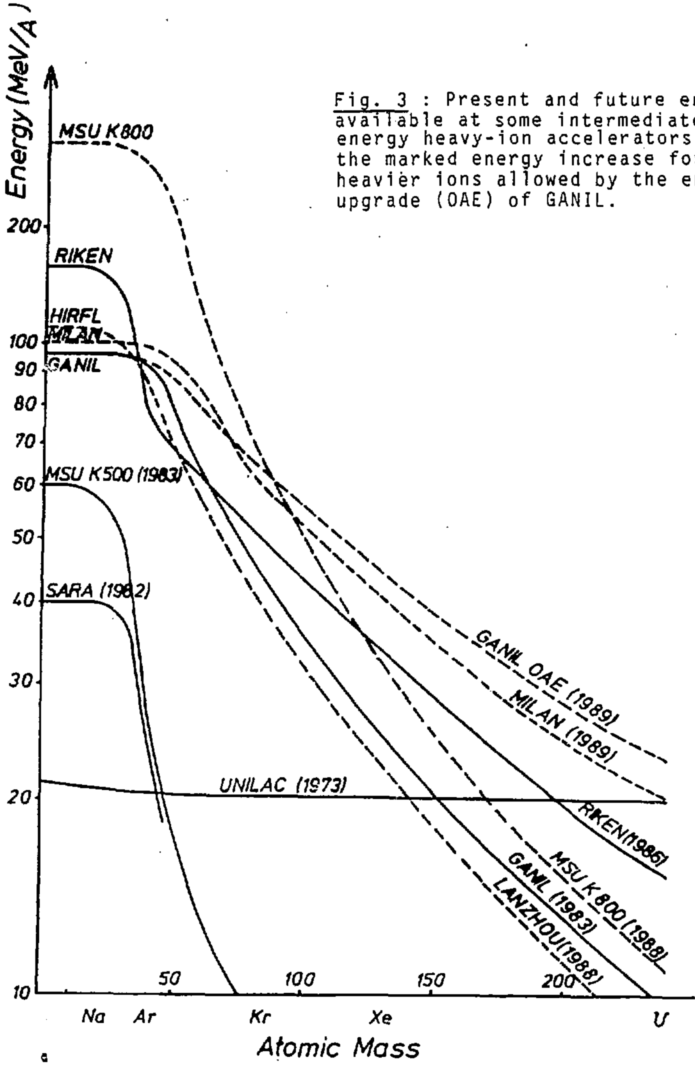


Fig. 3 : Present and future energies available at some intermediate-energy heavy-ion accelerators. Note the marked energy increase for heavier ions allowed by the energy upgrade (OAE) of GANIL.

2.4 The planned increase in beam intensity

The actual operation of GANIL has shown that the main limitation to an increase of the intensity will soon not come from the ion sources themselves but from the beam transport system. More precisely, it is in the axial injection part of this system, between the source and the injector cyclotron, that major losses occur due to charge space effects. The beam of very slow highly charged ions cannot be confined in the transversal direction, and neither in the longitudinal direction, after it has been bunched to enter within the phase acceptance of the cyclotron. The efficiency is limited to 10 % for the transmission from the ion source into the cyclotron, with an overall limit of 3 eμA.

A drastic improvement will come from a modification of this system, now fully studied, and which will be put into effect by the second half of 1990, after the completion of the operation described in the preceeding paragraph (§2.3).

It consists in two different improvements.

First, the ion source will be put on a platform at 100 kV instead of the 20 kV presently used. As a result the bunched ions will be transfered more swiftly into the cyclotron, the length of the faster moving bunch will be longer, both effects reducing considerably the effects of charge space. Beams up to 10 or 15 eμA should be correctly transported in that way.

Second, the optical aberrations in the line have been calculated in detail and will be appropriately corrected. The transmission efficiency should then reach about 40 %.

It is clear that these improvements, together with new gains anticipated for ions source productions, should result in an increase in the intensity of the beam on target by one order of magnitude. Light ion intensities are expected to reach at least 10^{13} ions per second.

This is of course directly beneficial for the production and study of nuclei far from stability.

2.5 A third selection in the LISE spectrometer

As indicated in §2.2, the selection imposed by the LISE spectrometer, is twofold. On one hand magnetic rigidity selects the fragments from the projectile, which are supposed to have all the same velocity close to the beam velocity, according to this A/Z value. On the other hand, the energy degrader, in-between the two dipoles, selects these fragments according to an energy loss law which varies roughly like $A^{2.5}$ $Z^{1.5}$ in the particular conditions of operation of LISE.

However all the fragments do not have the same velocity. First, the fragmentation process itself broadens the velocity spectrum. Second, the target thickness is increased so as to increase the yield of collected fragments, up to the point where the momentum acceptance of LISE (i.e. 5 %) is fully used. Third, the degrader itself, is usually rather thick in order to enhance the selectivity of the energy-loss parameter. This further broaders the velocity spectrum.

As a result, in the focal plane of LISE, the particles selected do not usually have a unique set of A/Z and $A^{2.5}/Z^{1.5}$

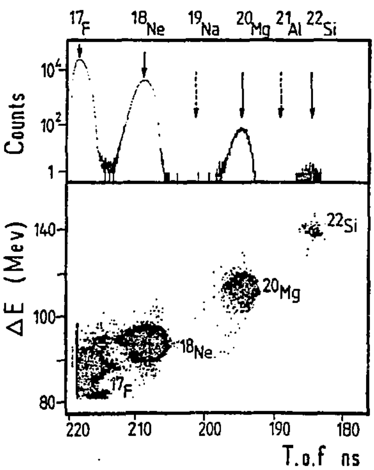


Fig. 4 : Experimental features of ^{22}Si and neighbouring nuclei observed in the reaction ^{36}Ar(85 MeV/nucleon) + Ni. Lower part: Two-dimensional display of fragments identified in the focal plane of LISE. (Spurious background events were eliminated by consideration of the redundant identification parameters) Upper part: Corresponding projected time-of-flight spectrum.

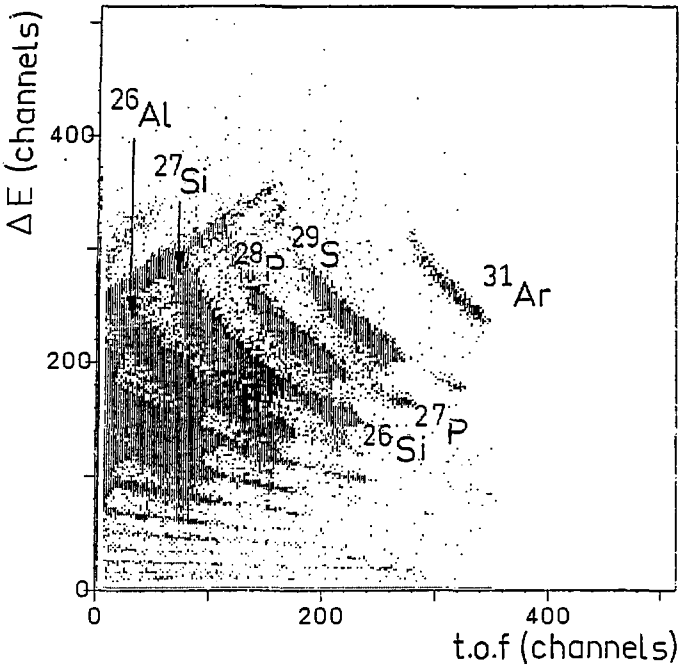


Fig. 5 : Two-dimensional display of the nuclei transmitted together with ^{31}Ar. This plot is presented without any off-line background elimination and shows all the heavy ions implanted into the telescope. Because of energy straggling in the degrader foil (477 μm thick), the isotopic separation, although sufficient for Ar identification, is not optimal.

values, within narrow limits. It is only the case in a few favourable cases, such as in the successful search for ^{22}Si (ref. [2]) where only a few isotones appear (fig. 4). In general, the broad spectrum of velocities result in a more extensive map of isotopes (fig. 5), hence in higher counting rates for the detectors.

This last effect is becoming prohibitive and presently restricts the benefits that could be expected from the improvements described in §2.3 and 2.4. Very often, with the current intensities available, the counting rates reach the tolerable limit of a few 10^3 counts per second.

Fig. 5 shows that most of this high counting rate comes from nuclei closer from stability which are of no interest for the experiment. Typicaly in the study of ^{27}S, which is very similar to the study of ^{31}Ar presented in fig. 5, the counting rates increased along the line of isotones from a few hundreds of counts for ^{27}S to several 10^5 for ^{23}Mg.

Thus it is clear that selecting a restricted zone of time-of-flight values would drasticaly reduce the counting rate, i.e. increase the selectivity of LISE.

For that purpose, a velocity selector, as a third stage of LISE, has been designed and will operate by the end of 1989.

It is a 10 m long device (fig. 6) consisting of 4 quadrupoles, 3 small-angle dipoles and a 4 m long electrostatic

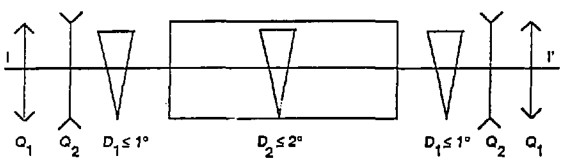


Fig. 6 : Sketch of the planned third stage of selection of LISE. The electrostatic deflector is represented by the rectangular box.

deflector. The selected isotope will emerge with a horizontal trajectory, while isotopes with different A/Z values (i.e. velocity values, since the Bρ selection has been operated) will emerge deflected. A 1.5 mm per % of velocity (or A/Z value) will be obtained.

In this way it is anticipated that it will be possible to make full use of the yield increase allowed by the increases in energy and intensity described in §2.3 and 2.4. Also the more effective selectivity of the fragments will result in better conditions for the spectroscopic studies of the transferred nuclides.

3. Other studies of exotic nuclei of astrophysical interest

The properties of exotic nuclei have consequences on astrophysical problems not only through the β-decay processes far from the line of stability which are determinant for nucleosynthesis, but also through the nuclear reactions induced by radioactive nuclei which occur in thermonuclear processes. The first reactions induced by radioactive beams have recently been studied at the Bevalac by Tanihata and his coworkers[16].

Exciting possibilities exist for the use of the large cross sections offered by fragmentation processes to produce radioactive nuclei emitted forwards and to analyse them through equipments such as LISE in order to form a beam of sizable intensity. Interesting results can be obtained in that way[17-18] (Table 1).

However the beams directly formed in that way are not always of practical use . First, as examplified in fig. 7, they are not pure, the level of contamination by other species depending strongly on the selection process. Furthermore they have too high a velocity to allow for two-body reaction studies, and their emittances are very poor.

All these defects can be suppressed is such beams are cooled, and decelerated in a ring as planned at the forthcoming SIS/ESR facility at Darmstadt.

Production mode			Secondary beam		
			Energy (MeV/u)	I/I_0	I (pps)
44 MeV/u + 99 mg/cm2	^{40}Ar Be	^{41}K	32	5.10^{-5}	$1.5.10^{7}$
		^{39}Ar	35	3.10^{-4}	10^{8}
		^{38}Ar	34	10^{-4}	3.10^{7}
		^{39}Cl	34	10^{-4}	3.10^{7}
		^{38}S	36	6.10^{-6}	2.10^{6}
45 MeV/u +	^{22}Ne				
332 mg/cm2	Ta	^{18}C	36	3.10^{-10}	3.10^{2}
417 mg/cm2	Ta	^{11}Li	36	$2.5\ 10^{-10}$	$2.5\ 10^{2}$
45 MeV/u + 187 mg/cm2	^{18}O Be	^{17}N	39	10^{-5}	10^{7}
		^{18}N	39	5.10^{-7}	5.10^{5}
		^{14}C	39	10^{-5}	10^{7}
		^{16}C	38	$\sim 5.10^{-7}$	5.10^{5}
		^{17}C	38	2.10^{-8}	2.10^{4}
		^{18}C	38	3.10^{-10}	3.10^{2}
		^{13}B	39	2.10^{-7}	2.10^{5}
		^{14}B	39	10^{-8}	10^{4}
		^{15}B	39	2.10^{-9}	2.10^{3}
		^{11}Be	39	2.10^{-8}	2.10^{4}
		^{12}Be	39	10^{-8}	10^{4}
		^{8}Li	38	8.10^{-8}	8.10^{4}
		^{9}Li	38	2.10^{-8}	2.10^{4}
65 MeV/u + 567 mg/cm2	^{18}O Be	^{17}N	46	$\sim 5.10^{-5}$	$\sim 5.10^{7}$
		^{18}N	47	2.10^{-6}	2.10^{6}
		^{14}C	46	$\sim 5.10^{-5}$	$\sim 5.10^{7}$
		^{16}C	50	2.10^{-6}	2.10^{6}
		^{13}B	47	2.10^{-6}	2.10^{6}
		^{14}B	47	2.10^{-8}	2.10^{4}

Table 1

Some examples of intensities obtained for secondary beams as compiled in ref.[18]

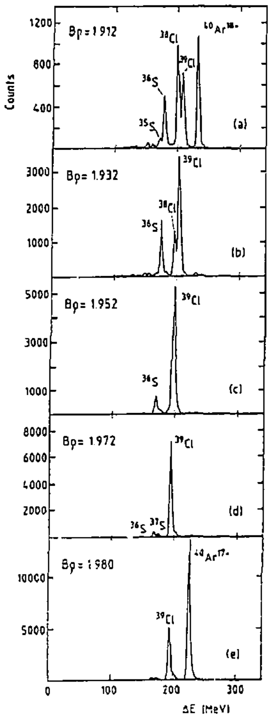


Fig. 7 : Effect of a Bρ variation on the ^{39}Cl secondary-beam purity. The beam compositions (ΔE spectra) are shown for 5 different values (in Tm). The ordinate scale corresponds to arbitrary units. The most abundant isotopes which compose the secondary beam are indicated next to the corresponding peaks.

Another possibility to obtain pure radioactive beams is to inject a flow of radioactive atoms, produced elsewhere with reasonably long half lives, in the ion source of an accelerator, dedicated or not. Several reports at this conference present such projects. A very promising one exists at Louvain-la-Neuve[19] (fig. 8). It uses one smaller cyclotron, CYCLONE 30, as a radioisotope factory to produce ^{13}N atoms which are fed into an ECR ion source, then accelerated by the major cyclotron CYCLONE to induce the H(^{13}N,γ)^{14}O reaction of obvious astrophysical interest. Beams of up to 8.5 nA of ^{13}N are expected.

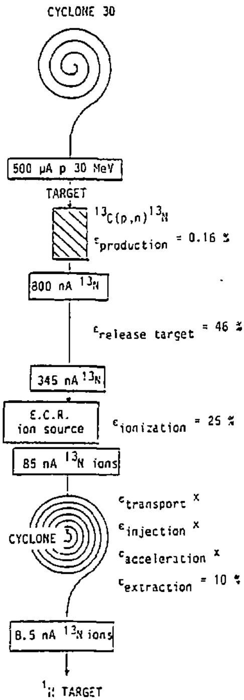


Fig. 8 : General scheme and estimate of the ^{13}N beam intensity in Louvain-la-Neuve project.

Some developments will be made at *GANIL towards the use of radioactive* beams beyond the recent total cross section studies[20]. First the gains in intensity and selectivity expected from the operations described in chapter 2 will make the high velocity radioactive beams purer and more intense. Second, a new spectrometer is currently studied, which would allow a large gain in *efficiency over LISE because its* broader angular acceptance. It would consist of a doubly achromatic system. In one operating mode, the first part of the spectrometer would select a radioactive species which could impinge on a target at the intermediate focal point, while the second part would analyse the isotopes produced in such an exotic-nucleus induced reaction.

Since many cross sections correspond to nuclear reactions of a astrophysical interest of the type $A\ (p,\gamma)B$ where A might be a radioactive nucleus, it has been proposed, when possible, to study the time-reversed reaction. If B is a nuclide which can be easily accelerated, this inverse reaction can be induced by making B interact with the electromagnetic field of another nucleus, preferably a heavy one. It is then possible to detect the proton and the A nucleus emitted, and to select those cases where their relative energy is low, as it is in astrophysical situations. Such an attempt to measure the $^{13}N(p,\gamma)^{14}O$ cross section at some 500 keV proton energy will be made this Fall at GANIL[21]. *In the first stage of the experiment an* ^{16}O *beam will be* used. The calculations show that high energy favours the cross section of the time-reversed reaction. Furthermore GANIL energies and equipments are well suited to detect both the proton and ^{15}N in a very small angle around 0° to make sure that only a very peripheral interaction (i.e. in the Coulomb field only) has occured. In a later stage, ^{14}O nuclei selected by LISE as discussed above could be used. It appears that this method, if it can be successfuly implemented, could be extended to other reactions of astrophysical interest.

Summary

The many new results obtained at GANIL on nuclei far from stability in the recent years point to the interest and possibility of achieving spectroscopic studies for such unusual nuclear species. Their role in the r-process, the large probabilities that they exhibit for radioactive modes which are poorely known or even absent for nuclei closer to stability make this field of nuclear physics a natural ground for cooperation with astrophysics. The new developments planned at GANIL for the next two years should allow a further extension of these studies, typically by two more isotopes on the neutron-rich side. It is also worth noting that the development of radioactive beams and the use of GANIL for studying time-reversed reactions for the measure of cross sections of astrophysical interest present valuable possibilities which are only in their initial stage.

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