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A.C.C. Villari and the SPIRAL group.

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GANIL (IN2P3/CNRS - DSM/CEA), B.P. 5027, 14021 Caen Cedex, France

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The present status of the radioactive ion beam facility SPIRAL, currently under construction, is given. SPIRAL is based on the very high intensity beams which will become available in the near future at GANIL (^2H to ^{40}Ar at 6kW and 96A MeV). The facility will produce radioactive ion beams using the ISOL (Isotopic Separator On-Line) method and a permanent magnet ECRIS (Electron Cyclotron Resonance Ion Source) which will allow for the production of multiple charged radioactive ions. The beam will be accelerated by a K=265 compact cyclotron and delivered to the existing experimental areas of GANIL.

1. INTRODUCTION

The SPIRAL [1] project at GANIL was funded in December 1993 by the IN2P3/CNRS, DSM/CEA and the Regional Council of Lower Normandy. Under the project leader, M. Marcel Lieuvain, a large collaboration [2] between laboratories in France and Europe has been established in order to construct and develop SPIRAL. The project is based on the ISOL technique for production of Radioactive Ion Beams (RIB).

The primary light or heavy-ion beam accelerated by the GANIL cyclotrons will bombard a production target located inside a well shielded cave (Figure 1). The radioactive atoms produced by nuclear reactions will be released from the target, which will be at high temperature (~ 2300 K), and will pass through a transfer tube into a permanent magnet ECRIS. The radioactive atoms will then be ionised up to charge states corresponding to $q/m = 0.09$ to 0.40 . After extraction from the ECRIS, the low energy RIB (acceleration voltage from 7kV to 34kV) will be selected by a relatively low resolution separator ($\Delta m/m = 4 \times 10^{-3}$) and injected into the new K=265 ($B_p = 2.344$ Tm) compact cyclotron CIME. The corresponding energy range varies from 1.7A to 25A MeV. After acceleration, the RIB will be selected in magnetic rigidity by the modified α -shaped spectrometer and directed to the existing experimental areas. The separation between isobars will be performed for the most part by the cyclotron (which is a good spectrometer for fast ions [3]) with a resolution of $\Delta m/m \sim 5 \times 10^{-4}$. It is also possible to improve the resolution of the cyclotron with an appropriate detuning of the isochronism during the acceleration of the ions. This procedure can improve the resolution in mass to $\Delta m/m \sim 1 \times 10^{-4}$ [4]. Additional separation can be achieved by placing a stripper foil or a degrader in the dispersive focal

plane of the spectrometer . In the latter case, however, significant losses in RIB intensity will occur.

Figure 1. Schematic view of the GANIL accelerators and the SPIRAL project.

SPIRAL will be operational in 1998 and experiments are planned to be programmed for the end of 1998

In parallel with the construction of SPIRAL, an important R&D effort is devoted to the production of RIB. Studies have been performed mainly with a view to optimising the production of rare gases using a carbon target. This target has been tested at high intensity (6kW of 30MeV protons) at Louvain-La-Neuve.

2. THE THI UPGRADE.

Today GANIL provides beams with intensities reaching 6×10^9 to 2×10^{12} pps for ions from ^{238}U to ^{12}C at energies from 24A to 96A MeV. The combination of the new ECR4 source operating at 14.5 GHz and an injection stage at 100 kV, has improved the intensity of the beam delivered to the second cyclotron (CSS2) to 2×10^{13} pps for ions up to ^{40}Ar and increased significantly the intensity for heavier beams. The safely transport of this high intensity beam through the second cyclotron up to the SPIRAL target is based in three main prerequisites:

1. The verification of the majority of power supplies for the accelerators.
2. The fast shut down of the beam if an abnormal intensity loss is detected.
3. The reduction of the phase width at the entrance of the cyclotron CSS2 using the new rebuncher R2.

The rebuncher R2 is necessary in order to increase the transmission through CSS2, which will be of the order of 98% after its installation. R2 has already been installed in the beam line and is presently being tested on-line. The improvement of the primary beam intensity as well as the possibility of acceleration of lighter ions down to ^2H is of paramount importance for the SPIRAL project, as the full intensity and variety of primary beams will be used for the production of RIB. The first high power beam should be accelerated in spring of 1997.

3. THE PRODUCTION SYSTEM.

The production cave is placed in a well shielded area beneath ground level in the machine building. In addition to the target-ion source system, both high and low energy "front-ends" will be installed in the cave. A view is shown in figure 2. Importantly, each component can be remotely removed from the cave.

Figure 2.

The production cave of SPIRAL.

- 1 - Target-Ion source
- 2 - High energy front-end
- 3 - Low energy front-end.

In the classic ISOL technique a proton or a light-ion beam is accelerated to a high energy and bombards a thick target producing radioactive nuclei by spallation reactions, fragmentation of the target and/or induced fission. Other reaction mechanisms, however, come into play with heavy ions. In particular, projectile fragmentation is the process of most importance. In all cases, the fragments are stopped in the target which is heated to a high temperature (1800K to 2300K) to facilitate the migration of the radioactive atoms to the surface. Usually the target is located a short distance from the ion source and the radioactive atoms effuse via a transfer tube to the plasma region where they are ionised and then accelerated. However, given the relatively short range of heavy ions (typically they stop in the production target) one may consider employing very small targets located inside the ion source. Such a configuration would thus eliminate the losses due to sticking of radioactive atoms in the transfer tube - a major source of losses in systems presently in use. As the atoms are ionised and accelerated in a manner identical to that for stable beams, the resulting radioactive beams have good dynamical and optical characteristics when compared with projectile fragmentation, as well as an energy which may be precisely adjusted. The originality of the GANIL project lies in the use of an extended range of heavy-ions, up to the maximum available energies (e.g..

96A MeV for ^{36}Ar). Such an approach differs from the proton (or light-ion) beam technique in that the projectile rather than the target is varied in order to produce the different radioactive species, thereby allowing the use of the most resilient and efficient production target for most cases.

For the commissioning of SPIRAL, a solution based on an external carbon target linked to the ECR source by a short transfer tube has been chosen. This simple system will deliver the first noble gas radioactive ion beam for SPIRAL. The carbon target has been chosen due to its excellent release properties, low atomic number and high sublimation temperature. This target guarantees the production of noble gases with reasonable yields [5] and can be used with high power primary beams. This requirement has necessitated the development of a special target design which can withstand such power loads while conserving fast release properties. From the production point of view, the temperature of the target should be as high as possible and its profile should be as uniform as possible, in order to minimise the delay time between production and release. The temperature profile is related to the properties of the Bragg peak, which is particularly pronounced in the case of heavy ions. Therefore, a special conical design which distributes uniformly the power density over the volume of the target has been developed (figure 3). This target has been tested successfully at Louvain-la-Neuve, Belgium using a 6kW proton beam of 30MeV. The range and shape of the Bragg peak of 30MeV protons is very similar to ^{20}Ne at 100A MeV. In figure 4 we show the evolution of the experimental temperature measured at two different radii in the target. The results are compared with a simulation which takes into account the geometry of the full system.

Figure 3.

The conical carbon target used in the Louvain-la-Neuve experiment with a 6kW proton beam. The slices are 0.7mm thick. The largest diameter is 45 mm.

Figure 4.

Evolution of the temperatures measured in the conical target with a 30MeV proton beam. Initial temperature : 300K.

Comparison with simulation:

T1 is the temperature measured at $r=1\text{cm}$ in the 23rd slice.

T2 is the temperature measured at $r=1.6\text{cm}$ in the 30th slice.

The permanent magnet ECRIS developed for ionising the radioactive atoms released from the production target, NANOGAN II, has a performance similar to an ECR-3 ion source (Caprice type) [6] such as that for the first tests with the separator SIRa [5]. The full system will be tested on-line in November 1996 using the separator SIRa before installation in the production cave. The first beams which will be accelerated with this system are listed in Table 1.

A new target-ion source system has been constructed for the production of condensable elements. This system has the target inside the ECRIS chamber. The primary beam crosses the ion source axially and hits the target placed downstream in the plasma region. Preliminary tests have demonstrated the viability of such a system. Using a primary ^{36}S beam (100pA) at 78A MeV, we have produced ^{35}S , $^{29,30,34,35}\text{P}$, $^{27-29}\text{Al}$, $^{27-29}\text{Mg}$, $^{24-26}\text{Na}$, $^{23-26}\text{Ne}$, $^{20-22}\text{F}$ and $^{20-22}\text{O}$. Preliminary results show that the efficiency of the system for noble gases is similar to that with an external target. For condensable elements the efficiency is one or two orders of magnitude smaller, as expected.

4. THE CIME CYCLOTRON.

CIME (Cyclotron pour Ions de Moyenne Energie) is a room temperature compact cyclotron of $K = 265$ with an average magnetic field between 0.75 and 1.56T and an ejection radius of 1.5m. The energy range is 1.7 to 25A MeV. The beam emittance at injection is limited to 80π mm mrad and at ejection will be below 10π mm mrad.

The magnetic is somewhat original and has 4 return yokes made of stacked thick slabs. This structure was chosen not only for its compactness but also for the resulting field homogeneity and low fabrication costs. The

magnet was manufactured by CREUSOT-LOIRE. The magnet has been put in place and the first field measurements are currently in progress (July 96).

The design of the RF resonators is rather classical with a cantilever dee and a sliding short circuit using spring contacts around the stems. One difficulty has been the design of a structure sufficiently rigid to avoid unacceptable sag of the dee and temperature dependent deformations. The resonators were ordered from SDMS (St. Romans, France) and delivery is foreseen in May 1997.

The injection into the cyclotron is made axially using a Mueller inflector of radius 34mm. This inflector has been optimised for the 3rd harmonic, corresponding to an energy range of about 4.8 to 11A MeV. The harmonics 2,3 and 4 can be accelerated with this central geometry. For harmonic 5, corresponding to the energy range 1.7A to 2.5A, a new inflector with a radius of 45mm is being investigated. In this case, a change of dee noses will be necessary.

The beam extraction is performed using two electrostatic and two magnetostatic channels with variable positions. The overall transmission of the cyclotron should vary from 30 to 60 % depending on the harmonic and energy of the accelerated beam.

The diagnostics of the beam inside the cyclotron will involve particle detectors, allowing for the tuning of very low intensities. Successful tests of a system involving a plastic detector placed on the radial probe of the CSS2 cyclotron have been performed recently.

5. SUMMARY.

In summary, we have presented a brief status of the SPIRAL project at GANIL. The production cave is presently being equipped and the first stable beam will be delivered in the fall of 1997. The magnetic circuit of the cyclotron CIME has been completed and the field measurements are in progress at the time of writing. The first stable beams will be accelerated at the end of 1997, while commissioning of the target and source assembly will begin in early 1998.

The first beams from SPIRAL are proposed to be noble gases with energies of 2.7 to 25A MeV, as shown in the Table 1. This table also lists the intensities expected after the first low resolution separator as well as the energies ranges after acceleration by CIME. The intensities has been extrapolated from the measurements made at 400W using SIRa or calculated using the code INTENSITY [7] and the experimentally measured efficiencies.

Table 1. Expected RIB intensities and energies for the first beams from SPIRAL.

Beam	RIB Intensity after the low energy separator (1). (pps)	Harmonic 3 Harmonic 2 30% ≤ T ≤ 40% (5)			Harmonic 4 10% ≤ T ≤ 30%(5)	
		W _{min}	W _{max} (MeV/amu)	W _{max}	W _{min} (MeV/amu)	W _{max}
⁶ He	6×10 ⁸ (2)	4.8	10.9	22.8	2.7	6.1
⁸ He	2×10 ⁶ (2)	"	"	16.3	"	"
¹⁷ Ne	5×10 ⁵ (2)	"	"	24.3	"	"
¹⁸ Ne	5×10 ⁷ (2)	"	"	22.9	"	"
¹⁹ Ne	7×10 ⁸ (2)	"	"	21.6	"	"
²³ Ne	2×10 ⁸ (3)	"	"	17.3	"	"
²⁴ Ne	7×10 ⁷ (3)	"	"	16.5	"	"
²⁵ Ne	5×10 ⁶ (3)	"	"	15.2	"	"
²⁶ Ne	7×10 ⁵ (3)	"	"	14.0	"	"
²⁷ Ne	5×10 ³ (3)	"	"	13.0	"	"
³² Ar	1×10 ³ (2)	"	"	21.4	"	"
³³ Ar	3×10 ⁵ (2)	"	"	20.7	"	"
³⁴ Ar	2×10 ⁷ (2)	"	"	20.1	"	"
³⁵ Ar	9×10 ⁸ (2)	"	"	19.5	"	"
⁴¹ Ar	3×10 ⁸ (4)	"	"	15.7	"	"
⁴² Ar	2×10 ⁸ (4)	"	"	15.0	"	"
⁴³ Ar	1×10 ⁸ (4)	"	"	14.3	"	"
⁴⁴ Ar	5×10 ⁷ (4)	"	"	13.7	"	"
⁴⁵ Ar	2×10 ⁷ (4)	"	"	13.0	"	"
⁴⁶ Ar	6×10 ⁶ (4)	"	"	12.5	"	"
⁷² Kr	4×10 ³ (2)	"	"	11.4	"	"
⁷³ Kr	4×10 ⁴ (2)	"	"	11.1	"	"
⁷⁴ Kr	1×10 ⁶ (2)	"	10.8	-	"	"
⁷⁵ Kr	3×10 ⁶ (2)	"	10.8	-	"	"
⁷⁶ Kr	5×10 ⁷ (2)	"	10.2	-	"	"
⁷⁷ Kr	9×10 ⁷ (2)	"	10.0	-	"	"

- (1) - The primary beam intensity is limited by security reasons to 2×10¹³ pps or 6 kW. The RIB intensity depend on the charge state used in the acceleration. The RIB intensities in the table are for He(1+), Ne(5+), Ar(8+) and Kr(10+).
- (2) - Intensity extrapolated from measurement at 400W with the SIRa separator.
- (3) - Calculated intensity using the parameters of the production system determined at SIRa and supposing a 6kW ³⁶S primary beam.
- (4) - As for (3) with a 1kW ⁴⁸Ca primary beam.
- (5) - Transmission with a Mueller inflector optimised to harmonic 3 and R_{inj} = 34mm.

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LPC/IN2P3-Caen, CENBG/IN2P3-Gradignan, CSNSM/IN2P3-Orsay,
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Service de Prototypes/CNRS-Meudon Bellevue.
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