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S^3 (Super Separator Spectrometer) is a device proposed for experiments with the very high intensity stable beams of LINAG, the superconducting linear accelerator of GANIL, which will be built in the framework of SPIRAL2. These beams, which will provide in a first phase of SPIRAL2 ions with A/q = 3, can reach intensities exceeding 100pμA for lighter ions (A$<$ 40 $-$ 50) depending on the final choice of the ECR (Electron Cyclotron Resonance) ion source. These unprecedented intensities open new opportunities in several physics domains, e.g. super-heavy and very-heavy nuclei, spectroscopy at and beyond the dripline, multi-nucleon transfer and deep-inelastic reactions, isomers and ground state properties and nuclear molecular resonances. An international collaboration interested in the aforementioned physics has been formed for developing technical solutions for this new instrument.

Keywords: Super-heavy, spectroscopy, transfer, fission, separator spectrometer

1. Introduction

The unprecedented intensities of the LINAG accelerator, the driver of the SPIRAL2 project [1], open new opportunities in several physics domains. These were discussed in the *SPIRAL2 Reactions Workshop* in October 2005 at GANIL and in the first meeting of the S^3 working group, in Paris, the 27-

28 June 2006. The main topics, which are addressed within the framework of S^3 are listed below.

1. Synthesis of Super-heavy elements
2. Very- and super-heavy element spectroscopy and chemistry
3. Study of reaction mechanisms and product distributions
4. Multi-nucleon transfer and deep-inelastic
5. Spectroscopy at/beyond the proton drip line
6. Nuclear molecular resonances
7. Production and study of isomers
8. GT strength through charge exchange reactions
9. Ground state properties of nuclei

All these subjects have the common feature of requiring the separation of very rare events from intense backgrounds.

Very rare events and excellent background suppression are, in fact, the central issues of this project. The importance of having a high intensity primary beam for observing rare events can be understood simply if one takes super-heavy synthesis as an example: Present technology allows one to use about 1pμA beam intensity of a heavy ion (^{70}Zn for instance) on a target (such as ^{208}Pb of 450μg/cm^2 thickness). Standard separators have transport efficiencies around 50% for the mentioned example [2]. Adopting a cross section of the order of 1 pb (which is the order of magnitude of the cross section for the synthesis of element 112 [3]), one arrives to a production yield for the synthesis of element 112 of about 6 events per month. This can be considered as the lower limit cross section for nuclear physics studies to identify and measure the first properties of ground states. Increasing the target thickness does not increase the yield, because the value of the mentioned cross section is only valid in a very tiny window in the excitation function, corresponding to an energy loss of about 5 MeV in the target. The gain in improving the separators cannot be larger than a factor 2. The only way to increase the sensitivity one or two orders of magnitude, i.e. to reach equivalent yield of 6 events per month for 0.1-0.01 pb, is to increase the beam intensity by one or two orders of magnitude.

With S^3, the study of *non-limiting* topics can also be improved significantly

For a factor 10 increase of beam intensity, all experiments, which can be performed today in one week, could with LINAG be performed in one day. For a factor 100 increase of beam intensity, all experiments, which can be today performed in one month, could be performed in less than one day. Possibilities will exist for measurements of masses, lifetimes and other fundamental ground state properties of extremely exotic nuclei that are currently not inaccessible with present yields, thereby, helping to build a better picture of the structure of nuclei at the extremes. Important measurements in other fields, such as astrophysics (study of GT strength with charge exchange reactions and properties of N=Z nuclei) or the production of long-lived isomers would also be enabled.

Various nuclear reactions, which could be studied with S^3 include:

(a) Fusion-evaporation
(b) Fusion-fission
(c) Massive-few nucleon transfer
(d) Deep inelastic
(e) Charge exchange

All these reactions have different kinematics and, as a consequence, different requirements for the separator and detection system. For a lot of them, the interesting reaction products are emitted at 0° along with the beam. In all cases the need of a separator and/or a spectrometer with unprecedented primary beam rejection is of paramount importance.

The need of a Separator/Spectrometer with very high primary beam rejection is a common technical requirement for all these studies

The S^3 collaboration proposes a Separator/Spectrometer tailored to respond to most of the requests of each physics topic. The main requirements are listed below.

(1) Primary beam suppression larger than 10^{12}
(2) Reasonable angular acceptance, of the order of 100 mrad
(3) Not only a zero degree device
(4) Different operation modes
(5) Adaptable to a wide energy range
(6) Wide momentum acceptance
(7) compatible with various detection apparatus

The resolution of the spectrometer is not considered as a crucial requirement at this stage of the studies. Anyhow, it has to be variable, depending on the various operating modes of the spectrometer. It will be defined at a later stage of the design.

High intensity primary beams for heavier nuclei ($A > 40 - 50$) are also a priority.

The acceleration of very high intensity heavier nuclei (A $> 40 - 50$) by LINAG opens new possibilities, such as working in inverse kinematics. This includes the possibility of using S^3 as an in-flight mass separator and performing reactions with exotic secondary beams. This option is only possible with the implementation of a RFQ with A/q = 6 and the use of the most advanced ion sources. Therefore, it is strongly requested to have the highest possible intensity for the whole range of masses. An estimation of the production yields for the ion source A-Phoenix and beams accelerated by an injector optimized for A/q = 3 and A/q = 6 is shown in Figure 1. Moreover, the need of a target, which can withstand such very high intensities delivered by LINAG is also an important requirement to be included in the design of the Separator/Spectrometer. The size of the object point of the separator on the target together with the angular acceptance defines the maximum emittance to be transported.

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The acceleration of very high intensity heavier nuclei (A$> 40 - 50$) by LINAG opens new possibilities, such as working in inverse kinematics. This includes the possibility of using S^3 as an in-flight mass separator and performing reactions with exotic secondary beams. This option is only possible with the implementation of a RFQ with A/q = 6 and the use of the most advanced ion sources. Therefore, it is strongly requested to have the highest possible intensity for the whole range of masses.

2. Methodology

2.1. *LINAG beam characteristics*

Beams from p to U will be available in LINAG with maximum intensity for heavy ions of the order of 1 mA (electric). The energy available ranges from 2A MeV to 14.5A MeV with a time resolution of the order of 200 ps (FWHM) for energies exceeding 3A MeV. The size of the beam on the target of S^3 is requested to be in the range of 2 mm (HO) x 20 mm (VE) with a flat beam profile flat (not parabolic or Gaussian) in order to spread the energy deposit on a wide area. As mentioned above, it is strongly requested to have the highest possible intensity for the whole range of masses. This is also important for working in inverse kinematics, opening the possibility to use S^3 as an in-flight mass separator and perform reactions with produced exotic species.

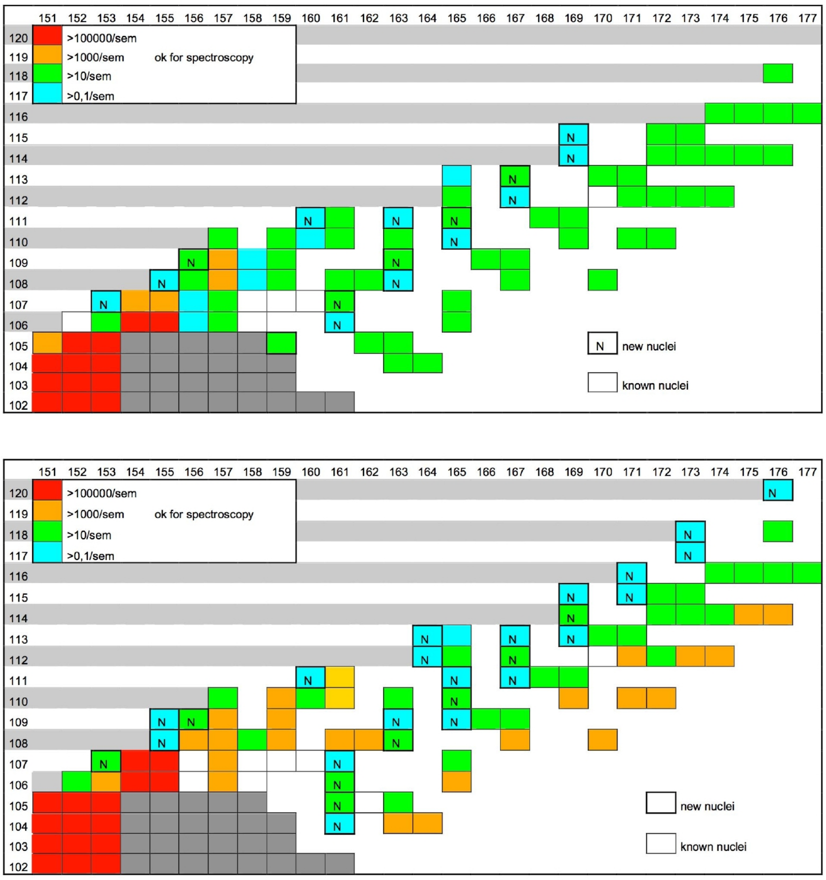

Fig. 1. The expected counting rates for selected SHE, with the ion source A-PHOENIX (for PHOENIX reference, see [4] and RFQ injector optimized for A/q = 3 (upper) and A/q = 6 (lower). With few exceptions, we have considered only 1n, 2n and 3n channels for cold fusion, and known hot fusion reactions from Z=112 to Z=118 (see [5]). We notably did not take into account reactions with lighter Ca isotopes or with symmetric systems, which leads to new isotopes. For cold fusion reaction (^{208}Pb targets), cross section systematic has been considered. For hot fusion reaction (^{48}Ca beams on actinides targets), measured cross sections have been considered. Target thickness is 400μg/cm2, set-up efficiency is 50%. Orange and red codes indicate that delayed spectroscopy can be performed for those nuclei. Blue and green indicate that the expected count rate is sufficient for synthesis confirmation.

2.2. *Targets*

Targets of any nature, including actinides, are needed in these experiments. Solid, liquid and gaseous targets will be used with thickness from 100

μg/cm^2 to about 2 mg/cm^2. In all cases, the beam is not stopped in the target. Currently, rotating targets are known to sustain intensities of the order of 1pμA (*e.g.* [6]).

The first questions which could emerge concerning the target is: How can a target survive under such huge beam intensity?

We propose some simple calculations, which seem to indicate the way to proceed, at least for solid targets mounted on wheels. The difference from current wheels is that the beam spot is multiplied by a factor of around 5 in ONE direction (not in both directions) and the speed of the wheel is significantly higher, when compared with present systems. These two assumptions seem to make it possible the use of very high beam intensities in S^3.

The simulations were done with the following assumptions and steps:

- Only cooling by radiation is taken into account. This is justified by the fact that the thickness of the target is small ($<$ 1mg/cm^2), which means that conductance can be neglected. Anyhow, conductance will help cooling, therefore the temperatures can be considered as overestimated.
- A simple radiation cooling calculation can be done considering Stefan-Boltzman black body law and supposing that the overall surface of the illuminated target radiates. This gives you the limiting temperature of the target for a wheel that turns at infinite speed. This is interesting to fix the maximum limits of the system and guide the following calculations.
- The code *Stefan* written by Roland Dayras (CEA/Saclay) is used to estimate the maximum and minimum temperatures of the target while the wheel is turning. It takes into account only radiation cooling, as mentioned above.
- In all cases, the beam profile is considered to be flat.

We show, as an example, the case of a small target wheel, for using with transactinide targets [7]. The target, in this case, could have a radius of 8 cm. Figure 2 shows a calculation for ^{48}Ca beam at 250 MeV on ^{243}Am of 450μg/cm^2. The operating temperature in this case is the ad-hoc maximum temperature allowed for the considered target (about 600°). It is roughly half the fusion temperature of the target. The emissivity used is equal to 0.8. The target contains a small fraction of carbon (helping to obtain a good emissivity). The walls in front of it should also be black. The environment is considered at the temperature of 40°C.

No calculation on the resistance of the targets was done. It should be investigated if centrifugal force influences the integrity of the target. Also

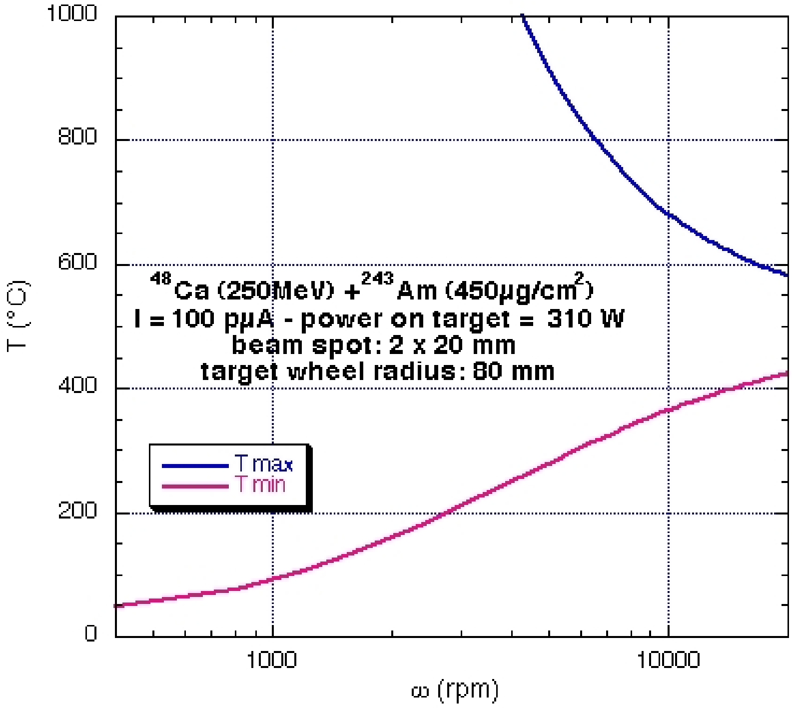

Fig. 2. Maximum and minimum temperatures of the target as a function of the speed rotation for a beam spot of 2mm X 20 mm and a target wheel of 80 mm radius.

sputtering should be considered. These targets require special development probably based on turbo-pump design. The issue of handling relatively large quantities of transactinide material (about 50 mg in this case) will also have to be addressed.

For low fusion temperature elements, e.g. lead, gaseous targets will be investigated.

2.3. *The new Super Separator Spectrometer*

In view of the various requests concerning the performance of the Separator/Spectrometer, two main concepts drive our design:

- S^3 is a two-step machine, allowing either to filter in successive stages or to work as a Separator connected to a Spectrometer
- Each stage is independent and can be turned off as necessary.

The basic concept of S^3 requires:

(a) a primary target
(b) a separator that reject the majority of the beam
(c) a secondary target or detection point
(d) a spectrometer or the second filtering part
(e) a final focal plane

The different operating modes of S^3 are briefly described below:

2.3.1. *Two stage separator*

This configuration (see Figure 3) is dedicated to experiments that need the best rejection. SHE synthesis is the best example to use this mode, as the focal plane has to be as clean as possible to avoid random correlations. Here, the second spectrometer is used as a secondary separator for a complementary rejection of unwanted particles. A combination of a Wien filter (or SHIP-like separator [8]) plus a gas filled spectrometer could be envisaged. Presently we are studying a configuration for the first separator, which uses a double dipole with a dispersive intermediate plane.

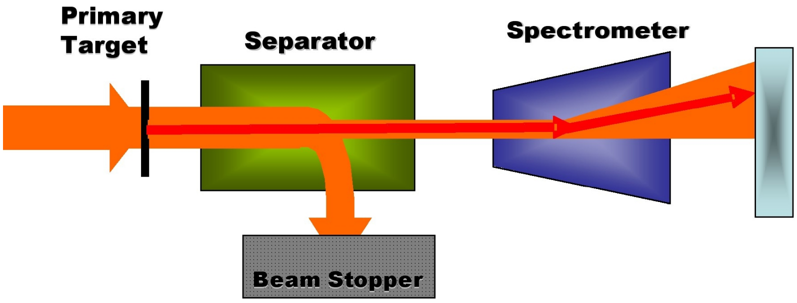

Fig. 3. S^3 in the high beam rejection mode.

2.3.2. *Secondary reaction mode*

In this mode, the interesting nuclei are still produced in the primary target point, but they can interact at a secondary target point (see Figure 4). Obviously, this can occur only if the production rate is high enough. The beam is rejected in the first part, so that the secondary target point is in a *low intensity* zone. The spectrometer part can be used as a standard spectrometer to analyze the secondary reaction products. It could measure their momentum and scattering angle and allow their identification in mass and charge. If necessary, the spectrometer can be rotated to study angular distributions.

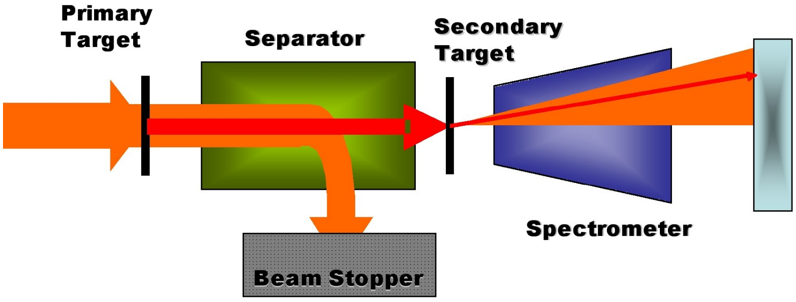

Fig. 4. S^3 in a two-stage separator mode. Most of the beam is stopped in a beam dump in the middle of the first section.

2.3.3. *Pure spectrometer configuration*

The first part of S^3 can be turned off, allowing the primary beam to be conducted up to the secondary target point (see Figure 5). This configuration shall allow the measurement of, *e.g.* multi-nucleon transfer with primary beams. The emission angles of the reaction products should be measured close to the grazing angle. The Spectrometer part can be rotated, as shown in Figure 5. The beam dump is located at zero degree. This configuration implies that the secondary target point should also be useable with relatively high beam intensities.

2.3.4. *Additional features*

(1) The primary target point can receive actinide targets and is placed in a special room, isolated from the rest of the separator. NO ANCILLARY detection can be used in this point.
(2) Preliminary studies show that an optical configuration of the Separator with a double dipole like *LISE* [9] or "ORNL-RMS" [10] and very large momentum acceptance (15%) can be a very elegant solution.
(3) The angle acceptance of the Separator is of the order of +/-75 mrad.
(4) The secondary target point allows the use of ancillary detection. It is an achromatic point.

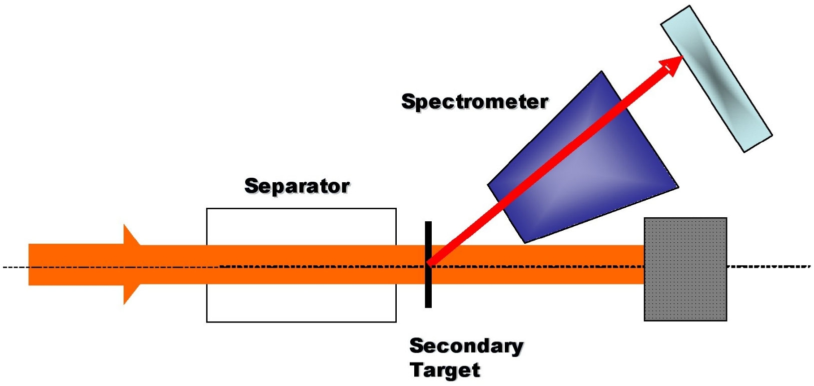

Fig. 5. S^3 in the pure spectrometer configuration.

(5) A gas cell can be placed in the Secondary target position. This allows stopping the fragments and conducting them to penning traps, for mass and decay measurements.
(6) The penning trap will be placed outside the main S^3 room.
(7) The Spectrometer can work in either standard magnetic spectrograph or gas-filled modes.

2.3.5. *Detection devices*

S^3 can be coupled to various detection devices according to the experimental requirements. We give here selected examples of detectors that could be used:

- Prompt detection around secondary target point (note that special care has to be considered for the shielding):

(a) Gamma detection: EXOGAM2, AGATA
(b) Particle detectors: MUST2, GASPARD
(c) Neutron array

- Detection at the final focal plane:

(a) Tagging detectors: MUSETT, BEST
(b) Delayed Gamma spectroscopy: EXOGAM, Germanium Box
(c) Identification detectors: For ΔE-E measurement
(d) Particle emission decay : 4π charged particle detector

(e) Tracking detectors: SeD-like emissive foil detectors for trajectory reconstruction
(f) Dedicated detection

2.3.6. *Mass measurements device*

The mass measurement device will be set up behind the S^3 separator section providing cleaner beams of ions produced in a fusion-evaporation reaction. This device will consist mainly of a cooler trap, a cleaner Penning trap and a high resolution Penning trap to carry out mass measurement. As the accuracy of Penning Trap spectrometer depends in the charge q of the measured ions, cooling of highly charged ions delivered by S^3 will give a significant improvement in the mass determination of very heavy nuclei. Depending on the counting rate and half-life of the nuclei of interest the mass spectroscopic technique will be either the Fourier Transform-ICR (non destructive, for long observation time and low counting rate) or the Time Of Flight-ICR (destructive, for short half life).

3. Summary

The unprecedented intensities of the LINAG accelerator, the driver of the SPIRAL2 project, open new opportunities in several physics domains.

S^3 (Super Separator Spectrometer) is a device designed for experiments with the very high intensity stable beams of LINAG, which will be built in the framework of SPIRAL2. These beams, which will provide in a first phase of SPIRAL2 ions with $A/q = 3$, can reach intensities exceeding 100pμA for a wide range of ions depending on the final choice of the ECR (Electron Cyclotron Resonance) ion source. Unprecedented beam suppression as well as large acceptance and different operation modes are goals for S^3.

Although the project is challenging, preliminary studies indicate that such a spectrometer is feasible. An international collaboration has formed to address the challenges of the S^3 project.

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