SUPER SEPARATOR SPECTROMETER FOR THE LINAG HEAVY ION BEAMS

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The Super Separator Spectrometer (S^3) will receive the very high intensity heavy ion beams from the LINAG accelerator of SPIRAL2. Its privileged fields of physics are the delayed study of rare nuclei and secondary reactions with exotic nuclei. The project is presently in a phase of conceptual design. It includes a rotating target to sustain the high energy deposit, a two stages separator (momentum achromat) and spectrometer (mass spectrometer). Various detection set-ups are foreseen, especially a delayed α, γ, and electron spectroscopy array and a gas catcher coupled to a low energy branch. We present here the current status of the project and its main features.

1. Overview

In 2011 the LINAG accelerator at GANIL will be able to produce stable heavy ion beams of unprecedented currents. They will be a factor 10 to 100 more intense than present beams. These stable ion beams will enable us to deepen our knowledge in many aspects of nuclear physics by various experiments:

- Synthesis and spectroscopy of super heavy elements
- Synthesis and spectroscopy of nuclei at or beyond the proton drip line
- Multi-nucleon transfer and deep inelastic reactions
- Production mechanism studies and reaction product distributions
- Production and study of isomeric states
- Study of ground state properties of rare nuclei

To use these high intensities above 10^{14} particles per second, it is necessary to develop a new kind of device. It should separate the interesting nuclei which are an only a tiny part of the ions after the target – most of them are beam ions that did not interact with the target. The aim is to obtain after separation counting rates of the order of 1 kHz or less, compatible with a normal detection. The S^3 spectrometer will be design to achieve this goal.

S^3 is a device which includes:

- A durable target, able to sustain high beam currents
- A separator which has the two main functions of rejecting the beam ions to prevent them from reaching the detection system and identifying the mass of the reaction products
- A detection setting which changes according to the running experiment.
- A coupling to a “low energy” branch for high precision measurements.

Besides its fundamental functions, it should also possess a wide angular and charge state acceptance. Moreover, the spectrometer should cope with the different kinematical conditions due to the different reactions studied: inverse or direct kinematics, one or multi nucleon transfer. “Key experiment” simulations have enabled us to estimate the necessary performances of S^3. Present information about the project can be found on the S^3 webpage [1].

2. Physics objectives

The physicists' collaboration has established as a priority the delayed study of nuclei produced by fusion reactions. This covers the study of neutron deficient nuclei as well as very and super heavy elements. The high production rates will permit detailed studies of nuclei that are today produced only with rates of few per day, either through decay spectroscopy (alpha, proton, electron, gamma…) of ground-state property measurements in ion or atom traps or chemistry apparatus. Nevertheless, S^3 will be also a versatile device, which could also be used in some cases for studies of light nuclei produced by transfer reactions, or neutron rich nuclei with deep inelastic scattering and secondary reactions with nuclei produced in the primary target.

2.1. *Super heavy elements*

The high intensity beams of LINAG will give unprecedented opportunities for the synthesis of new elements, as well as, for detailed studies of the already known elements, most notably:

Produce new isotopes from the neutron poor elements produced by cold fusion to the neutron richer elements of hot fusion and obtain information about their properties.

- Systematic cross section measurement to gain insight about the mechanisms of fusion and fission.
- Perform transactinide chemistry with the heaviest elements.
- Get spectroscopic information for elements up to Ds (Z=110) and learn about collectivity around the islands of deformation (^{254}No, ^{270}Hs).
- Hunt for new K-isomers to obtain information about the single particle states.
- Measure ground states properties of SHE like their masses, charge radii, etc.

This physics program requires the following experimental conditions:

- The highest intensities of beams, especially for masses > 50 (^{48}Ca is a must and heavier beams are required to go to the heaviest elements).
- A wide range of targets, including actinide targets that are necessary for all hot fusion reactions.
- High angular and $B\rho$ acceptance, due to the large emittance of the produced nuclei and their charge state distributions.
- High reaction channel selectivity, to have a background rate at the focal plane as low as possible. This includes physical m/q selection to exclude high-rates of adjacent masses.
- In-flight mass resolution. The mass determination of the produced SHE is critical to validate the production of new elements. It would be a unique property of S^3.
- A detection system for alpha, electron, gamma spectroscopy at the focal plane and a gas catcher system to transfer ions to traps.

2.2. *Neutron-deficient nuclei*

Fusion evaporation reactions can also produce a wide range of lighter neutron-deficient nuclei with a variety of interesting properties: proton emission, super-allowed beta decays, shape coexistence, isomers with information on single particles states and correlations between nucleons. New isotopes with masses in the range 100-200 could be produced. Masses of these nuclei are of interested for the study of the rp-process. Current facilities can fill in some of the gaps in mass measurements, but only a facility like S^3 could reach nuclei such as ^{99,100,101}Sn, ^{98,99}In, ^{95,96}Cd. The region around the ^{100}Sn nuclei is of utmost interest, since this nucleus is at the drip line with two closed shells and N=Z. It is a benchmark to investigate the states near the Fermi surface and how their wave functions reflect single particle motion. Several aspects have to be studied:

- Masses, lifetimes, and charge radii in the region.
- Beta-decay studies.
- Beta-delayed particle spectroscopy.
- Single-particle structure from transfer reactions in neighboring nuclei.
- Proton-capture rates at astrophysical energies on critical nuclei in the region.
- Identification of low-lying states by Coulomb excitation.
- Reaction mechanism studies at or below the fusion barrier.

The requirements for such studies are the following:

- The highest intensities of beams, especially for masses > 50. The most interesting nuclei are produced with symmetric fusion reactions (with ^{58}Ni or heavier).
- High angular and $B\rho$ acceptance, since particle evaporations increase the angular distribution of the nuclei.
- In-flight mass resolution of 1/300. Due to the high fusion cross section of medium mass nuclei, it is absolutely required to have at least an A/q separation of reaction products, to limit the final counting rate to less than 10^9pps (for a gas catcher) or 10^6pps (for secondary reactions).

2.3. *Production of neutron rich nuclei with transfer/Deep inelastic reactions*

Very high primary beam intensities open also the possibilities of producing neutron rich exotic nuclei in large numbers, either through the transfer of few nucleons on light nuclei, or with massive transfer for heavier ones. The physics topics addressed here have been largely presented and discussed in the SPIRAL2 project. Undoubtedly, the neutron rich beam intensities produced by SPIRAL2 through U fission will be much higher in all the regions covered by the fission peaks, but it could be possible with S^3 to produce nuclei outside these zones, either lighter or heavier. For example, multiple nucleon transfer in a ^{136}Xe+^{208}Pb reaction can produce neutron rich nuclei on the ^{208}Pb region and with ^{48}Ca+^{208}Pb reaction, neutron rich nuclei can be significantly produced in the N=28 region. On the light side, the reaction ^{12}C(^{13}C,2p)^{11}Be can give very high yields (~5.10^{8}pps) of ^{11}Be, competitive with an ISOLDE type facility.

The very high intensities on S^3 targets will prevent any kind of prompt spectroscopy of these nuclei – which is the "traditional" method to study them. However, it could be possible to study them in an additional reaction with a secondary target and perform a high cross section reaction like nucleon transfer or Coulomb excitation.

Such reactions have very specific requirements, significantly different from the fusion-evaporation reactions.

- Very high angular and momentum acceptances. Reaction products have a very large angular and momentum distribution, much bigger than the fusion-evaporation reactions.
- For most reactions, the production cross sections are not necessary peaked at 0°.
- High magnetic and electric rigidity. Reaction products have rather large energies (10MeV/n or more), and Bρ of 1.5Tm and Eρ>30MV are required, the later being the most difficult to reach while still retaining good separator properties for the fusion-evaporation studies described above.
- Nuclei selection. A large number of exit channels are open and the contaminants closer to the stability are most of the time overwhelming. This required a very good selection. A pure momentum selection maybe possible with the lightest nuclei, but it may not be sufficient for heavier ones. A mass selection is very challenging due to the high electric rigidity required.

3. S^3 requirements

Simulations have been performed for different key experiments covering the above mentioned physics topic. From these experiments, we have derived requirements for the S^3 facility.

3.1. *Beam*

The best ion source is required in order to reach the highest intensities. The basic A/q=3 injector of SPIRAL2 has reasonable performances for the lightest ions (up to Argon), but it is clear that major physics topics require heavier beams (^{48}Ca, ^{58}Ni, ^{136}Xe…) that could only be produced with competitive yields (10pμA or more) with the A/q=6 injector.

The incoming beam must be spread on the target in order to reduce the local heating. A 1mm x 1cm beam is required on the target. In order to reach the 1 cm size, two solutions are studied, either a fast Beam Raster Magnet system, that wobbles the beam on the target or a non-linear focusing beam expander that uses octupoles in front of the target to expand the beam extension and to have a rectangular (not Gaussian) beam profile on the target.

For experiments requiring non 0° operation, a beam swinger appears to be a more practical solution than a spectrometer rotation. It is an ensemble of 2 magnetic dipoles in front of the target than allow the beam to impinge on the target with 5 to 10°. In this case, a specific target chamber and a specific beam dump are required.

3.2. *Target*

The basic target for S^3 will consist of a high speed (>2000 t/min) rotating wheel, with a variable diameter depending on the material (100 to 600 mm). Cooling systems (Helium jet) are possible. Various diagnostics (electron beam) are considered for the on-line target monitoring. For stable elements, high fusion temperature compounds (PbS) should be used when available. They have already proven their durability.

Actinides targets (Pu to Cm) are necessary for the full super heavy element programs. Basically, actinide target are small (~8cm diameter) wheels. The material is deposited on backings. While delicate to handle and use, such targets have already been used in other European facilities (PSI, GSI). The S^3 collaboration has established contacts in order to study the existing technical solutions and the appropriate safety requirements

As long as the beam intensities are from 10-20pµA (which are the maximum intensities reached for ions with A>50 with existing, state-of-the-art sources), our preliminary thermal calculations show that some materials can sustain the beam energy deposit as long as the wheel velocity is above 2000t/min and their diameter is large (>500mm for Bi, 135mm for actinides). Such characteristics can be reached with existing equipment.

If we go to higher intensities (~100pµA, that could be reached with the next generation ion sources), faster rotating wheels are needed (5000 t/min). It is also necessary to use high melting point materials.

Future work will involve more detailed and realistic thermo-mechanical studies for different experimental conditions, as well as development of a faster rotating wheel (>3000 t/min) in order to go for higher intensities and to reduce the amount of actinide material required by reducing the target wheel size.

3.3. *Optics*

The following are the required parameters for the spectrometer.

- An excellent primary beam suppression (10^{13} in most cases) at 0°
- A charge state acceptance of ± 10%
- A Bρ acceptance for each charge state of ± 10%
- A large angular acceptance in both plane of +/- 50 mrad
- A magnetic rigidity Bρmax equal to 1.5 Tm
- An electric rigidity Eρmax equat to 10 MV
- A mass resolution of 1/300 (FWHM)

We will present the technical solution proposed for S^3 in the next section.

3.4. *Detection*

The basic detection system for S^3 will be an implantation detector for Recoil-Decay-Tagging experiments. Such detector technology already exists (e.g.: Great at Jyväskylä [2]) and, if it can still be improved, it will be sufficient for a large range of experiments. This detection set-up will include:

- Emissive-foil detectors for time of flight and ion tracking; these detectors already exist in a larger version on the VAMOS spectrometer [3] and similar models are currently being studied at CEA-Saclay Irfu.
- An "implantation" stripped silicon detector for the detection of the recoiling nuclei, E and time measurement as well as alpha decay detection; its size will be 10x10cm, with high segmentation (128x128 strips), like the presently built MUSETT detector (CEA Saclay, Irfu). In parallel, the collaboration within the S^3 project is being proposed by an Argonne National Laboratory R&D program to develop a highly segmented silicon detector with digital electronics and triggerless acquisition, optimized for recoil decay tagging detection with high trigger rates (spectroscopy around ^{100}Sn).
- A tunnel detector combining 4 silicon detectors perpendicular to the implantation detector; it will detect alpha and conversion electrons escaping from the implantation.
- Gamma detection; the clovers of EXOGAM2 are compatible with this kind of setting, but we plan to have a dedicated high resolution gamma detection in a further stage.

For secondary reactions, the main constraints on the detection system arise from the final counting rate on the secondary target which comes from the contaminants and the possibly low energy of the reaction products, especially in case of evaporation residues. In this case, tracking and identification are a critical issue.

Both aspects should be considered on a case by case basis. The detection system for secondary reaction could include:

- A tracking system in front of the target, in order to reconstruct the trajectories of the incoming ions.
- For the high energy ions (10MeV/u), Z identification of the ions in front of the target could be possible.
- Detection around target will depend on the experiment. The MUST2 particle detector array can be used for secondary transfer reactions. A specific detection system has to be foreseen for Coulex experiments.
- Identification of the ions after target: for low energy reactions (<5MeV/n), the ions must be identified after the target. This could possibly be done by an annular Bragg chamber (in project for the Isolde Accelerator).
- For some experimental cases, an active target chamber could be considered for secondary transfer reactions.

Such detection systems are so far outside the scope of the basic S^3 project and must be considered for specific experiments. Nevertheless, aspects like encumbrance, compatibility, are considered in the base project.

The S^3 spectrometer will be able to purify the interesting ions from the beam and other nearby contaminants. Nevertheless, as previously underlined, an isobar contamination cannot be avoided in some cases. Therefore, it is required that an additional selection occurs after the gas catcher. In any case, the incoming flux in the ion trap should be less than 10^9 pps if a good efficiency is necessary.

The connexion of S^3 to a low energy branch allows for a wide range of measurement on the ground states properties of the atoms. This branch includes:

- A gas catcher that stops the ions at the end of the spectrometer.
- A purification step. It could be a gas cell coupled to a RF extractor that sends the ions to a very high resolution mass spectrometer for purification (CARIBU gas catcher and separator [4]). A mass resolution above 20000 allows for the separation of the different isobars. It could also be a laser ionization trap that ionizes a selected isotope that is then brought to a rough mass separator and then to the detection set-up (Leuven Isotope Separator On-Line) [5].
- A low energy beam line that accelerates the ions to 40keV and transports them to the detection set-up. It send the selected ions either to the DESIR experimental area when built, or, for some specific cases, into detection devices in the S^3 room.
- The detection itself: ion traps, collinear laser spectroscopy, beta-NMR, chemistry set-up… Since all these equipments are foreseen to be installed in the DESIR facility, it is clear that a connection to this room is highly valuable. The efficiency of a gas catcher, typically of 10%, can be as high as 40%, down to a few %, depending on the nature of the ions, the total counting rate in the catcher…

3.5. *Optical Design: Momentum Achromat + Mass separator*

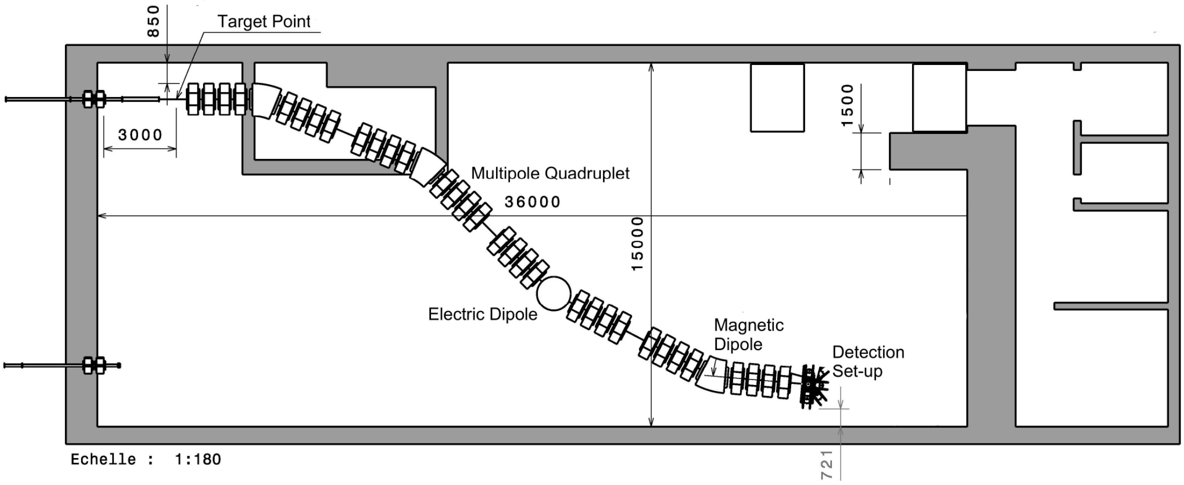

Fig 1: Foreseen Layout of S^3

3.5.1. *Characteristics of the layout*

While several options have been studied [6], we ended up in a layout which can answer most of the requirements. In this layout, a momentum achromat is combined with a mass spectrometer (see Figure 1). It is similar to the Oakridge RMS [7]. The first stage makes a first Bρ selection of the ions. The transmitted ions are then focused on an achromatic image point that is the target point of the mass spectrometer. At the final focal plane, the ions are spatially distributed according to their mass over charge ratio. Due to the highly symmetric set-up, this lay-out naturally cancels most of the high orders aberrations [8]. This makes the intermediate focal point very clean and allows a very good mass resolution.

3.5.2. *Magnetic elements*

This design requires the use of multipoles that superposed quadrupoles and sextupoles fields in compact (40cm length), wide aperture (30cm diameter) elements. Four identical multipoles form a multiplet and there are eight identical multiplets in the layout. In a “warm” technology solution, the sextupoles are imbedded within the quadrupoles by dipole and compensation coils. Nevertheless, the large apertures of the elements imply strong fields and thus, especially in the sextupoles, high currents and so high power consumption. That’s the reasons why we also are considering a superconducting technology which could overcome these constrains.

3.5.3. *Simulations*

First and second order calculations are shown here for the reaction ^{48}Ca+^{248}Cm→ ^{292}116. As initial conditions for the simulations, we take a beam spot size of ±0.5 mm in x by ±5 mm in y, ±50 mrad in x and y divergence, 5 charge states (70%), and ±4.6% energy spread (2σ) for each charge state.

The calculated transmission of ^{292}116 in these conditions is 57%. At the final focal plane, the mass dispersion is 6.7 mm/%. The second order mass resolution is $M/\delta M=350$ at the centre, and decreases at the edges due to the optical aberrations. The focal plane size is roughly 14cm x 6cm for 5 charge states. A further optimization of the aberration corrections is in progress.

The beam is stopped in the first multiplet after the first magnetic dipole. That requires internal shielding to limit the heating of the surrounding magnets. In some experiments where there is a superposition of the magnetic rigidity of the interesting nuclei and some beam charge states, the beam is stopped at the dispersive plane of the momentum achromat by cooled “fingers”. Each finger stops a few % of the beam. The total transmission is reduced by 10-20% depending on the kinematics.

4. Conclusions

The design presented here achieves a combination of beam suppression, evaporation residue transmission and mass channel selection unique in the world. It will enable unique experiments such as in-flight mass identification of superheavy elements, and studies of very weak evaporation channels (^{100}Sn, for example). It has a two-stage selection (magnetic rigidity and mass) that will achieve very good rejection of both the beam and adjacent mass channels of reaction products. It is especially optimized for fusion evaporation reactions in direct and symmetric kinematics and the delayed study of rare channels.

In some experiments where the momentum selection is sufficient (e.g. transfer on light nuclei), the first momentum achromat part can be used as a standard magnetic spectrometer with a final focal point for a secondary target.

5. Acknowledgements

The authors emphasize that S^3 is the work of a wide collaboration from which they are only the spokespersons. They thank all the present and future contributors of this project.

References

1. S^3 webpage : http://irfu.cea.fr/en/Phocea/Vie_des_labos/Ast/ast_technique.php?id_ast=943
2. R.D. Page et al., *Nucl. Instr. and Meth.* **B204**, 634 (2003)
3. A. Drouart & al., *Nucl. Instr. & Meth.* **A579**, 1090 (2007)
4. G. Savard & al., *Nucl. Instr. & Meth.* **B266**, 4086 (2008)
5. Yu. Kudryavtsev & al., *Nucl. Instr. & Meth.* **B304**, 236 (2003)
6. A. Drouart, B. Erdelyi, B. Jacquot, S. Manikonda, J. A. Nolen, H. Savajols and A. Villari, *Nucl. Instr. & Meth.* **B266**, 4162 (2008)
7. C.J. Gross & al, *Nucl. Instr. & Meth.* **A450**, 12 (2000)
8. B. Erdelyi, J. Maloney, J. A. Nolen, *Phys. Rev. ST Accel. Beams* **10**, 064002 (2007)