EURISOL DS Project

Deliverable M2.1

Apparatus specification for key experiments

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Achieved Date (month): 21

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Project acronym:	*EURISOL DS*
Project full title:	*EUROPEAN ISOTOPE SEPARATION ON-LINE RADIOACTIVE ION BEAM FACILITY*
Start of the Project:	*1st February 2005*
Duration of the project:	*48 months*

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The Physics and Instrumentation Task of the EURISOL Design Study has compiled a list of around 25 specimen experiments. These have emerged from the presentations at the Trento workshop (T10-03) and discussions at the subsequent Task meetings. The full list of specimen experiments is available at the URL http://ns.ph.liv.ac.uk/eurisol/spec_expts.htm or via www.eurisol.org. At the meeting in Bordeaux on 2nd – 3rd October 2006 (T10-05), it was agreed that the following aspects would be investigated further during the remainder of the Design Study:

1. improved neutron detection schemes for β–decay studies
2. a sweeper magnet coupled with ancillary neutron, γ–ray and charged particle detector systems
3. coupling charged particle and γ–ray detectors around the target and the incorporation of cryogenic and polarized targets
4. the conceptual design of a recoil separator and its target chamber, as well as improving cross section calculations for superheavy elements.

These aspects are directly relevant for 8 of the specimen experiments (see table below), which are therefore those selected for further investigation. A further 2 specimen experiments relating to low-energy β beams are already being investigated within the Task.

Aspect	Specimen Experiment(s)
1	Beta-delayed two-neutron emission
2	Structure beyond the neutron drip line: $^{26-28}$O One or two neutron or well defined cluster (like alpha particle) break up Isospin dependence of correlations
3	Mapping of single particle energies using transfer reactions Isospin dependence of correlations
4	In-beam spectroscopy of heavy elements Synthesis and decay of the heaviest elements Optical spectroscopy of the heaviest elements

These specimen experiments are described briefly below. The numbers refer to the aspects listed above that are relevant for each specimen experiment. More detailed descriptions of the apparatus envisaged under aspects 2 – 4 are provided on the subsequent pages.

Very little is known about nucleon-nucleon correlations in the atomic nucleus. One of the best probes from the theoretical point of view is to study the correlated emission of two neutrons following β decay, since the Coulomb barrier does not perturb the neutrons. Experimentally, the main challenge is to improve neutron detectors to a point where it will be possible to measure the correlated neutrons' properties with sufficient sensitivity and precision, which is the issue to be addressed by aspect 1.

Three of the specimen experiments relate to studies of superheavy elements, namely their synthesis and measuring their radioactive decay properties, in-beam γ-ray and conversion electron spectroscopy studies, and optical spectroscopy measurements. The beam intensities required for these studies are ~100 pnA or greater, which is higher than for most other experiments and represents a significant technical problem. All of these require a recoil separator to transport the unreacted beam so it can be dealt with safely and to isolate the nuclei of interest with high efficiency and high beam suppression. Rutherford scattering of the beam could result in significant accumulations of radioactive ions stopped in the vicinity of the target. This could pose a radiation safety hazard when changing targets and could cause unacceptably high counting rates in spectrometers at the target position for the in-beam spectroscopy experiments. The target chamber therefore requires extremely careful design. Finally, there exists considerable scientific uncertainty about the magnitudes of the cross sections expected for synthesizing superheavy elements, so further theoretical work on this is essential. These issues are to be addressed under aspect 4.

EURISOL could allow nuclei *beyond* the neutron drip line to be investigated for certain light elements. One exciting specimen experiment would use intense beams of very neutron-rich neon isotopes to explore the unbound isotopes of oxygen, including ^{28}O to address the question of whether this nuclide really is doubly magic. In addition to studying their low-lying structure, two- and four-neutron correlations will be explored. This experiment requires a large gap sweeper magnet, coupled with a charged particle detector array that will measure masses up to A~30 and Z up to ~10. A high acceptance neutron detector array is also essential. This will also have to be capable of simultaneous multi-neutron detection and allow the rejection of cross-talk events. These will be considered under aspect 2.

A large gap sweeper magnet and multi-neutron detection capability with low background are also required for the specimen experiment proposed to study the interior part of nucleon wavefunctions. The probe for this experiment will be one-neutron, two-neutron or well-defined cluster (e.g., an α particle) break up. In addition, a high-efficiency γ–ray detector array will be required to measure the excitation energy of the projectile. These difficult experimental requirements will be investigated under aspect 2.

The specimen experiment proposed to study the isospin dependence of nucleon correlations poses similar experimental problems, with the additional complication of requiring a polarized target in order to provide unambiguous measurements of the nucleons' j values. By using one-proton removal and (d,^{3}He) transfer reactions with beams of neutron-rich lead isotopes, the variation of the absolute occupancies as a function of isospin will be explored. The technical requirements needed to fulfil this goal will be explored under aspects 2 and 3.

The final specimen experiment to consider is the mapping of single particle energies using transfer reactions, such as (d,p) or (p,d). This is the most direct way of measuring shell gaps far from stability and assessing the modification of magic numbers, which is a primary physics motivation for radioactive beam facilities such as EURISOL. To achieve this, a very efficient system for the coincident measurement of charged particles and γ–rays needs to be employed. In addition, polarized targets will be required to allow analysing powers and j values to be measured. This experimental scenario therefore falls under the auspices of aspect 3.

In addition to this future programme of investigations, work is already being undertaken as part of Task 10 of the Design Study to provide conceptual designs for experiments with low-energy β–beams. Two specimen experiments have been proposed to perform nuclear structure studies and fundamental tests using the neutrino beams to measure nuclear isospin and spin-isospin excitations, and to measure the

Weinberg angle at low momentum transfer and test the Conserved Vector Current hypothesis on the weak magnetism form factor.

Related work to that outlined above is already being undertaken by existing collaborations (e.g., AGATA, FAZIA, etc.) and it is intended to keep abreast of these developments rather than duplicating the effort. Similarly some of the developments required for other specimen experiments are being pursued through EURONS JRAs (e.g., TRAPSPEC, LASPEC, ACTAR) and this work will not be replicated. However, it is anticipated that some of the fruits of this parallel work will be fed into the final report of the EURISOL Design Study.

A large-gap sweeper magnet for EURISOL

The study of neutron-rich nuclei is an important task in order to achieve a detailed understanding nuclear structure and to reliably model stellar evolution processes. In this context, break-up reaction with nuclei close to the neutron drip line or neutron knockout reactions are an efficient tool. These studies often require the detection of charged particles, gamma rays and neutrons in coincidence.

A commonly used tool for these measurements is a large-gap sweeper magnet, which allows deviating charged particles either onto a detection set-up or into a high-resolution spectrograph, whereas the neutrons continue their straight-line flight into a neutron detection array. In such a way, the heavy charged fragment and the neutrons are separated and can be detected independently and without mutual interference.

A typical device consists of a target station as close as possible to the entrance of the sweeper magnet, the large-gap sweeper magnet, a stand-alone detection set-up at the exit of the sweeper magnet or a high-resolution spectrograph with its associated detection devices, and a high-efficiency neutron detection array.

Installations of this type exist today at the NSCL of Michigan State University (Sweeper + neutron wall or Mona detector) or at GSI (ALADIN + LAND). We will use the recently completed MSU sweeper to give a few technical details in the following table.

Gap	140 mm
Bending angle	40°
Bending radius	1 m
Beam rigidity	4 Tm
Maximum current	500 A
Weight	25 t

Table: Basic characteristics of the MSU sweeper magnet.

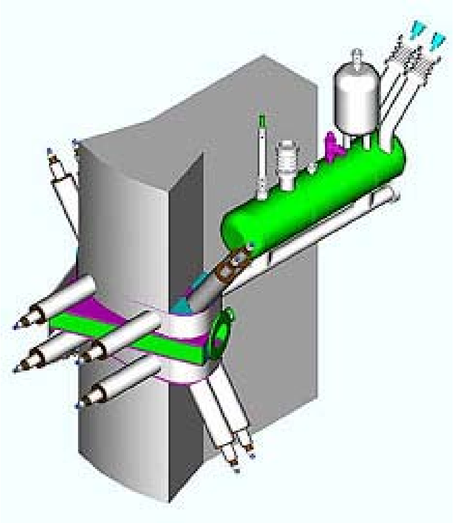

Figure: Schematic view of the MSU sweeper magnet

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To allow for fragment tracking, a pair of fast position-sensitive detectors (e.g. PPACs) is necessary in front of the target to determine the beam impact position on the target. The stand-alone detection set-up should consist of two position-sensitive detectors (e.g. drift chambers), an energy-loss detector (e.g. an ionisation chamber) and a residual-energy detector (e.g. one or two plastic scintillators). This set-up allows for an event-by-event identification of the detected fragments and for their tracking from the target to the detection plane. By this means, the momentum vector of the fragments at the target position can be calculated and, together with the measurement of the neutron momentum, the complete kinematics of the reaction can be determined.

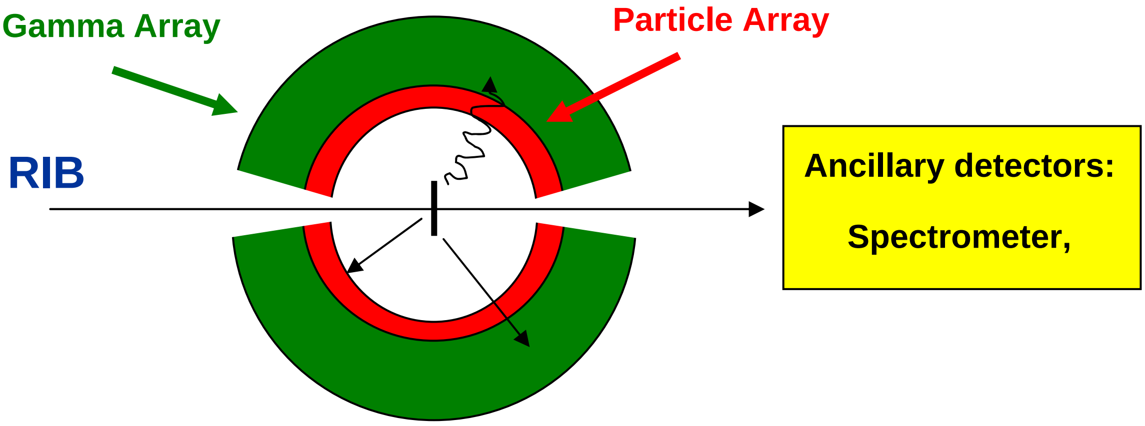
Such a set-up allows for the acquisition of high-quality data in break-up or knockout reaction with neutron-rich fragments.

The cost of such a device, based again on the MSU sweeper, is about 1M€.

Direct Reaction Studies at EURISOL

Direct reactions such as light-ion transfer are a unique tool for the investigation of nuclear structure. The relative simplicity of the reaction mechanism, involving only a few degrees of freedom, allows precise theoretical calculations to be made and nuclear structure information to be extracted from experimental data. Hence, direct reactions have been used extensively in the past with stable beams and have contributed greatly to our present knowledge of stable nuclei. Recently, with the advent of radioactive ion beams, it has become possible to use direct reactions to study exotic nuclei. For example, themes central to nuclear physics such as the evolution of shell structure, modification of the spin-orbit interaction, changes to nucleon-nucleon pairing in the isospin asymmetric medium, clustering, reaction mechanisms and aspects of nuclear astrophysics can be explored. Such studies are revealing the dramatic changes that occur both in the nuclear structure and in the reaction mechanism itself. The beams of exotic nuclei that will be delivered by EURISOL will allow a greatly increased range of exotic nuclear systems to be produced and studied via direct reactions.

Direct reaction studies with RIBs are performed in inverse kinematics and generally comprise a recoil detector array surrounding a light target coupled to a spectrometer to identify the heavy projectile-like fragment. A schematic experimental set-up is shown below.



Major new challenges will be imposed on the recoil array by the beams from EURISOL and this will necessitate the development of a completely new generation array of this type, with fully integrated particle and gamma detection and having the highest resolution, efficiency and solid angle coverage possible. For example, medium and heavy nuclei have increased level densities in comparison to the light nuclei studied today from present-generation RIB facilities. A system with experimental energy resolution that is dramatically improved over present-day arrays therefore needs to be developed. Additionally, the structure of exotic nuclei will be strongly influenced by the proximity of continuum states and thus the properties of both bound and unbound excited states will be important to study. The detection system must therefore be able to identify and measure both types of states. Further, recent direct reaction studies with exotic nuclei have shown that it is very important to include the coupling of different reaction channels to reach a comprehensive description of the reaction mechanisms involved. It is likely that such effects will become increasingly important in reactions involving the more exotic nuclei produced by EURISOL. The detection system must therefore be able to measure simultaneously as many reaction channels as possible.

The design of the array must therefore overcome these new experimental challenges. The basic concept of the array is to provide the simultaneous detection of recoil particles and γ-rays in a fully integrated and seamless way, with the maximum possible resolution, efficiency and solid-angle coverage. Such techniques will gain a large factor in excitation energy resolution compared to particle detection alone and permit the use of thicker targets to increase the available luminosity. The reaction channel selection and the spectroscopic information obtained will also be greatly improved. All essential reaction channels will be measured simultaneously, together with scattering to both bound and unbound excited states.

The array will offer solid angle coverage close to 4π for both particles and gamma rays. In such a "4π"+"4π" ensemble, the gamma detectors will surround the particle detectors and also be used to detect the fast charged particles. The granularity of the gamma detector will be determined by the requirement of balanced contributions between intrinsic and Doppler-induced resolution. Overall, the array should have particle identification (PID) with excellent position and angular resolution (~0.1-0.5 mm and 1-5 mrad, respectively), together with large dynamic range and PID capabilities to at least $Z = 10$. The gamma detection stage must have the best possible efficiency and resolution. The array will also be designed to couple to ancillary detection systems. For example, magnetic spectrometers will be necessary for detection of the projectile-like fragments. The use of cryogenic and polarized targets will also be necessary in some cases.

The proposed array is made up of two components: the **Particle Array (PA)** and the **Gamma Array (GA).** The PA will cover a solid angle of 4π with highly-segmented telescopes comprising position-sensitive semiconductor detector layers, most probably Si-based, surrounding the reaction target. The GA will consist of a highly-segmented array of scintillation crystals or semiconductor detectors arranged in a spherical geometry and also covering 4π solid-angle. It will be fully integrated mechanically with the PA and will be placed in vacuum. R&D into the GA material will be needed but possibilities include CsI, $LaCl_2$ or $LaBr_3$(Ce) in the case of scintillator material and Ge in the case of semiconductor material. It is important to note that the GA will be used to detect both gamma rays and fast charged particles that punch through the PA. The granularity of the gamma detector will be determined by the requirement of balanced contributions between intrinsic and Doppler-induced resolution. Overall, the array should have particle identification (PID) with excellent position and angular resolution (~0.1-0.5 mm and 1-5 mrad, respectively), together with large dynamic range and PID capabilities to at least $Z = 10$. For particles that stop in the first layer of the PA, two PID schemes will be employed: time of flight techniques for energies below 2 A.MeV (the start signal will be derived from the HF and/or the beam tracking) and pulse shape discrimination techniques for energies above 2 A.MeV. Above about 8 A.MeV, particles will punch through the first layer of the PA and traditional energy loss methods will be used ($\Delta E+E$). Modularity of the mechanics, front-end electronics and data acquisition is an essential feature of the array. It gives flexibility to the array and increases its physics scope by allowing the possibility of introducing other detector types, such as neutron detectors, FAZIA modules and AGATA modules. Finally, the array will also be designed to couple to ancillary detection systems. For example, magnetic spectrometers will be necessary for detection of the projectile-like fragments. The use of cryogenic and polarized targets will also be necessary in some cases.

We intend to study designs for this array and its performance for various test reactions. Similar studies are already underway for the design of the direct reactions array GASPARD, proposed for the SPIRAL2 facility under construction at GANIL. We will start with reactions such as ^{78}Ni(d,p)^{79}Ni and ^{132}Sn(d,p)^{133}Sn at typical energies of 10 A.MeV.

An efficient recoil separator device for the study of heavy elements at EURISOL

The intense neutron-rich beams available at EURISOL will allow the study of heavy elements that cannot be produced through reactions with stable beams. The main goals will be push towards the deformed shell gap at N=162, the possible spherical shell gap at N=184, and to extend the range of spin and excitation energy at which the nuclei are populated.

The requirements are similar for SHE studies, decay and prompt spectroscopy, and reaction dynamics, although less severe performances are required for prompt spectroscopy studies.

- Mass resolution is not essential, as tagging techniques and genetic correlations can be used to identify implanted recoils. It can be useful to obtain a rough (1%) identification of evaporation residues in some SHE synthesis experiments.
- High transmission efficiency is a priority for symmetric, asymmetric and inverse kinematics reactions. The separator should improve on existing devices for reactions such as 48Ca + 208Pb (i.e. > 40%).
- A high beam suppression factor $>10^{12}$ is essential in order to maintain a low counting rate at the focal plane.
- The separator should be able to deal effectively with reactions such as Ca+Pb and Sn+Xe.
- The momentum acceptance should be larger than 12% to preserve a good transmission for very asymmetric reactions.
- The angular acceptance should be larger than ± 5 degrees.
- The focal plane image size should be compact to allow the addition of Ge and Si detectors in close geometry.

The ideal focal plane set-up is made of four consecutive elements: a time of flight detector, an implantation Double Sided Silicon Strip Detector, a tunnel of charged particle detectors and gamma-ray detectors. It should be capable of measuring alpha, proton, gamma, beta, electron and fission activities with high efficiency. The ability to measure K- and L-X rays is valuable in determination of transition multipolarities. The data acquisition system should also allow flexible correlation between the various detector groups.

Dumping of the unreacted beam beyond the target and suppression of background due to Rutherford scattering of the beam in the target chamber are additional issues that require careful consideration.