EURISOL: an European Isotope Separation On-Line radioactive ion beam facility

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Abstract. The EURISOL program aims at the construction, beyond the year 2013, of the “next-generation” European Isotope Separation On-Line (ISOL) Radioactive Ion Beam (RIB) facility. It will extend and amplify the exciting work presently being carried out at the first generation RIB facilities in Europe and other parts of the world. The EURISOL facility will play a complementary role to the recently approved upgrade of the GSI facility at Darmstadt, Germany, the European “next-generation” In-Flight RIB facility FAIR.

1. Introduction
In the report \textsuperscript{[1]} published by the NuPECC Working Group entitled “Radioactive Nuclear Beam Facilities”, it was stated that the next generation of radioactive ion beam facilities should aim at having an intensity of accelerated radioactive beams being a factor 1000 higher than any facility presently running or in the commission stage. Such facilities should clearly be complementary if more than one is needed to cover the foreseen physics issues, and together they should be second to none worldwide. The scenario emerging from the NuPECC report is that the European option will at least include an In-Flight Facility. The facility should be based on in-flight fragmentation or fission of high-intensity heavy ions. This facility is the future GSI accelerator complex, which could consist of a high intensity, high-energy synchrotron with an accumulator ring. The energy range of the RIBs would here cover the region from a few hundred MeV/u to about 1 GeV/u.

EURISOL - an Isotope Separation On-Line (ISOL) post-accelerator facility which would be a very powerful complement to the proposed GSI In-Flight Facility. The aim is to produce exotic beams in the neutron rich side with the good beam characteristics due to a linac re-accelerator with energies up to 150 MeV/u (A=130) and intensities in the order of 1012 pps for $^{132}$Sn.

The construction of the EURISOL facility is expected beyond 2015 after the development of “second generation” facilities as SPIRAL2 and SPES addressing some of the main technological challenges. The main structure of EURISOL will consists of: (i) a driver accelerator; (ii) a neutron converter to generate high-energy neutrons for exotic isotope production; (iii) a high power (Multi Mega Watt - MMW) target-ion-source unit for two-step isotope production (neutron induced), and several direct target stations (100 kW) in which exotic isotopes are directly produced by the driver beam impinging on the target material.

Targeting for ISOL facility is traditionally a very active R&D area as shown by the continuous effort devoted to this item by the ISOLDE facility at CERN. Neutron rich exotic nuclei are essentially produced by U or Th fission and the target material is mainly natural U or Th.
Figure 1. Some of the burning issues at present-day radioactive beam facilities.

In oxide or carbide form, the Charge Breeder to increase ion charge state from 1+ to n+ for an effective acceleration process: At the REX-ISOLDE facility, an Electron Beam Ion Source (EBIS) is used, while the SPIRAL facility at GANIL will employ an Electron Cyclotron Resonance (ECR) ion source. A Charge Breeder R&D project is concerned with determining the optimal solution. For the post-accelerated beams, it would be interesting to cover the entire energy range up to a maximum energy of about 100 MeV/u, i.e. in the fragmentation regime. Note that to run a complete physics program, one should also have a “low energy” output. It is part of the facility the development of dedicated up-to-date experimental instrumentation.

2. The EURISOL concept
2.1. Furthering target and accelerator technology
A 4-year Design Study began in 2005 in order to work on the technologically challenging aspects of the project, the instrumentation and the radiation safety issue. Synergy with other projects is being examined, including a feasibility study for the new “beta-beam” neutrino proposal, forming an integral part of the Design Study. After this, possible sites will be ready for a full Engineering Design, to be followed by construction of the facility. Researchers and engineers of several European laboratories are collaborating in twelve tasks to further the EURISOL design. The EURISOL layout consists of superconducting linear accelerator providing protons of energy 1 GeV and an impressive power of 5 MW, but also capable of accelerating deuterons, $^3$He and ions up to mass 40. The beams will impinge simultaneously on two types of targets, either
Figure 2. Nuclear chart in the light- and medium-mass region. The circles indicate areas with possibly new magic numbers. The right-hand side shows the single-particle energies for nuclei close to stability and for nuclei with a large N/Z ratio.

directly or after conversion of the protons into neutrons through a loop containing 1 ton of mercury surrounded by kilograms of fissile material. The unstable nuclei produced diffuse out of the target, are ionized and selected, and can be used directly at low energy or reaccelerated by another linear accelerator to energies up to 150 MeV per nucleon in order to induce nuclear reactions. Prototypes of some of the most critical parts of the facility are being built within the Design Study.

2.2. Multi Mega Watt target station
Technical preparatory work and demonstration of principle for a high-power station for production of beams of fission fragments using the mercury proton-to-neutron converter-target and cooling technology is carried out in collaboration with the communities working on spallation neutron sources, accelerator-driven systems and neutrino factories. The converter will be surrounded by large amounts (4 Kg) of fissile material.

2.3. EURISOL driver
The EURISOL Driver is a superconducting (SC) linac that includes 5 different sections: injector, low-β section, medium-β section, high-β section and CW beam splitter. The lengths of the injector and of the SC part are 12 m and 247 m, respectively, while the 4-way beam splitting
section is 55 m long. An additional extraction sector is located at the beginning of the high-β section, giving a beam line for 264 MeV deuterons. All cryostats are planned to work at 4.5K.

2.4. EURISOL post-accelerator complex
Three independent post-accelerators, fed by separate target ion-source systems, should be incorporated into the facility. This will allow to feed three different experimental areas in parallel: a very-low-energy area (< 1 MeV/u), a low-energy area (between 1 and 5 MeV/u), and a high-energy area (from 5 MeV/u up to the maximal energy). A maximum energy of 150 MeV/u for the benchmark $^{132}$Sn$^{25+}$ beam is envisaged. Moreover, maximum energies in the vicinity of 80-100 MeV/u would be very welcome for “heavier” beams. RFQ and Super Conductive Linacs are the key items to develop the EURISOL post acceleration system.

2.5. Safety issues
The increase of the RIB intensities by a factor of 100-1000 compared to presently operating facilities will give rise to challenging issues in terms of nuclear safety and radioprotection. In the framework of the radiation characterization and safety studies detailed special attention is devoted to estimate the prompt and residual radiation fields in the MMW target and its surroundings. An important safety and radioprotection objective is to demonstrate the feasibility of the EURISOL project over the entire life cycle, including decommissioning. The large quantities of radioactive wastes produced in the bulk shielding of the MMW target at the end of the EURISOL facility operational lifetime require radiological characterization. In this context it is important to assess the issues related to radioactive wastes arising during the facility operation.

3. EURISOL physics
Over the past two decades, RIB physics has been driven by remarkable discoveries which have added new elements to the nuclear paradigm. As yet we have only explored a relatively small part of the nuclear landscape, especially on the neutron-rich side where the limit of stable nuclei is only known for the lightest elements. We may expect that more discoveries will be made in the light of the new developments with the guide of a theory framework of growing predictive power. There are, at present, already a number of identified challenges and exciting issues that will be addressed in the coming years (see figure 1). One of the main motivations for a new high-performance nuclear physics facility will be the physics at the drip-lines. The largest unknown nuclear territory is on the neutron-rich side of stability but there are also many interesting physics issues on the neutron-deficient side namely close to the proton dripline. The heavy-element region represents a special subject of interest for the characterization of the valley of stability in the super-heavy region. At present, we are approaching a delineation of the one-proton drip-line, i.e. the limit of stability for proton-rich, odd-Z nuclei. The observation of proton radioactivity gives some definite points where the drip-line is situated. The heaviest known case is $^{185}$Bi (N=102, Z=83) [2]. However, the two-proton drip-line, the limit for proton-rich, even-Z nuclei, has been reached only up to nickel (Z=28). The situation is even more dramatic on the neutron-rich side of the valley of stability, where, except for the lightest nuclei, we are still far from reaching the neutron drip-line. Indeed, the neutron drip-line is at present known only for elements up to fluorine (Z=9). Studying nuclei far from the stability line allows to verify the shell structure in these unknown regions. The concept of the mean field and the consequent shell structure encountered in nuclei lies at the heart of our current understanding of the nuclear many-body system. Yet direct empirical verification of this structure has only been possible up to now for nuclei on, or a few nucleons away from, the line of stability, since it is only with nucleon transfer reactions that we can directly probe the single-particle structure. For the remainder of the nuclear chart we rely on extrapolation or interpolation in regions between
the well-known magic numbers. In fact, even this traditional textbook property of nuclei is predicted to break down far from stability, as nuclei become weakly bound and increasingly diffuse at the surface. Experimental evidence of vanishing shell effects at N=20 and N=28 for nuclei with large neutron excess has already been found by many experimenters. In these cases, the neutron-proton interaction is thought to be responsible for changes in the single-particle orbital spacings and consequently for shell effect weakening [3]. See figure 2. In addition to the effect described above, it is expected that the surface of medium-mass, very neutron-rich nuclei would be essentially composed of diffuse neutron matter [4]. As a consequence, the derivative of the mean-field potential is thought to be weaker, reducing the spin-orbit surface term. The magicity at N=40 and N=70 would be enhanced as a result, whereas the N=50 and N=82 gaps would be reduced, turning the mean-field description of nuclei back towards one which corresponds more closely to a pure harmonic-oscillator (HO) potential. A specific feature of HO magic numbers is that a change of parity occurs across the gap. It is therefore expected that excitations which preserve the parity symmetry across a gap, for example electric quadrupole excitations, would be strongly hindered. These modifications of the shell ordering would provide new magic numbers and new ways to generate collectivity. It is well known from studies of nuclei close to the line of $\beta$-stability that nucleons preferentially form pairs (proton pairs, neutron pairs) in the nucleus under the influence of the short-range nucleon-nucleon attractive force. However, surprisingly little is known about the basic properties of the particle-particle force as it relates to pairing. In most models, schematic average pairing interactions [5] are usually treated by means of the BCS approximation. They perform remarkably well when applied to nuclei in the neighbourhood of the valley of stability. Here, pairing can be treated as small perturbation acting in the neighbourhood of the Fermi surface. The development of EURISOL will allow many very neutron-rich nuclei to be produced for the first time. Such drip-line nuclei are unique laboratories for studies of neutron pairing properties [6, 7], and thus of effective interactions, in a neutron-rich environment. The exploration of a series of isotopes and isotones, progressively moving away from the region of stability, has brought many surprises (e.g. new shapes at low energy, phase and shape coexistence, intruder states). Learning about the evolution in moving even further out may give access to a better understanding of these phenomena. Moreover, experiments may reveal the missing elements needed to get to a unified understanding of these phenomena, or indicate hints of new symmetries and interactions governing the nuclear many-body system. One interesting possibility is to continue a systematic investigation of their $\beta$-decay and, in particular, of their $\beta$-delayed particle emission processes. Such decay modes are typical for exotic nuclei; they are to a large extent understood experimentally and will therefore provide very powerful probes for investigations of the nuclear structure at the drip-lines. Experimentally one has up to now observed many different types of $\beta$-delayed particles [8] i.e. p, 2p, n, xn, d, t and $\alpha$. It is obvious that such decay modes become more frequent as one goes away from the $\beta$-stability line, since the Q-values become larger and the particle separation energies lower.

3.1. Superheavy elements
Nuclear chemists and physicists strive to complete the Mendeleiev table of the elements by discovering ever heavier elements and studying their chemical and physical properties. The high intensity radioactive beams from EURISOL will lead to the production and study of new isotopes of these elements and possibly to the discovery of the elusive long lived “magic” super-heavies that are expected to be located in a region of mass $\sim$300 amu and Z$\sim$114-118. It is not possible to reach this region without the use of reactions with neutron rich beams. Up to now isotopes with Z in the interesting region have been produced but the mass is not high enough, more neutrons are necessary.
3.2. Exotic radioactivity

The targets at the EURISOL facility will allow a number of hitherto unknown exotic nuclei to be produced. One interesting possibility is to continue a systematic investigation of their radioactive decay. Recently a new type of radioactivity has been discovered in very neutron-deficient nuclei, where two protons are emitted simultaneously by the nucleus.

4. Nuclear astrophysics

4.1. The r-process

Approximately half of the nuclear species in nature beyond iron are produced via neutron capture processes on very short time scales in neutron-rich astrophysical environments, i.e. the so-called r-process. Only under such conditions is it possible that highly unstable nuclei near the neutron drip-line are produced, also leading - after decay back to stability - to the formation of the heaviest elements in nature like Th, U and Pu. Despite its importance, the exact stellar site where the r-process occurs is still a mystery. The key to its understanding will probably only be obtained from a close interaction between astronomy, cosmos-chemistry, nuclear physics and astrophysical modeling of explosive scenarios. The questions of neutron capture, $\beta$-decay and mass measurement in the regions of closed neutron shells will be carefully investigated with the high intensity RIBs of EURISOL.

4.2. Neutron stars

Neutron stars are the remnants of core collapse supernovae. They are the most compact stellar object after black holes. Indeed, pulsars (space lighthouses), and magnetars, generating the most intense magnetic field of the Universe, are neutron stars. The modeling of their inner crust is essential in order to understand the cooling process of the star, and also observational irregularities (glitches).

The crust is composed of neutron-rich nuclei immersed in a neutron gas. Vortices (quantum tornadoes) at work in the nuclear matter of the neutron star could be the explanation for glitches. The investigation of exotic nuclei is essential to understand the crucial role of superfluidity in these systems. EURISOL will open a new field of experiments on neutron-rich nuclei aimed at a better understanding of neutron stars.

4.3. X-ray bursts

The energy generated by nuclear processes on the surface of accreting neutron stars is observed as short X-ray bursts if the nuclear burning is unstable. In such scenarios, matter is accreted for hours or days until a thermonuclear explosion is triggered by the ignition of the triple-alpha reaction and the break-out reactions from the hot CNO cycles into the rapid proton-capture process (rp-process) - a sequence of $(\alpha,p)$, $(p,\gamma)$ and $\beta^+$ reactions. There are many open questions concerning X-ray bursts. In many cases, the motivation is to obtain information on neutron stars and on the properties of matter under extreme conditions. To answer these questions, experimental masses and electron-capture rates on neutron-rich nuclei are now needed and can be provided by a facility like EURISOL.

5. Fundamental interactions

5.1. Beyond the standard model

The study of nuclear decay modes has played a crucial and undeniable role in determining the basic structure of fundamental interactions. In particular, $\beta$-decay has contributed to establishing such aspects of particle physics as parity violation, the nature of the neutrino or lepton number conservation, and has thus provided the experimental foundations for a large part of the Standard Model (SM) of electroweak interactions. Precision measurements
in nuclear $\beta$-decay and in atomic transitions constitute simple means to search for signatures of new interactions or small violations of the fundamental symmetries. At low energies the search for new physics beyond the SM is a very exciting activity presently carried out at several ISOL facilities, as well as at cold and ultra-cold neutron sources around the world. The importance of this field, where the atomic nucleus is used as a laboratory for the tests of fundamental conservation laws, has been recognized in the description of the EURISOL proposal and is considered to be one of the four key areas of modern science on which RIB facilities will have a major impact.

5.2. Beta beam
Neutrinos come in three varieties. One of the major discoveries of the last decade is spontaneous oscillations between these neutrino families, which imply that neutrinos are not massless as previously assumed. In order to learn more about these elusive particles and perform stringent tests of quantum symmetries, neutrino physicists need a new type of neutrino beam called beta-beam. The neutrinos would be produced by the radioactive beta decay of massive amounts of unstable nuclei, for example $^6$He and $^{18}$Ne, accelerated close to the speed of light. The seed nuclei would be produced by EURISOL and the beta-beam facility, elaborated within the Design Study, would be a natural extension of EURISOL.

6. Key experiment
The Physics and Instrumentation Task of the EURISOL Design Study, lead by R. Page of the University of Liverpool, has compiled a list of around 25 key experiments which could be performed at EURISOL. These have emerged from the presentations at a workshop held at ECT*, Trento in January 2006 and discussions at the subsequent Task meetings. Since the science case for EURISOL is continuously evolving the list should not be regarded as being definitive, but rather as a snapshot of the diverse and exciting physics opportunities that will be available with the EURISOL facility.

- Super-allowed beta decay and the weak-interaction standard model
- Correlation measurements in nuclear beta decay to search for physics beyond the standard model
- In-beam spectroscopy of heavy elements
- Synthesis and decay of the heaviest elements
- Optical spectroscopy of the heaviest elements
- Neutron capture cross sections of radioactive nuclei
- The r-process path between the N=50 and N=82 shells
- Ground-state two-proton radioactivity
- Beta-delayed two-neutron emission
- Structure beyond the neutron drip line: $^{26-28}$O
- Mass of $^{78}$Ni ground state
- Magnetic moments of isomers in the $^{78}$Ni region
- Charge radius of $^{78}$Ni
- $^{44}$Ti Abundance as a Probe of Nucleosynthesis in Core Collapse Supernovae
- One or two neutron or well-defined cluster (like alpha-particle) break-up
- Isospin Dependence of Correlations
- Systematics of Isoscalar Giant Resonances in Exotic Nuclei
- Mapping of Single Particle Energies using Transfer Reactions
• The density dependence of the symmetry energy
• Neutron-proton effective mass splitting
• Isospin dependent phase transition
• Isospin fractionation and isoscaling
• Fundamental tests with low energy beta-beams
• Nuclear structure studies with low energy beta-beams

We present in the following some of these experiments, particularly relevant for our Italian community interests.

6.1. The r-process path between the N=50 and N=82 shell
A systematic study of the basic nuclear structure properties of neutron-rich nuclei on the process path between the N=50 and N=82 major neutron shells is proposed for measurements at the Nuclear Astrophysics Sector of EURISOL. Measurements of these basic properties will provide the fundamental information for extension to neutron-rich nuclei of the nuclear structure and reaction models needed for full-scale r-process nucleosynthesis studies.

Nuclear structure properties of neutron-rich nuclei are of paramount importance for the understanding and modeling of the r-process, responsible for the synthesis of approximately half of the elements heavier than iron. Presently available experimental information on basic properties such as masses and decay schemes of neutron-rich nuclei do not include nuclei in the r-process path in the regions between the N=50, 82 and 126 shells. The observables we are interested in are: nuclear mass (S_n, Q_n), half-life (β-decay T_{1/2}), β-delayed neutron emission probability (P_n). Additional important observables are: energies and J^2 of excited states, ground-state deformation, neutron-capture rates. The proposed experiment will consist of a systematic study of basic nuclear structure properties of neutron rich isotopes of (possibly) all elements from Fe to Sn, covering all waiting-point nuclei in the r-process path between the N=50 and N=82 neutron shells. Depending on beam intensities obtainable, the following isotopes will be studied (mass number range given for each element): 68(8)−74Fe, 73−75Co, 78Ni(*), 79(8)−81Cu, 80(8)−84Zn, 81(8)−87Ga, 84(8)−90Ge, 87(8)−95As, 90(8)−98Se, 91(8)−101Br, 96(8)−106Kr, 101(8)−107Rb, 102(8)−110Sr, 105−113Y, 108−118Zr, 111−123Nb, 114−124Mo, 121−125Tc, 124−126Ru, 127Rh, 128Pd, 129Ag(*), 130Cd(*), 131In(*), 132Sn(*). Nuclides marked with (*) have been already measured and will be used as benchmark cases.

Detection system will consist of a penning trap mass spectrometer for mass measurements (see e.g. ISOLTRAP), laser ion-source for half-life measurements (e.g. RILIS at ISOLDE). Multi-coincidence set-ups will be used with various detection systems.

From the theoretical point of view, modern nuclear structure models for the nuclear mean field, will be the main ingredient of the study. Also, capabilities for large-scale shell-model calculations (needs the development of appropriate residual interactions to be employed in studies of nuclei far from stability). Full dynamical calculation of r-process nucleosynthesis with inclusion of the nuclear physics input obtainable from the experimental data.

6.2. Neutron capture cross sections of radioactive nuclei
Radioactive nuclei produced in the various nucleosynthesis processes play a special role in nuclear astrophysics. Alive radioactivity in the Universe can nowadays be detected with satellite based gamma-ray observatories (RHessI, INTEGRAL) via the characteristic decay lines or by mass spectroscopy of stellar dust grains. This information can be used for testing stellar models like supernova explosions or for obtaining information about the age and the chemical evolution of the Universe. For this purpose it is however required to measure stellar reaction rates, which lead to the production and destruction of these radioactive isotopes. In some cases (e.g. for (p,γ)
and \(((\alpha,\gamma)\) reactions) the measurements can be performed in inverse kinematics by producing low energy radioactive beams. In cases where this possibility does not exist (e.g. \((n,\gamma)\) reactions) isotopically enriched radioactive targets have to be used for determining the reaction rates.

There is a long list of radioactive isotopes, which can be observed alive in the solar system. The explanation of the detected amount is a challenging test for stellar models and nucleosynthesis calculations (for details see the overview paper by Wasserburg et al [9]). The respective \((n,\gamma)\) rates are the crucial nuclear physics input for such calculations. So far, experimental data for these rates are almost completely missing. As examples for the many required data, this proposal focuses on the two radioactive nuclei \(^{60}\text{Fe}\) and \(^{107}\text{Pd}\). \(^{60}\text{Fe}:\) The production of \(^{60}\text{Fe}\) in massive stars depends strongly on the very uncertain \(^{59}\text{Fe}(n,\gamma)\)^{60}\text{Fe} and \(^{60}\text{Fe}(n,\gamma))^{61}\text{Fe} cross sections. The long-lived \(^{60}\text{Fe}\), with \(T_{1/2}=1.5\times10^6\) yr has been detected in deep sea sediments [10] and is likely to originate from a nearby supernova, which triggered the formation of the solar system. This isotope can also be observed by the \(\gamma\)-ray satellite INTEGRAL [11] via the decay of the daughter nucleus \(^{60}\text{Co}\). This will be important to constrain the \(^{60}\text{Fe}\) output of supernovae. So far, no experimental data are available for the \(^{59}\text{Fe}(n,\gamma)^{60}\text{Fe}\) cross section, whereas the available theoretical predictions between 1.8 mb and 3.4 mb deviate by almost 100%. \(^{107}\text{Pd}\): Spectroscopic observations of elements on the surface of a dozen very old, metal-poor halo stars (see e.g. [12]) found very good agreement with the solar r-process pattern for nuclei above barium \((A>138)\). This can be interpreted as product of an early, very robust r-process, which always operates in the same way, independent of the initial conditions.

Nuclei below barium, however, are under-produced compared to the solar r-abundances. For the discussion whether a second r-process is needed to explain the observations, Silver is most interesting since its observed abundance is particularly low. This could point to a problem with the neutron capture cross sections of the related isotopes. In case of Ag, the cross sections of the two stable isotopes \(^{107}\text{Ag}\) and \(^{109}\text{Ag}\) are known with uncertainties of 3%. However, a large fraction of elemental Ag is produced by the radiogenic contribution of \(^{107}\text{Pd}\), which has a half-life of \(6.5\times10^6\) years. \(^{107}\text{Pd}\) was also found in several iron meteorites but the amount cannot be consistently explained with current models taking into account the correlation to other radioactive nuclei \((^{60}\text{Fe}, ^{26}\text{Al}, ^{41}\text{Ca})\) [1]. So far, there is only one measurement of the neutron capture cross section of \(^{107}\text{Pd}\) [13], which was performed with a fission product Pd sample with a very low (16%) enrichment in \(^{107}\text{Pd}\). At present, many neutron capture experiments on radioactive samples cannot be performed because the required masses of a few hundred milligrams of isotopically enriched samples are not available. In addition, backgrounds from the activities of such samples are prohibitive as well. The advent of new, high flux neutron sources (e.g. n_TOF at CERN or the Frankfurt neutron generator at the Stern-Gerlach Zentrum, FRANZ) will allow for precision measurements on minute samples of 1016 atoms only. Therefore, we propose to produce isotopically enriched samples by ion implantation of radioactive beams. The proposed experiment will consist in the implantation of radioactive nuclei in a thin carbon backing to produce isotopically enriched samples.

6.3. \(\beta\)-delayed two-neutron emission

Very little is known on nucleon-nucleon correlations in the atomic nucleus. One way to study these correlations is search for correlated emission of two nucleons. The best probes from a theoretical point of view is most likely the emission of two neutrons, as the neutrons are not perturbed by the Coulomb barrier. When moving further and further away from the valley of stability, the Q values for \(\beta\)-decay increase more and more. Close to the drip line, \(\beta\)-delayed particle emission is observed. Even further away, \(\beta\)-delayed two-nucleon emission can be observed and studied. \(\beta\)-delayed two-proton emission has been observed experimentally for 9 different nuclei, but only the decay of \(^{31}\text{Ar}\) has been studied to some extent. On the neutron-rich side, \(\beta\)-delayed two-neutron emission has been observed for 7 nuclei with branching ratios ranging from

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Very little is known on nucleon-nucleon correlations in the atomic nucleus. One way to study these correlations is search for correlated emission of two nucleons. The best probes from a theoretical point of view is most likely the emission of two neutrons, as the neutrons are not perturbed by the Coulomb barrier. When moving further and further away from the valley of stability, the Q values for \(\beta\)-decay increase more and more. Close to the drip line, \(\beta\)-delayed particle emission is observed. Even further away, \(\beta\)-delayed two-nucleon emission can be observed and studied. \(\beta\)-delayed two-proton emission has been observed experimentally for 9 different nuclei, but only the decay of \(^{31}\text{Ar}\) has been studied to some extent. On the neutron-rich side, \(\beta\)-delayed two-neutron emission has been observed for 7 nuclei with branching ratios ranging from
1% to 10%. However, correlations between the two neutrons have not been searched for in any of these nuclei. These correlations may yield valuable information about the pairing of nucleons inside the atomic nucleus, which is not accessible otherwise. In particular, two-neutron emission has a decisive advantage over two-proton emission, which is that the Coulomb barrier does not affect the two neutrons and a possible correlation should be observable outside the nucleus. Beyond their interest for correlation studies, the decay characteristics of these nuclei are also of interest for the modeling of the astrophysical rapid-neutron caption process. To identify new two-neutron emitters and to study their decays, these isotopes have to be implanted into a catcher, which is surrounded by a high-efficiency, high-granularity neutron detection system. The observables to be measured are the half-life of the nucleus, the energy of the neutrons and in particular the angle between the two neutrons. In addition, to complete the $\beta$-decay scheme, $\gamma$-radiation should also be observed.

The known $\beta$-2n emitters are $^{11}$Li, $^{17}$B, $^{17}$C, $^{30,31}$Na, $^{32,33}$Na, but many others are expected close to the neutron drip line. These isotopes can be produced e.g. by fragmentation reactions or by deep inelastic reactions. After implantation in the center of the detection set-up, the neutrons will be detected and their energy and angular correlation will be determined. High-intensity neutron-rich stable or radioactive beams at about 100-150 MeV/nucleon for fragmentation or deep inelastic reactions

To produce the aforementioned nuclides by projectile fragmentation, a high-resolution, high-acceptance fragment separator is needed to separate the exotic species from the bulk part of less exotic nuclei. At the end of this separator, a high-efficiency, high-granularity neutron set-up is needed to give access to the individual energies of the two neutrons and their emission angle.

The interpretation of the experimental data requires sophisticated theoretical models which describe coherently the nuclear structure part and the nuclear dynamics of the emission process. Most of the models available today treat only one of the two parts reasonably well. These models have to be refined and new concepts like time-dependent approaches have to be implemented. In particular, the experimental observables to study e.g. the pairing force are not very well established.

6.4. Structure beyond the neutron drip line: $^{26-28}$O

Intense beams of very neutron-rich Ne isotopes will be employed to explore the unbound isotopes of oxygen, including doubly-magic $^{28}$O. In addition to their low-lying structure, n-n and 4n correlations will also be explored. The character and structure of the very neutron-rich isotopes of oxygen, $^{26-28}$O have been long standing issues in nuclear structure. Indeed, $^{28}$O remains arguably the only doubly-magic system that remains to be observed. Numerous experiments performed over the last 15 years have demonstrated that $^{24}$O is almost certainly the last particle stable oxygen isotope. Present research is limited by production rates to improving the ground state mass excess of $^{24}$O, searching for the (unbound) first excited states of $^{23,24}$O as well as the (bound) ground state of $^{25}$O - to date no bound excited states have been seen or are predicted in $^{23,24}$O. Interestingly, based on the current limits set on the energy of the first $2^+$ state in $^{24}$O, Brown suggests that this nucleus is “doubly magic”. Moreover, the same shell model calculations indicate that $^{26-28}$O are only weakly unbound. Given that the neutron-rich F isotopes are particle bound up to at least $^{31}$F ($^{28,30}$F are unbound) - some 6 neutrons beyond $^{24}$O - and that $^{28}$O (N=20) lies just below the N~20 island of inversion, $^{26-28}$O represent very sensitive tests for modern nuclear structure models.

The ground and low-lying excited states of $^{26-28}$O, as reconstructed from the $^{24}$O fragments and coincident neutrons are the interesting observables in this experiment. It will be performed in the following way: a high-energy beam of $^{28-30}$Ne will be reacted on a thick (~500 mg/cm$^2$) Be or C secondary reaction target. The unbound $^{26-28}$O will be populated via two-proton removal/“knockout” reactions ($\sigma \approx 100\mu$b). The beam velocity fragments - $^{24}$O and neutrons
will be detected at very forward angles. The relative-energy spectra for $^{26-28}\text{O}$ will be reconstructed from the measured momenta of the fragments. $^{28-30}\text{Ne}$ beams of intensities of 104 pps or more, with energies of $\sim$100-150 MeV/nucleon will be required. Charged fragments will be detected using a large-gap, sweeper magnetic spectrometer, coupled with a position sensitive Si-CsI array - the measurement of $A$ and $Z$ for masses up to 30 and $Z$ up to 10 is required. The neutrons will be detected in a high-acceptance detector array which will provide a measurement of the positions and times-of-flight. To achieve the desired statistical accuracy in a running time of 1 week, an overall (geometric and intrinsic) one-neutron detection efficiency of $\sim$50% is required. In addition, the identification and measurement of multi-neutron events ($M_n = 2-4$) and the rejection of cross-talk events is essential. Improved shell-model calculations, both classical and in the continuum, of the low-lying structure of the $^{26-28}\text{O}$ are needed. Ideally these calculations will take into account the results of ongoing experimental studies of the less neutron-rich O and F isotopes.

6.5. Mass of $^{78}\text{Ni}$ ground state
Neutron-rich, doubly magic $^{78}\text{Ni}$ is a key nuclide on the neutron-rich landscape. Its mass is a fundamental observable that will test model predictions. Shell gaps in exotic nuclei are the subject of intense investigation due to their sensitivity to little understood components of the nuclear force, and their importance, for the neutron-rich nuclides, in astrophysical $r$-process calculations. The nuclide $^{78}\text{Ni}$ will provide key tests of the most up-to-date model predictions. Here we address the measurement of its mass.

The mass will be measured, as part of a systematic mass measurement program addressing the $n$-rich landscape. The directly produced ISOL beam of $^{78}\text{Ni}$ will be used, and about 20 ion/s of 50 keV $^{78}\text{Ni}$ are needed. An advanced Penning trap system similar to the ISOL TRAP/ISOLDE set-up will be used (cf. MATS design at FAIR, or TITAN at TRIUMF).

On the other hand, from the theoretical point of view, mass model predictions are also needed.

6.6. Magnetic moments of isomers in the $^{78}\text{Ni}$ region
The neutron-rich, doubly magic nuclide $^{78}\text{Ni}$, and neighbouring nuclides, are expected to have isomers arising from cross-shell excitations. Their magnetic moments will provide benchmark tests of shell-model predictions. Shell gaps in exotic nuclei are the subject of intense investigation due to their sensitivity to little-understood components of the nuclear force, and their importance, for the neutron-rich nuclides, in astrophysical $r$-process calculations. The nuclide $^{78}\text{Ni}$, and its neighbours, will provide benchmark tests of the most up-to-date shell-model predictions. Here we address measurements of excited-state magnetic dipole moments.

The magnetic dipole moments will be measured by time-differential perturbed angular distributions (TDPAD) as part of a wider program to characterize isomers in the $^{78}\text{Ni}$ region of the neutron-rich landscape. Secondary fragmentation of a radioactive $^{81}\text{Ga}$ beam will be used. 100 A MeV $^{81}\text{Ga}$ is needed to produce, by fragmentation, 103 ion/s of $^{78}\text{Ni}$, with about 10% in isomeric states. Beam pulsing, on a $\mu$s time scale, is needed. A dipole magnet and Ge gamma-ray detectors are needed as well as theoretical shell model prediction.

6.7. Charge radius of $^{78}\text{Ni}$
Following up the previous section, here we address the measurement of its charge radius, as part of a wider program to determine, by laser spectroscopy, nuclear radii and moments in the $^{78}\text{Ni}$ region. The charge radius will be measured, as part of a systematic program addressing the $n$-rich landscape. The directly produced ISOL beam of $^{78}\text{Ni}$ will be used. an intensity of 20 ion/s of 50 keV $^{78}\text{Ni}$ will be needed.
6.8. $^{44}$Ti abundance as a probe of nucleosynthesis in core collapse supernovae

Core collapse supernovae are remarkable astrophysical sites, representing one of the most extreme physics laboratories in Nature. There is immense interest in attempting to elucidate the physics that drives them, and perhaps the single most important diagnostic tool at our disposal is the isotope $^{44}$Ti. Unlike any other observable, it combines the specificity of isotopic (not elemental) abundance, can be observed promptly and directly (by γ-ray observing satellites), and its production can be associated with specific aspects of the core collapse mechanism. The quantitative interpretation of these observations urgently requires that several key nuclear reaction rates, such as $^{44}$Ti(α,p) and $^{45}$V(p,γ), must be measured. Despite there being general agreement on the mechanism by which a massive evolves and explodes, some fundamental uncertainty remains; even the best models fail to generate a robust explosion. Gamma-ray emission from the decay of newly synthesized $^{44}$Ti, and $^{44}$Ca excesses in pre-solar grains, provide a powerful tool for testing the dynamics used in a particular model. However, for this method to be useful, several key nuclear reactions that determine the abundance of $^{44}$Ti urgently need to be determined.

Reaction rate near and within Gamow window are the important observables in this case as well as spins, parities, energies and widths of low energy resonance. Direct measurement of the $^{44}$Ti(α,p)$^{47}$V reaction: a previously attempted measurement [14] was unable to explore the astrophysical interesting energy regime. Extrapolation of the result to lower energies suggests the $^{44}$Ti(α,p)$^{47}$V reaction rate is significantly higher than previously expected (reducing the amount of $^{44}$Ti synthesized), but too much uncertainty remains to be useful. An experiment with sensitivity at energies corresponding to those in the astrophysical environment is needed. Indirect measurements of the $^{45}$V(p,γ) reaction such as $^{45}$V(p,p) and (for example) $^{45}$V(d,p): extremely limited data exist up to now [15] and do not cover the relevant energy region. Shell model and isobaric analogue considerations [16] suggest several relevant states should be suitable for this technique. Beam properties necessary to perform such a test are: low energy (∼0.5-2 MeV/u) beams of $^{45}$V and $^{44}$Ti and beam currents in excess of 107 pps. On the other hand the detection system will consist of silicon charged particle arrays, similar to the Louvain-Edinburgh Detector Array. Several targets have to be used: a CH$_2$ target for the $^{45}$V(p, p) measurement, a deuterated polyethylene target for the $^{45}$V(d,p) measurement, a thin window/windowless gas target for the $^{44}$Ti(α,p) measurement, with a thickness of ∼1018 atoms cm$^{-2}$. Hydrodynamical and network calculations are needed to allow interpretation of results as well as shell model calculations to help identify states in $^{46}$Cr.

6.9. One or two neutron or well defined cluster (like α-particle) break-up

The goal of this experiment would be to study the interior part of wave functions of nucleons and clusters and to check the limits of validity of mean field and single particle concepts. The long-range and short-range correlations can vary as a consequence of the isospin dependence of the N-N interaction. An example of study of new reaction mechanisms: full kinematics reconstruction deep inelastic experiments.

Spectroscopy of light exotic nuclei has been very successful by using surface reactions such as break-up or transfer. Do spectroscopic factors just represent asymptotic properties of wave functions? Slightly deep inelastic reactions with heavy exotic projectiles can answer this question as well as show the limits of mean field concept validity.

Neutron and core energy or parallel momentum distributions and absolute break-up cross sections plus angular correlations (n-core) would be the observables to be measured. Forward peaked neutron- (or proton-) core coincidence, corresponding to impact parameters for which projectile and target, both heavy nuclei, interact at distances shorter than the strong absorption radius. (This is also a check of the transparency of the optical potential for n-rich nuclei.) Gamma rays from the projectile and possibly the multiplicity of neutrons from target de-
excitation.

We need to perform an experiment that would simultaneously explore the reaction mechanism and give information on the projectile structure. This requires a target which is very well known: the best is $^{208}$Pb because the neutron-target optical potential is parameterised better than any other and its excited states are well known. The ideal incident energy is around 60 A MeV. A relatively high intensity incident beam is needed. If all detectors have a good efficiency and large solid angle coverage, then even an intensity of $10^3$ pps would be acceptable. With an improved set-up of the type employed in [17], for example, we should be able to undertake in triple-coincidence measurements for the following observables: i) the valence neutron in-plane and out-of-plane momentum ($\theta$ and $\phi$) distributions and the neutron energy or parallel momentum distribution. In the case of a two-neutron halo nucleus, also two-neutron-core angular correlations. ii) The same three observables for the core (or its fragments); $\gamma$-rays from the core to distinguish ground state from excited states. iii) Finally the excitation energy of the target from the low-energy neutron multiplicity measured over $4\pi$ or the target $\gamma$-rays. The resolution for i) and ii) should be good enough to infer the invariant mass (excitation energy $E^*$) of the projectile. The $\gamma$-rays from the excited core should also be measured in order to determine the $E^*$ of the projectile. The important point would be to define the reaction plane such that the position of the neutron with respect to it would be determined (azimuthal angle). Absolute cross sections should be measured as well. Data should be handled by performing an event-by-event impact parameter analysis. From the angular distribution and energy distribution of the neutron at very large impact parameters (selecting the Coulomb break-up mechanism) the valence neutron separation energy of the projectile may be estimated. For each excited state of the core (all events in coincidence with a certain $\gamma$-ray from the core), the peak positions of the core and neutron parallel momentum distributions and the excitation energy of the target via the neutron multiplicity could be used to map the total final energy distribution. For each single particle state thus identified we go down in core impact parameter mapping the wave function up to the distance at which the core does not survive the interaction with the target. This is the point at which strong correlations and clustering effects enter the game. If a single neutron breakup can still be identified in coincidence with each individual cluster, the same game reconstructing the neutron momentum distribution should be played and “spectroscopic factors” (overlaps) could be deduced for the neutron with respect to each cluster. A fairly accurate map of the correlations should thus be obtained. Well-focused, high intensity ($10^5$ pps), 50-80 A.MeV, $^{38}$Ne to $^{46}$Ar or heavy Ni (depending on availability) will be needed. Experimentally such studies rely heavily on large area, high efficiency, and high-granularity neutron detector arrays, the further development of which should be envisaged for EURISOL. For example a neutron $4\pi$ (liquid scintillator) detector (like ORION) but with much lower background for the neutrons from the target and a detector like DEMON for the forward neutrons would be needed, plus $\gamma$-ray detectors. Coupling with a large gap spectrometer sweeper magnet would be highly desirable. Theoretical support needed for interpreting such experimental results consists of advanced shell model calculations, developments of break-up models including full kinematics, microscopic optical potentials for neutron rich nuclei.

6.10. Isospin dependent phase transition

The fragmentation phase transition will be quantitatively studied as a function of isospin and charge and located in the phase diagram of asymmetric nuclear matter. Scaling observables from sources differing in charge/isospin will be developed to control data selection criteria. Beam energies overcoming the fragmentation threshold will be needed.

Nuclear matter is known to present at least two major phase transitions: a transition to the quark-glue plasma at high energy density, and a transition to a nucleonic vapour phase at a temperature of a few MeV. We want to determine quantitatively the low temperature
phase diagram of nuclear matter and the characteristics of the expected liquid-gas phase transition. If multi-fragmentation experiments in the past 10 years have established approximate values for the temperature, energy and density of this phase change, its nature and order are still largely unknown, as well as its isospin dependence. Studying the transition with finite nuclei has the extra advantage of also revealing the thermodynamic anomalies, which should be associated with first order phase transitions of any finite system (negative heat capacity, negative susceptibility, negative compressibility, bimodal distributions). Such signals have already been observed with stable beams and need now to be confirmed and studied as a function of the isospin asymmetry. This physics case has strong interdisciplinary connections with atomic, molecular, and cluster physics. In the framework of EURISOL, we expect important synergies with the Limits of Stability subtask. On the theoretical level, the study of multi-fragmentation with exotic beams has also important astrophysical consequences. Indeed multi-fragmentation is a unique laboratory for the formation of inhomogeneous structures due to Coulomb frustration. Such structures have to be correctly modeled for the supernovae explosion process and the cooling dynamics of proto-neutron stars. The main observables needed to characterize the transition and locate it on the phase diagram \((\rho_n, \rho_p)\) are the energy threshold for fragmentation, temperature measurements, inclusive and exclusive charge scaling, IMF multicharge correlations, fluctuations and bimodality observables. All these observables individually bear intrinsic ambiguities and need to be measured at the same time on the same data set. The onset of fragmentation can be established using well-developed techniques for stable beams: identification of a fragmentation source, calorimetric measurement, fragment multiplicities and velocity correlations. The change of the fragmentation threshold with the source charge and asymmetry allows the charge and asymmetry dependence of level densities, limiting temperature and instability properties to be accessed. New physics will be searched for looking for scaling violations of fragment observables. The different phase transition signals used for stable beams will be crossed and compared with dedicated simulations to confirm and locate the transition line on the phase diagram.

Different isotopes of medium and heavy beams from neutron poor to neutron rich (e.g. \(^{56}\text{Ni} \rightarrow \ ^{74}\text{Ni}, \ ^{106}\text{Sn} \rightarrow \ ^{132}\text{Sn}, \ ^{200}\text{Rn} \rightarrow \ ^{228}\text{Rn}\)) in an energy range 30-100 A.MeV will be used as beams. The detection system will consist of (i) \(4\pi\) and low threshold complete A and Z identification for IMF (FAZIA); (ii) \(4\pi\) neutron detector; (iii) high angular resolution \(\Delta\theta<0.5\) LCP and neutron arrays for correlation measurements. Extensive realistic simulations of the collision dynamics (HIPSE,MD) will be needed to support data selection criteria. Both microscopic and macroscopic statistical models (LGM, AMD, SMM, MMM) have to be employed to give quantitative predictions on phase transition observables. Dedicated statistical simulations including the experimental constraints have to be developed. A theoretical improvement of evaporation codes for side feeding corrections will be needed.

7. Conclusions
In this paper we have presented some of the results of the first four years of Design Study for the proposed next generation European facility for unstable beam, EURISOL. It is the hope of our community that such a project will be approved and finally realized for the progress of Nuclear Science.

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