Updated Physics and Instrumentation case for ISOL facilities and for EURISOL

This report contains the conclusions drawn from a series of topical meetings initiated by the User Executive Committee of the EURISOL Users Group within the scheme of Task 2, "Physics and Instrumentation" of the EURISOL-NETWORK, which is part of the ENSAR contract supported by the European Commission.

A comprehensive documentation relative to the activities of the EURISOL Users Group is available on the website http://www.eurisol.org/usergroup/

The User Executive Committee of the EURISOL Users Group is an elective body whose members are at present

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Previously

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The goal of the activity was to keep updated the physics case for EURISOL as presented by the "Key Experiments" report of the EURISOL DS project which ended in 2009. There were five meetings summarised in the following table.

Title of Topical Meeting	Date	Place	Chair	Number of participants	Number of talks
The formation and structure of r-process nuclei, between N=50 and 82	December 2009	Catania, Italy	A. Bonaccorso	65	25
Neutron-deficient nuclei and the physics of the proton-rich side of the nuclear chart	February 2011	Valencia, Spain	B. Rubio	70	30
Physics of light exotic nuclei	October 2012	Lisbon, Portugal	L. Ferreira	40	26
Going to the limits of mass, temperature, spin and isospin with heavy Radioactive Ion Beams	July 2013	Krakow, Poland	A. Maj	71	40
Innovative Instrumentation for EURISOL	July 2014	York, UK	A. Andreyev	42	25

The detailed proceedings of the five topical meetings and the slides presented can be found on the ENSAR website at www.ensarfp7.eu/projects/eurisol-net/documents.

The formation and structure of r-process nuclei between N=50 and 82

Nuclear structure properties of neutron-rich nuclei are of paramount importance for the understanding and modelling of the r-process, responsible for the synthesis of approximately half of the elements heavier than iron. Because the r-process path is not fully known and will encompass a large number of neutron rich nuclei, nuclear properties for hundreds of isotopes ranging from the light to superheavy nuclei and up to the neutron drip line, in particular the regions between the N=50, 82 and 126 shells, are relevant to the r-process. These properties include ground and excited state properties (masses, deformations, spectra of excited states and nuclear level densities, spontaneous beta decay or fission probabilities,...) as well as the properties of interactions with nucleons, alpha particles and photons. In neutron star environments, the high-density equation of state of asymmetric nuclear matter is also required. One of the main goals of future facilities and in particular EURISOL is to make direct measurements of a large number of these neutron rich isotopes and to benchmark nuclear models to make reliable predictions for those which will remain inaccessible.

As far as experimental needs are concerned, two major orientations can be envisioned: First, the measurement of given properties for a large set of nuclei that would enable a global analysis (and extrapolation) in the framework of microscopic models of properties such as nuclear masses, radii, low-lying excited states, giant resonances; Second, the specific measurement of a given property that could bring new insights into the physics of exotic neutron-rich nuclei and could have a significant impact on the extrapolations of existing models. As examples, the following nuclear effects still require further experimental effort: the neutron skin thickness, the N=82 and N=126 shell closures, the imaginary component of the neutron optical potential for n-rich nuclei, the pre-equilibrium contribution to reactions induced by exotic n-rich nuclei, the nuclear level densities at high energy and/or for exotic nuclei, the dipole strength at low energies. Such new measurements will be fundamental in our understanding of the physics of exotic nuclei. As discussed above, it should also be recalled that today we are still far from being capable of make reliable microscopic nuclear predictions on the description of β-decay and reaction mechanisms, including the equilibrium, pre-equilibrium and direct capture process as well as the radiative neutron capture rates and fission properties of exotic n-rich nuclei. Some of the important observables to measure are discussed below.

The recent achievements pave the way for a study of ground-state properties of the most exotic nuclei, achievable only with the next generation facilities, like EURISOL. The half lives of r-process nuclei are in the range of hundreds of ns, well within the reach of current Penning trap setups. Therefore the experimental reach for mass measurements will depend mainly on the gain in yield of the future facilities. Another limiting factor is the isobaric purity of the beams for which it is expected that the generalization of resonant ionization laser ion sources (RILIS), multi reflection time of flight spectrometers (MRTOF) and the improvement of High Resolution mass Spectrometers (HRS) will bring great improvements, useful for many types of measurements.

Beta-decay properties such as ground state half lives (T1/2) and beta-delayed neutron branching ratios (Bn) of neutron rich nuclei are very important ingredients in r-process calculations. In addition, proper measurements of the B(GT) distributions (and Q-values, which can be derived from ground state mass differences) are very important in order to validate the models which are used to estimate half-lives and Bn values of nuclei unreachable even with EURISOL.

The determination of neutron capture cross sections require indirect methods such as the Trojan Horse method or transfer reactions such as (d,p). Some studies on neutron captures at the N=82 shell closure are expected to be achieved at the presently available facilities thanks to the high production rate of N=82 nuclei around Sn and Cd. However there are some more exotic phenomena, such as a new subshell gap predicted at N=90 in the Sn isotopic chain, i.e. for ^{140}Sn. Therefore the production of new very neutron-rich nuclei, with higher N/Z ratios than those presently available, would be necessary to see the change of nuclear interaction in a more diffuse potential. The effect could be detected through the presence of low ℓ orbits at low excitation energy.

The Pygmy Dipole Resonance (PDR) plays an important role in neutron capture. Its measurement in isotopic chains extending to very neutron-rich systems may further reduce the uncertainty on the parameters (c.f. the symmetry energy) governing the presently available NN model interactions. The use of different bombarding energies, of different combinations of colliding nuclei involving different mixture of isoscalar/isovector components, together with an analysis based on microscopically constructed form-factors, can provide the clues to reveal the characteristic features of these states. Important quantities which define our understanding of nuclear physics can be constrained by measurements of the collective strength in very neutron rich exotic nuclei produced at EURISOL.

For a long time it was believed that ^{132}Sn could present a weakening of the spin-orbit gap and thus represent the limit of applicability of traditional mean field approach. However from the experimental analysis rather "normal" spectroscopic factors have been deduced and exotic features would lie beyond ^{132}Sn. Spectroscopic data on nuclei with both proton and neutron holes, relative to ^{132}Sn are rare. Shell-model calculations are able to reproduce the observed decay schemes close to the N = 82 shell closure, however the agreement becomes worse when moving further away. These problems may arise due to some collectivity being present in these nuclei or a difference between hole-hole and particle-particle (or particle-hole) interactions. Coulomb excitation measurements are necessary to search for any collective effects. More spectroscopic data are also needed to further test the shell-model predictions and to improve the interactions. Through the unique possibility of offering secondary fragmentation of intense neutron rich beams such as ^{132}Sn, ^{144}Xe or ^{144}Cs, EURISOL will be able to deliver intense beams of the required In, Cd, Ag, and Pd isotopes.

The collision dynamics in dissipative heavy ion reactions, from low to intermediate energies, is expected to be sensitive to the details of the nuclear interaction away from normal density. Hence dynamical processes involving very exotic beams will allow one to address the study of the nuclear interaction in terms of energy density functionals and, in particular, to constrain the isovector terms and the so-called symmetry energy. This has important implications in the astrophysical context and also for the understanding of the structure of exotic systems. In fact, energy density functionals are probably the only possible framework to describe medium-heavy nuclei and are widely employed also in the study of astrophysical objects, such as compact stars. In investigations of the reaction dynamics, different effective interactions are implemented into transport codes employed to simulate the collision. Then results can be compared to experimental data for specific reaction mechanisms and related observables. A key role in this approach is played by the possibility at EURISOL to study the same reaction over a wide range of incident energy such that different densities will be sampled. Another example of reactions, nowadays out of reach, is the use of neutron rich radioactive beams such as ^{92}Kr on a ^{238}U target. Multi–nucleon transfer and deep–inelastic processes following this reaction will populate with high cross–sections neutron–rich Se, Kr, Rb, Sr nuclei presently completely unknown. Finally we stress the importance of more intense beams for studies involving population/excitation of single particle and/or collective resonances near threshold with indirect methods like (n,d) transfer, Trojan Horse method, breakup reactions or Coulomb excitation above the particle emission threshold.

Future ISOL facilities, and in particular EURISOL, will be instrumental in providing the nuclear data indispensable for forging our understanding of the r-process and the abundance of the elements, while most certainly revealing novel and unexpected manifestations of nuclear structure along the way!

Neutron-deficient nuclei and the physics of the proton-rich side of the nuclear chart

Contrary to the neutron-rich side of the valley of stability, the proton drip line is known for odd-proton-number nuclei up to the lead region (Z=82), whereas it is known up to the zinc region (Z=30) for even-Z nuclei. Therefore, the proton-rich 'territory' is easier to access and a larger number of nuclei has already been studied.

Proton or two-proton emission either from nuclear ground states or from excited states fed by β decay is an important tool in particular close to the limits of stability. Due to the inherent high detection efficiencies obtained for these decay modes, they are very sensitive probes and allow, already with very limited statistics, to extract essential nuclear structure information e.g. concerning the sequence of single-particle orbitals, the properties of the nuclear force and nuclear deformation. EURISOL would allow us to significantly refine the information available on many one- or two-proton emitters as is already the case for the emblematic nucleus ^{141}Ho, for which the half-lives of the ground and isomeric states, the fine structure of both states, and the energies of the rotational bands built on the two states are known. This very complete information, at present only available for one single nucleus, is extremely important in order to fine tune theoretical nuclear models.

The properties of nuclei with equal or very similar numbers of protons and neutrons had been an intense field of research in the last two decades, both experimentally and theoretically. The structure of these nuclei provides essential information on the isospin symmetry of the nuclear force or on proton-neutron correlations. The very recent discovery of excited states in the N = Z nucleus ^{92}Pd and the claim of the presence of an isoscalar T = 0 pairing correlation at low spins is a big step forward in our understanding of these phenomena. Future in-beam studies of exotic neutron-deficient nuclei performed with intense radioactive heavy-ion beams such as those provided in the future by EURISOL will significantly boost this field, especially when going towards the possibly heaviest bound N = Z nucleus in nature, ^{112}Ba (N=Z=56).

The measurement of gamma-ray and conversion electron intensities allows one to calculate the internal conversion coefficients of nuclear transitions and consequently to determine their electric or magnetic character as well as their multipolarity. Such measurements are especially important in the study of very heavy elements. With the beams and instrumentation provided by EURISOL, the heaviest nuclei will become accessible and enable us to access basic nuclear structure information for these very heavy nuclei which will then allow the extrapolation of these properties to the regions of the super-heavy element region.

A key tool at all nuclear physics laboratories is laser spectroscopy. The different variants of this technique give access to basic observables like charge radii, nuclear magnetic and electrical quadrupole moments and spins in a model-independent way. Recently developed schemes like the collinear resonance ionisation spectroscopy allow to work with beam intensities as low as one particle per second. Laser ionisation sources have also the potential to produce isomerically pure beams. The production rates envisioned at EURISOL will give us the possibility to perform these kinds of studies over the whole chart of nuclei.

Nuclear beta decay is a traditional tool to extract information on nuclear structure. From these data one can deduce lifetimes and B(E2) values which indicate the deformation of the nucleus.

Another way of accessing this information is by measuring the -decay strength functions and comparing them to predictions from nuclear theory. The total absorption spectroscopy is particularly well-suited for this purpose. At EURISOL, e.g. the heaviest and most exotic N ≈ Z nuclei will become available for these studies.

According to theoretical models, exotic excitations such as Pygmy resonances, observed in neutron-rich nuclei, can also develop in light and medium mass proton-rich nuclei. In contrast with neutron-rich nuclei, the separation between the electric Pygmy Dipole Resonance and the Giant Dipole Resonance increases as the nucleus becomes more proton-rich. Possible cases of interest for the EURISOL facility could be the proton-rich argon nuclei where the Pygmy resonances could be studied in detail in proton-rich nuclei and confirm predictions of nuclear models.

Clusterisation of light nuclei into alpha particles in N=Z nuclei is a well-known phenomenon which is revealed in the binding energies of nuclei "composed by alpha bonds". This effect is, however, not very strong and it is clear that fermionic effects dominate over cluster effects even at the ground-state level. A very interesting experimental observation is the appearance of clusterisation at the neutron drip-line. The same effect, perhaps attenuated, should exist at the proton drip-line and this unexplored aspect could be part of the EURISOL scientific programme by fragmenting proton-rich nuclei or using transfer reactions.

The chain of the magic tin isotopes starting with doubly-magic ^{100}Sn and ending beyond doubly-magic ^{132}Sn is very interesting from the nuclear structure point of view. Inverse kinematics reactions using beams of these nuclei for Coulomb excitation and transfer reactions allow one to locate single particle states. Coulomb excitation is also used to pin down information on nuclear deformation. These experiments will exploit the future possibilities of EURISOL by pushing the experiments to the extremes of the chart of nuclei.

Nuclear β decay between isobaric analogue states of spin-parity 0+ and isospin T=1 provides valuable information for testing the Standard Model of particle physics. These so-called super-allowed beta decays are of pure Fermi type so that the theoretical description is very simple. The most precise matrix element of the Cabibbo-Kobayashi-Maskawa quark-mixing matrix, V_{ud}, is obtained from these beta decays. In order to progress further, one needs either to study heavier T_Z=0 cases or to improve the precision of the measurements for T_Z=-1 nuclei. One current limitation is the production rates for these isotopes, something that could be clearly improved with EURISOL. New theoretical and experimental efforts are also needed to provide valuable data for evaluating isospin symmetry breaking corrections. Nuclear mirror transitions are an alternative access to the V_{ud} matrix element which can provide a new independent data set.

The rp-process is the main source of energy and determines the X-ray light curve in the X-ray bursts of thermonuclear explosions in the Galaxy. The path is dominated by proton captures and gamma decays. A quantitative comparison between X-ray burst calculations and typical X-ray burst observations has obtained excellent agreement but has also shown that the nuclear physics of the rp-process is not sufficiently well known to test the calculations at the level of precision provided by observations. The main reason is that the key (p,gamma) reactions happen on unstable nuclei while indirect methods do not reach the desired level of accuracy. Work on this topic is already on-going in different laboratories. Experiments e.g. with ^{25}Al or ^{26}Al^{m} will be possible at EURISOL.

In conclusion, there are many extremely interesting physics problems related to neutron-deficient nuclei, especially at the N=Z line, which demand further experimental investment. All of them necessitate higher intensities of radioactive beams than presently available. EURISOL will play a decisive role, in particular when high beam intensities are combined with state-of-the-art experimental equipment.

Physics of light exotic nuclei

Light exotic nuclei were at the core of the early discovery of phenomena like "nuclear halos", which boosted the experimental and theoretical activities related to physics with radioactive beams. They still hold a special place in the panorama of recent activities. They provide in fact the testing grounds for all basic nuclear structure models, from the shell model to cluster models towards the most recent "ab-initio" theories which try also to incorporate reaction models. This path will clarify also the clustering phenomena appearing as threshold effects.

Besides the bound exotic nuclei we are now able to study unbound nuclei just across the drip-line. They represent another open field of research, in which experimental techniques and theoretical models have to be developed further. Some unbound nuclei are sub-constituents of Borromean nuclei. Here the three-body description of the system requires a very accurate knowledge of the neutron-core and neutron-neutron interactions. Direct peripheral reactions and their influence on elastic scattering and fusion plus particle decay studies together with the shell model will help obtaining such knowledge.

Nuclear astrophysics, the "free and everlasting kingdom of exotic nuclei" will benefit from all such progress. Last but not least beta-decay experiments and related models, from which and for which radioactive beams were first developed will continue to be of fundamental importance and often the only means to study high lying excited states. In general from the experimental point of view, the large intensity values of light radioactive beams allow for the most precise measurements of quantities such as absolute cross sections, angular distributions, momentum distributions, and nuclear decay observables, which are of key importance for modern reaction theories.

Binding energies can be calculated for open shell isotopes such as ^{44}Ca by state-of-the-art methods, which handle intrinsic degeneracies of open shell systems by allowing the breaking of particle number symmetry. There are at present several versions of ab-initio methods in which quantum mechanical many-body equations with controlled approximations can be increasingly improved to the point that convergence is reached for the observable. Converged results are considered precise "ab initio" results. An important conclusion, which consistently emerges from all theoretical analyses, is that three-nucleon forces are crucial for both global nuclear properties and detailed nuclear structure, and that many-body correlations due to the coupling to the particle continuum are essential as one approaches the particle drip lines. There is also a new generation of many-body methods which use realistic nuclear interactions from chiral effective field theory (EFT) and three-nucleon interactions. Chiral three-body forces lead to repulsive contributions to the interaction among excess neutrons that change the location of the neutron dripline from ^{28}O (with two-body forces only) to the experimentally observed ^{24}O. Also, it was shown that three-body forces are key to explain the N=28 magic number, leading to a high 2+ excitation energy in calcium isotopes. Moreover, chiral 3N forces improve the agreement with experimental masses predicting a flat behaviour of the two-neutron separation energy from ^{50}Ca to ^{52}Ca. Finally the calculation of neutron matter energy provides tight constraints for the symmetry energy and chiral EFT interactions constrain the properties of neutron-rich matter below nuclear densities to a much higher degree than is reflected in current neutron star modelling. The shell model success relies heavily on the accuracy of the effective interaction used. This is presently being pursued via the introduction of higher order terms, three-body forces and possibly inclusion of positive energy states.

Clustering is a "threshold" effect which can be discussed within the Continuum Shell model. Here the coupling to positive energy states and the use of energy dependent Hamiltonians give rise above particle-emission threshold to non-hermitian components of the effective Hamiltonian. Such components concentrate the continuum coupling on a single state thus giving rise to clustering via the appearance of collective near-threshold phenomena in the ensemble of shell model states. In the Fermionic Molecular dynamics method, one starts with Gaussian wave packets, builds up Slater determinants as many-body states and then diagonalises the Hamiltonian. Then the derivation of a low-momentum effective interaction is the clue to getting an accurate description of the lightest s-p shell nuclei. Recent results include descriptions of the large extension of the Hoyle state in ^{12}C, the radii of ^{17}Ne and ^{18}Ne and the rates of the important astrophysical reactions like $^{3}He(\alpha, \gamma)\,^{7}Be$ and $^{3}He(\alpha,\gamma)^{7}Li$. Clustering evidence and paring effects are evident in breakup reactions and also in measurements of observables linked to the presence of cluster structures of nuclear excited levels accessible via the evaporation processes starting from an excited compound nucleus.

Elastic scattering experiments clarify how breakup and transfer reactions are dominant reaction channels due to the weak initial nucleon binding and deplete elastic distributions in the case of halo nuclei compared to their closest neighbours. The same seems to be the case also for fusion at or above barrier energies. Reaction theories presently available include microscopic continuum discretised coupled channel calculations for energies around the Coulomb barrier, with two-body and three-body projectile wave functions and cluster wave functions. At high energies the eikonal model is appropriate and it is now possible to include core excitation in the reaction dynamics. The three-body Faddeev/Alt-Grassberger-Sandhas multiple scattering expansion can be applied to study data for breakup on a proton target. Microscopic calculations of the optical potential for light nuclei, in which volume and surface effects are distinguished, are also of primary importance. Knock-out, Coulomb breakup and transfer reactions are used to obtain spectroscopic information on single particle state occupancies. Multi-phonon excitations can be used to describe the Pygmy resonance effects. The dipole response in the neutron-rich nucleus ^{20}O has been studied via a new method based on an equation-of-motion phonon method. The results show that this mode is excited with a relatively small strength because coupling and the coexistence with multi-phonon excitations damp the dipole mode.

Nucleo-synthesis reactions can be studied accurately at ISOL facilities. The necessity to have in the future low energy, proton-rich beams (less than 2 MeV/u) with intensities in excess of 10^{7} pps, and high purity has been stressed. The reaction $^{18}F(d,\alpha^{15}O)n$, which is the first application of the Trojan Horse method using a radioactive beam at RIKEN is a very interesting testing ground. Also two-proton decay from excited states in ^{18}Ne can be calculated microscopically, showing the possibility to assign the angular momentum and parity of specific high energy excited states in ^{18}Ne. These states are very narrow, and prefer to decay by one proton emission to the excited states of the daughter ^{17}F, rather than to the ground state.

Beta-delayed multi-particle emission is energetically allowed only close to the driplines. It is of interest since it proceeds via highly excited states in the daughter nucleus and can give unique physics information: particle emission can populate many more states than the ones allowed by beta-decay spin-parity selection rules. Thus several types of experiments would require long beam times with our present experimental techniques, but facilities like EURISOL will be necessary for progressing in the field.

Nuclei at and beyond the driplines are one of the more interesting aspects of physics of light exotic nuclei. They live as resonance states in a similar way as elementary particles. They can be obtained by neutron transfer to the continuum from a weakly bound target, or projectile fragmentation of an exotic bound nucleus. The goal is to establish the ordering of the levels, their resonance energies and angular momenta. This field still needs detailed studies to establish a correct understanding of the reaction mechanisms, the best observables to be measured and a method to extract unambiguously structure information from the data.

Going to the limits of mass, temperature, spin and isospin with heavy radioactive ion beams

The topics “high spin”, “high atomic mass and charge”, and “ground state properties for extreme isospin” were elaborated with special emphasis on the peculiarities and boundary conditions in terms of beam species, intensities and production schemes, projected for next generation radioactive ion beam (RIB) facilities like SPIRAL2, FAIR, FRIB, RIKEN and eventually EURISOL.

Activities related to the topic of high-spin states, using stable beam facilities, were at its peak in the two last decades of last century. Experimental evidence for such rotational phenomena was provided by the structure of rotational bands and related features. Discrete in-beam γ-ray spectroscopy with deep-inelastic reactions turned out to be efficient in elucidating high-spin structures in neutron-rich nuclei. Giant Dipole Resonances (GDR), measured for high spins and high temperatures, were found to be a very useful probe to study the bulk properties of hot nuclei. But the most spectacular outcome of such studies was the discovery of super-deformed high-spin structures throughout the whole chart of nuclei. On the other hand the search for predicted hyper-deformed structures was not conclusive as fission competition does not permit to transfer sufficiently high angular momentum to the nuclei of interest and available for stable beam experiments.

EURISOL, expected to deliver neutron-rich highly intense beams, will extend the exciting field of high spin physics towards unexplored, very exotic regions of the nuclear chart, using fusion reactions. The fission limit for very neutron-rich nuclei, produced via fusion-evaporation reactions, is expected to be higher by at least 10 units of spin, due to a significant increase of the fission barrier with the increasing neutron number. For the Cd - Yb mass region, with extremely large angular momenta (up to 90 ħ) for neutron-rich species, theory predicts hyper-deformed nuclear states to occur with large probability. Favourable shell-effects at low temperatures and the contribution from the liquid drop energy term, at spins even higher than 80-90 ħ, produce a well-defined minimum associated with very large deformations. In-beam γ-ray spectroscopy of deep-inelastic reaction products will greatly benefit from radioactive beams. At sufficiently high temperatures the quantum (shell) effects disappear and the nuclei can be described by classical “macroscopic” models.

In the high-temperature and high-spin regime new shape change phenomena are predicted to occur, as for example the nuclear Jacobi and Poincare shape transitions. These phenomena can be investigated using, e.g. γ decay of the GDR. Also isospin mixing, a subject currently of interest in theoretical investigations, can be studied as a function of nuclear temperature using the GDR decay. The use of stable beams permits the isospin mixing systematic study below A=80 nuclei, while the use of radioactive beams, like those provided by EURISOL, will permit this type of studies for heavier nuclei. At very high temperatures the multi-fragmentation process sets in. High intensity neutron-rich beams will give the possibility to study the isospin dependence of the fragment production process.

The search for the so called “island of stability” of superheavy elements (SHE) is still one of the most intriguing tasks of modern nuclear physics. Apart from the synthesis and basic properties for α-decay and spontaneous fission, the investigation of the nuclear structure of those heavy species has revealed interesting features like K-isomerism for nuclei as heavy as ^{270}Ds, or the population and observation of spins beyond 20 ħ for species like ^{256}Rf. Following the predictions of the major theoretical approaches, the region of spherical shell-stabilized nuclei is out of reach for stable species as projectiles for the traditional fusion–evaporation production scheme.

Neutron rich exotic nuclides will be necessary to compose the required proton and neutron numbers. The intensities projected for the next generation RIB facilities, however, are limited and exclude SHE synthesis via the classical approach. Systematic studies of reaction mechanism and nuclear structure features together with alternative methods, like e.g. deep inelastic reactions and the employment of the compound nucleus spin distribution are promising approaches to the problem.

The description of heavy nuclei employing the most advanced theoretical models is the basis for a successful advancement towards the heaviest species. Deformation, tri-axial behaviour and the prediction of single particle levels, pointing to the formation of the next proton and neutron shell gaps, are at the focus of RMF models, in particular, including quasi-particle vibrational coupling (QVC), and relativistic energy density functional calculations (REDF). In combination and in continuous exchange with ever advancing experimental nuclear structure results a successful progress towards the region of superheavy spherical shell stabilized species seams promising, in particular, given the perspectives opened by RIB facilities with EURISOL at the horizon. New experimental methods are being applied, like precise mass measurements in Penning traps, developed, like laser spectroscopy of stopped species, or envisioned and possibly appearing at the horizon, like the use of neutron-rich radioactive ions as projectiles, provided with higher intensities at EURISOL or its follow ups. Ground state properties, like the nuclear binding energy are major ingredients towards an understanding of the heavy species themselves as well as for the model predictions.

The variation of isospin towards extreme values into the neutron rich region of the chart of nuclei, possible with a facility like EURISOL, is expected to provide a highly promising discovery potential for ground and metastable state properties of atomic nuclei. Ground-state properties, like charge radii, atomic masses, nuclear and magnetic moments, spins and parities can be investigated in a variety of experiments. Precision experiments and model independent techniques are often applied at ISOL facilities providing high intensities and cold low-energy beams. In a few rare cases also post-accelerated radioactive ion beams can be employed. Isotope shift measurements have been a rich source of model independent information for charge radii. In a simple liquid drop type of picture, charge radii have a simple mass dependence. In reality, the nature is more complex and some of the isotopic chains demonstrate large deviations – implying action of the underlying nuclear structure. Various theoretical models have been applied to reproduce such behaviour, but a fully consistent approach is still missing. Additional challenges for theories are set by other discontinuities observed experimentally. With the EURISOL facility, low-energy radioactive ion beams will cover longer isotopic chains while target and ion source development will make new elements available for similar studies. The investigation of isomeric states, caused by various decay hindering features, by traditional decay spectroscopy as well as by modern techniques employing storage rings and ion traps provides direct information on the underlying nuclear structure. Nuclear and magnetic moments are rich sources of structure information, like valence particle configurations, nuclear deformation, effective charges and collective properties.

The equation of the state (EOS) of asymmetric nuclear matter has great influence on astrophysics and testing of nuclear models. Experimentally the symmetry energy of the EOS is rather poorly known. With β-delayed fission, fission studies can be extended to nuclides farther from stability as recently demonstrated. The next step of such studies would require identification of fission fragments, measurement of total kinetic energies for fission fragments and further exploration of odd-even staggering. All these research activities will profit from the expected properties of rare isotope beams provided by EURISOL in terms of intensities up to very exotic isospin.

In summary, the next generation RIB facility EURISOL has promising interesting opportunities for the physics at the extremes of mass, temperature, spin and isospin. Exploration of the chart of nuclides towards extreme isospin, in particular for neutron rich species, highest excitation, mass and charge will receive a boost towards new shores in understanding extremely exotic nuclear species.

Innovative Instrumentation for EURISOL

The aim of the meeting was to review the instrumentation and techniques planned for the upgraded ISOL facilities HIE-ISOLDE, SPES and SPIRAL2 and discuss the possible future ideas and developments for the EURISOL facility. Large collaborations have formed around the projects for the new facilities, with the aim of designing new detection instruments and further develop the associated detection techniques, in order to take full advantage of the forthcoming opportunities. To avoid duplication of the efforts, groups working around similar detection concepts (or technologies) for different facilities were closely collaborating, sharing ideas, and often also sharing manpower. Many new instruments were designed from the start with the idea of being portable, and thus having the possibility of being installed at different facilities. The activities and networks within ENSAR were an important factor in this process. Presentations at the York workshop gave overviews of the status of HIE-ISOLDE, ALTO at Orsay, SPES, SPIRAL2, NUSTAR and ISOL@MYRRHA. They showed indeed an impressive large variety of newly-developed instruments, but also revealed the synergies existing among the groups working on those instruments. Such synergies will be of course crucial in the future, for the realisation of instruments for EURISOL.

The possibility of using storage rings to perform nuclear reactions on an internal target has been tested at the ESR at GSI. Although several challenges have to be overcome, positive results indicate the feasibility and potential of this technique which exploits the recirculation of the radioactive beam to compensate for the reduced target thickness. The project to install a storage ring at HIE-ISOLDE would open new horizons in this respect, not limited to nuclear reactions but also for laser spectroscopy, decay spectroscopy and atomic physics. Related to nuclear reactions are the developments in recoil separators and spectrometers. New technologies and ideas have emerged recently: the use of multipoles to compensate for aberrations in large-acceptance instruments, which could simultaneously retain a high efficiency and achieve an effective spatial separation of the beam species; the techniques for ion separation at low energy, which employ laser ionisation and multi-reflection time-of-flight (MR-TOF) separators to achieve very high beam purity. The latter two techniques are now being used in combination with ion traps to achieve a fast and effective mass purification, with resolving powers comparable to that of Penning-trap techniques and time scales one order of magnitude smaller. This has now pushed further the limits of ion analysis in high-precision ion traps towards shorter-living species, allowing for example mass measurement with single-ion sensitivity for nuclides with a very low production rate and strong contaminants. Thanks to their beam-analysis potential, MR-TOF devices will be incorporated in the Target-and-Ion-Source Development (TISD) programs, as for example at ISOLDE. Related to ion handling are the developments of new targets for reaction experiments. The polarised-proton target at RIKEN is a fine example, and the outlook towards obtaining such a device at room temperature opens important possibilities for detailed spectroscopy through reaction studies using the intensities available for exotic beams at the forthcoming facilities.

The latest developments in the detection of charged particles and neutrons, and improvements of scintillators for γ-ray radiation, were reviewed in a number of presentations. The use of an active target - a gaseous time-projection chamber, where the detection gas is at the same time the target of the reaction to be studied - for spectroscopic reaction studies has been already successfully employed in a number of cases. The development of new-generation detectors of this kind (in Europe, the ACTAR-TPC project) holds important promises for the exploitation of the most rare and weak beams at the new facilities. For the detection of charged particles, Si detectors have so far played the most important role with many set-ups present at all radioactive ion beam facilities worldwide. Such devices will continue their role thanks to important steps forward in the technique especially concerning particle identification, as shown by the GASPARD project. Several important challenges remain for both kinds of detectors, as the demand for dynamic range, count rates, resolution, efficiency, and a very large number of channels to be handled in small spaces, all increase when dealing with rare events to be selected in a potentially high-polluted sample. In this respect it was suggested that it would be beneficial for our community to look in other directions, to the needs and developments present in other domains around these problems.

The realisation of the NEDA array for neutron detection summarises the characteristics of devices designed to work at the new-generation facilities: modular, portable, with a particular attention to integration with other detection arrays. At the same time, NEDA represents a significant step forward in detection efficiency, neutron-γ and neutron cross-talk discrimination and count-rate capability. The development of new organic scintillator materials is followed closely by the collaboration. Similarly, inorganic scintillators have made very important progress in the last ten years thanks to the development of new materials. Performances of $LaBr_3$(Ce) are between those of traditional scintillators and Ge crystals. The drawbacks of $LaBr_3$(Ce) (high internal radioactivity and high cost) are being countered by the research on other materials which may achieve similar performances. These exciting developments are coupled with new techniques for light collection and translation such as avalanche photodiodes, possibly organised in arrays as in silicon photomultipliers. The new-design arrays such as PARIS and CALIFA take advantage of these materials using them in phoswich arrangements for the efficient detection of high-energy γ-rays and protons. The use of new detection materials (in particular fast and efficient scintillators) and the conditions to be expected at new facilities, all the way to EURISOL, are considered in the design of the new detection arrays.

Combining the developments in technology to improve established research methods was the subject of a number of presentations. The possibility of bringing electron scattering to the domain of radioactive nuclei is the aim of two projects. The ELISe project at FAIR uses a geometry with two colliding beams, while SCRIT at RIKEN combines instead the principles of storage rings and ion traps to build an internal ion target in an electron storage ring. A proof-of-principle measurement has demonstrated the feasibility of this technique. The state-of-the-art and future improvements in well-established methods such as fast timing, electron conversion and recoil decay tagging were reviewed. Similarly, a review of methods to measure nuclear moments, spin and charge radii pointed out how the developments in laser methods have achieved ultra-high sensitivity (collinear spectroscopy) and energy resolution (with laser trapping techniques). For these reasons, laser techniques will very likely play a fundamental role in the study of the properties of the most exotic nuclei. It was however noticed that, in the years that separate us from EURISOL, introduction of completely new technologies is not to be excluded. Such sudden shifts have been observed in the past, and have taught us that new exciting developments may sometimes force us to re-think our methods completely.

Conclusion

Through five topical meetings with a large participation of experts and young scientists the physics and instrumentation case for future ISOL facilities and in particular EURISOL has been updated. A strong and compelling physics case concerning nuclei at the confines of stability throughout many regions of the nuclear chart has been delineated. Expected new manifestations of nuclear structure and their importance for the understanding of astrophysics questions were underlined. This compilation reinforces the importance for Europe to realize in a timely fashion the objectives of the NuPECC long range plan for the completion of the facilities HIE-ISOLDE, SPES and SPIRAL2 and to fulfil the conditions for a start up of the construction of EURISOL.