EURISOL Design Study

Task 10 – Physics and Instrumentation

The Physics and Instrumentation Task of the EURISOL Design Study has compiled a list of around 25 key experiments. 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 continually evolving, this list should not be regarded as being set in stone, but rather as a snapshot of the diverse and exciting physics opportunities that will be available with the EURISOL facility. New ideas are always welcome!

Key Experiments

- 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
- In-source spectroscopy and production of isomeric beams with a laser ion source

Super-allowed beta decay and the weak-interaction standard model

Abstract

Proton-rich N = Z isotopes in the vicinity of ^{100}Sn will be used to determine the super-allowed beta decay ft value and to determine the vector coupling constant g_v of the weak interaction. The measurements with high-Z isotopes are crucial to test the nuclear-structure dependent corrections needed to determine g_v and to determine with improve accuracy the V_{ud} matrix element of the Cabbibo-Kobayashi-Maskawa quark mixing matrix.

Keywords

Super-allowed beta decay, weak interaction, Cabbibo-Kobayashi-Maskawa quark mixing matrix

Physics case

The weak-interaction standard model assumes that the vector current is conserved and thus not modified by the nuclear medium. This implies that the transition strength of super-allowed beta decay is the same for all nuclei. Therefore, from the measurement of the *ft* values of super-allowed decays, one can determine the vector coupling constant g_v and, by comparing the vector coupling constant from semi-leptonic decays to the coupling constant of the purely leptonic muon decay, one obtains the V_{ud} matrix element of the CKM quark mixing matrix.

This type of beta-decay studies has been performed on T_z=-1 and 0 nuclei between ^{10}C and ^{74}Rb with a precision of the order of several 10^{-4}. The main contribution to the error in these studies is no longer experimental, but due to the nuclear-structure dependent corrections, which have to be determined by nuclear models. Therefore, beyond increasing the experimental precision on the quantities already measured, it becomes more and more important to improve the precision of these correction terms.

The model calculations show that the nuclear-structure dependent terms increase with nuclear charge and can therefore be tested more easily. However, at the same time, the calculations become also more difficult due to the larger model spaces needed. However, in the vicinity of ^{100}Sn, this problem can be overcome by using ^{100}Sn as a shell-model core. It is expected that this will significantly improve the precision achieved on the nuclear-structure dependent corrections and therefore increase the overall accuracy.

The nuclei which are proposed to be studied include ^{94}Ag and ^{98}In. Lighter N=Z nuclei like ^{90}Rh or ^{86}Tc should also be considered. However, it is expected that for these nuclei the uncertainty of the nuclear-structure dependent corrections will increase significantly.

Observables

For these studies, the beta-decay half-life, the branching ratio of the super-allowed decay branch and the beta-decay Q value have to be measured with a precision of 10^{-3} or better.

Proposed experiment

For the half-life and branching ratio measurements, pure samples of ^{94}Ag and ^{98}In will be accumulated in an RFQ cooler, transferred into a Penning trap for purification and then ejected onto a tape system to transport the activity to a detection set-up, where the half-life will be determined by means of a plastic scintillator or gas detector set-up and the branching ratios by means of a high-precision Germanium detector.

The beta-decay Q value will be determined with a Penning trap system like ISOLTRAP or JYFLtrap.

Requirements

Beam properties

High-purity ISOL beams of 10^4pps of ^{94}Ag and ^{98}In

Detection

For the half-life measurement, fast timing detectors like plastic scintillators of Geiger detectors with high counting-rate capability have to be developed. The main difficulty is the efficiency calibration of Germanium detectors with a precision of several 10^{-4}. This demands a several years R&D program. Both measurements will highly profit from a cooler-storage setup to accumulate and purify the ISOL beams.

For the Q value measurement, a high-efficiency Penning trap system is needed.

Theoretical support

The limiting factor for the determination of the vector coupling constant and the V_{ud} matrix element are the theoretical corrections needed to take into account the influence of the nuclear medium on the *ft* values.

These corrections are two fold: nuclear-structure dependent corrections due to isospin symmetry breaking and QED correction due to e.g. the interaction of the lepton emitted in the decay with the charge of the daughter nucleus. These corrections are difficult to calculate. Only one complete set of calculations exists today. The precision of V_{ud} and g_v will greatly profit from new theoretical studies.

Correlation measurements in nuclear beta decay to search for physics beyond the standard model

Abstract

Precision measurements of different correlations between the spins and momenta of the particles involved in nuclear beta decay permit to extend our knowledge on the structure and the symmetry properties of the weak interaction. The different correlations probe different properties of the weak interaction thus providing complementary information.

Keywords

Correlation measurements in nuclear beta decay, non standard model weak interactions, parity violation, time reversal violation, superallowed Fermi transitions, mirror transitions, Gamow-Teller transitions

Physics case

Correlation measurements in nuclear beta decay are a very sensitive tool to investigate the presence of exotic (i.e. scalar or tensor type) weak interaction components, search for right-handed charged weak currents and search for new sources of time reversal violation. The most interesting correlations are the beta-neutrino correlation, the beta asymmetry, the beta particle longitudinal polarization and the D- and R-triple correlations. These all depend on different non-standard model properties of the weak interaction, with different sensitivities, thus providing complementary information.

Contrary to experiments at high-energy colliders, the small changes in the values of the correlation coefficients that one searches for in such beta decay experiments are independent of the precise particle that would act as intermediate boson for the non-standard model interaction one is probing. However, a new intermediate boson could only be demonstrated directly at a collider.

Taking into account that the nuclear structure of the probe nuclei should be well understood, the most interesting isotopes for such experiments are the isotopes with $0^+ \rightarrow 0^+$ superallowed Fermi beta transitions, the T=1/2 mirror nuclei and selected light to medium heavy nuclei with strong Gamow-Teller transitions and well known nuclear structure. The T = 1/2 mirror nuclei are of particular interest as nuclear structure corrections for these are well understood. In order to reach the best possible sensitivity for new physics with these mirror nuclei, the precision on the ft-values for most mirror transitions has to be improved by at least an order of magnitude.

Observables

Observables to be determined in these experiments are the beta-neutrino correlation *a* (sensitive to scalar and tensor currents), the beta asymmetry *A* (sensitive to right-handed currents and tensor currents), the beta particle longitudinal polarization *G* (mainly sensitive to right-handed currents) and the *D*- and *R*-triple correlations (sensitive to time-reversal violation).

Proposed experiment

Measurements of the different above mentioned beta-decay correlation coefficients are to be performed. The probe isotopes should be selected such as to maximize the sensitivity to the weak interaction property to be investigated, while at the same time minimizing the effects of nuclear structure corrections.

To reach the highest sensitivity for non-standard model physics in correlation experiments with T=1/2 mirror nuclei additional measurements are required in order to improve the precision on the ft-values for the mirror transitions by at least an order of magnitude.

In order to work with isotopically clean samples, to minimize or avoid effects of scattering of the beta particles and to allow undisturbed detection of the recoil ions, many of these experiments will require the use of ion traps (Paul or Penning traps) or atom traps (Magneto Optical Traps). These three types of traps are complementary with respect to ease of operation, possibilities for isobaric purification, ease of combination with different detector types, etc. The type of trap to be used will thus have to be determined for each experiment separately in order to maximize the precision that can be reached.

Further, the beta asymmetry *A,* as well as the *D*- and *R*-triple correlations require polarized nuclei. Therefore, the necessary tools should be implemented/developed to polarize the nuclei (or inject polarized nuclei) in these traps. For MOT atom traps this was demonstrated already using optical pumping, which is also applicable to ions in a Paul trap, while for a Penning trap ions would have to be polarized before injection, e.g. with a collinear laser set-up. To reach the best possible precision on the correlation coefficient one is trying to determine, the degree of nuclear polarization should be determined with high precision. When optical pumping is used this can e.g. be done by monitoring the excited state population with photoionization.

Requirements

Beam properties

These measurements require low energy (< 150 keV) beams i) of the nine isotopes with well studied $0^+ \rightarrow 0^+$ superallowed Fermi beta transitions, ii) of the T=1/2 mirror nuclei and iii) of selected light to medium heavy nuclei with strong Gamow-Teller transitions and well known nuclear structure. Intensities ranging from $\approx 10^5$ to $\geq 10^8$ at/s are needed for these experiments.

Detection

Different types of detectors will be required, ranging from scintillators and solid state detectors for beta particles to micro channel plate detectors for recoil ions. In some cases multi wire proportional chambers for detection of the beta particles will be useful/needed too.

Theoretical support

For some nuclei shell model calculations will be required to determine the weak magnetism matrix element that determines the leading order recoil order correction for most correlation coefficients.

In-beam spectroscopy of heavy elements

Abstract

The high-spin structure of heavy nuclei will be investigated using state-of-the-art in-beam spectroscopic techniques. The data obtained will be used to constrain current theoretical nuclear models, and will provide a stringent test of their predictive power for the heaviest nuclei on the nuclear chart.

Keywords

Heavy Elements, In-beam spectroscopy, gamma-decay, internal conversion, nuclear structure

Physics case

High-spin studies of heavy nuclei provide data, which are essential to test modern nuclear theories. The combination of efficient recoil separators with gamma-ray and conversion electron spectrometers has led to a wealth of new nuclear structure data for deformed nuclei in the region of ^{254}No. This high-spin data has allowed systematic studies of the moments of inertia, multi-quasiparticle configurations and rotational bands based upon single-particle states in odd-mass nuclei. An experimental determination of such parameters allows a critical assessment of the predictions of nuclear models to be made. One example is the prediction of the excitation energies of multi-quasiparticle configurations, which are sensitive to the ordering and energies of the underlying single-particle states.

Observables

A state-of-the-art detector array will be built around the target position to detect prompt radiation emitted in the decay of high-spin states in heavy nuclei. For low-energy transitions in high-Z nuclei, internal conversion is the dominant decay mode. The system should therefore be capable of simultaneous detection of gamma rays and conversion electrons. The system will be coupled to the recoil separator and focal plane spectrometer to be used for synthesis and decay experiments. The observables to be obtained are then: transition multipolarities, excited state spins and excitation energies, internal conversion coefficients, isomeric ratios and g-factors (through decay intensity ratios).

Proposed experiment

Tagging techniques (recoil, recoil-decay, isomer) will be used to extract the prompt radiation of interest from the background due to fission. So far, in the region of ^{254}No, such studies have been confined to cold fusion reactions using ^{208}Pb or ^{209}Bi targets. The advent of radioactive beams will allow a wider range of nuclei to be studied, and will also allow higher spin and excitation energy to probed through use of more symmetric reactions. One example would be to probe high-spin states in ^{254}No using the ^{92}Kr + ^{164}Dy reaction. A simultaneous alignment of $i_{13/2}$ protons and $j_{15/2}$ neutrons is predicted to occur at around 30ħ in ^{254}No, beyond the current spectroscopic limit. Further interesting predictions are that nuclei such as ^{260}Rf should be gamma-soft, with a very low-lying 2_2^+ state. A systematic study of Rf isotopes would be possible using reactions such as ^{132}Sn + $^{130-136}$Xe. Another approach would be to use, for example, more neutron-rich Ca isotopes in cold fusion reactions with targets such as ^{204}Hg, ^{205}Tl, ^{208}Pb and ^{209}Bi, in order to systematically study the nuclei close to those already investigated. It should be noted that for in-beam studies the required beam intensities may be below 100 pnA depending on the case in question.

Example Reactions:

$$^{92}\text{Kr} + {}^{164}\text{Dy} \rightarrow {}^{256}\text{No}^*$$
$$^{132}\text{Sn} + {}^{130-136}\text{Xe} \rightarrow {}^{262-268}\text{Rf}^*$$
$$^{50}\text{Ca} + {}^{204}\text{Hg} \rightarrow {}^{254}\text{Fm}^*$$
$$^{50}\text{Ca} + {}^{205}\text{Tl} \rightarrow {}^{255}\text{Md}^*$$
$$^{50}\text{Ca} + {}^{208}\text{Pb} \rightarrow {}^{258}\text{No}^*$$
$$^{50}\text{Ca} + {}^{209}\text{Bi} \rightarrow {}^{259}\text{Lr}^*$$

Requirements

Beam properties

The beam properties required are much the same as for the synthesis and decay experiments. As the expected excitation functions are narrow, the energy resolution should be better than 1% and emittance should be no worse than with presently available beams (5π mm mrad or better). This aids beam suppression in the separator devices.

Some **stable** beam operation will be necessary to perform calibration of the various detection systems with known activities. A large variety of stable ion beams with reasonable (10-100 pnA) intensity will be required.

Detection

The array surrounding the target will be coupled to the separator and focal plane spectrometer to be used for synthesis and decay measurements.

Gamma-ray spectrometer

The ideal gamma-ray spectrometer for use with radioactive beams should be highly efficient, have high count rate capabilities and have full parallel readout. The high counting rate capability is necessary in order to allow the maximum beam intensities to be used. It goes without saying that the array should have excellent energy resolution and high granularity to minimize Doppler broadening for the symmetric reactions envisaged.

The AGATA (Advanced Gamma Tracking Array) array, currently under development, fulfills all the aforementioned requirements. As it is envisaged that the AGATA array will be used in a number of different institutions, (conventional?) alternatives could also be investigated for use at EURISOL.

Conversion-electron spectrometer

In high-Z nuclei, the decay of low energy transitions proceeds predominantly by internal conversion. It is therefore of importance to employ electron spectroscopic techniques in the study of the heaviest elements. The spectrometer should have a high (>10%) efficiency over a broad range of electron energy up to around 500 keV. In order to resolve L and M conversion electrons, the intrinsic energy resolution should preferably be around 1 keV. The device should work in conjunction with the recoil separator or spectrometer, and be capable of measuring high counting rates.

Electron-gamma coincidence measurements are essential in the study of heavy nuclei.

Theoretical support

Again, the data obtained in these measurements will provide essential input to constrain nuclear models, and to enhance their predictive power. Theory should also guide the experimentalist to the nuclei where new phenomena in the region are most likely to be found.

Synthesis and Decay of the Heaviest Elements

Abstract

The decay properties of very neutron-rich isotopes of the heaviest elements will be investigated. Production of such isotopes will require the highest possible beam intensities that can be provided by the EURISOL facility. The major goals of the experimental programme will be to push towards the predicted closed neutron shell gap at N=184 and to obtain systematic data on nuclear decay modes, half-lives and masses at the upper extreme of the Segré chart.

Keywords

Heavy Elements, Nuclear Spectroscopy, Closed Shells, Masses

Physics case

One of the fundamental themes in Nuclear Physics has been the investigation of the limits of stability in terms of mass and proton number. A subject of much debate has been the location of the next closed proton and neutron shells above doubly magic ^{208}Pb (the superheavy island of stability). One major goal of experiments in the superheavy element region is to address this question. On the proton side, contemporary theories suggest either Z=114, 120 or 126 to be the location of the next closed shell. In the neutron case, most theories suggest N=184. The beam intensities expected in the initial phase of the EURISOL will render direct studies of nuclei with such high proton number impossible. However, it will be possible to produce very neutron-rich nuclei and nuclei with slightly lower proton number. The data obtained in these experiments will be invaluable in constraining and testing modern nuclear theories.

Observables

The decay properties of nuclei produced in fusion-evaporation reactions will be measured, irrespective of the decay mode involved. The detection system to be built should allow measurement of charged particle decays, spontaneous fission, any coincident radiation (gamma rays/electrons), and the spatial and temporal correlations between the various radiation types. Such a system will allow determination of such observables as: ground state and excited state spins, decay half-lives and masses (via decay chains to known nuclei).

Proposed experiment

As the expected beam intensities at EURISOL are likely to be at least an order of magnitude lower than those currently available at stable beam facilities, production of isotopes with cross sections below 10 pb will be extremely difficult. However, many nuclei of interest are inaccessible without the use of radioactive beams. The major physics goals here will be to obtain confirmation of the decay properties of nuclei such as ^{267,268}Db or ^{271,272}Bh, which are produced in the decay chains of element 115. These nuclei are very neutron rich, and will be difficult to synthesize even with radioactive beams. One neutron-rich beam that will be produced with high intensity is ^{132}Sn. Target selection is difficult due to the lack of odd-Z neutron-rich targets. One possibility to produce the compound nucleus ^{269}Db is to use a combination of ^{132}Sn with a radioactive ^{137}Cs target ($T_{½}$=30.17a). Additional interest in ^{267}Db comes from the fact that it has neutron number N=162, which is a deformed shell closure.

It will also be of interest to attempt the production of slightly less neutron-rich nuclei to complete the systematic study of isotopes which reside between the chains produced through hot and cold fusion reactions. Such studies are aided by the large number of stable isotopes with N=82 which can be used in conjunction with beams of ^{132}Sn to produce various compound nuclei two neutrons above the N=162 deformed shell closure. The use of ^{90,92}Kr beams (which should also be produced with high intensity) with ^{181}Ta and ^{186}W targets will enable compound nuclei such as ^{271,273}Mt and ^{276,278}Ds to be produced.

In order to push towards N=184, reactions of ^{132}Sn on targets such as ^{154}Sm, ^{160}Gd, ^{164}Dy or ^{170}Er could be used, but the expected beam intensities are well below those needed to make such studies possible is a reasonable beam time.

Hot fusion reactions of a beam such as ^{44}Ar could also be employed with actinide targets such as ^{232}Th or ^{238}U to make the compound nuclei ^{276}Hs or ^{282}Ds which are situated close to the tails of the chains produced in Dubna.

Example Reactions:

$$^{132}Sn + ^{137}Cs \rightarrow ^{267}Db^{*}$$

$$^{132}Sn + ^{132,134,136}Xe \rightarrow ^{264,266,268}Rf^{*}$$
$$^{132}Sn + ^{138}Ba \rightarrow ^{270}Sg^{*}$$
$$^{132}Sn + ^{139}La \rightarrow ^{271}Bh^{*}$$
$$^{132}Sn + ^{140,142}Ce \rightarrow ^{272,274}Hs^{*}$$
$$^{132}Sn + ^{142\text{-}150}Nd \rightarrow ^{274\text{-}282}Ds^{*}$$

$$^{90,92}Kr + ^{181}Ta \rightarrow ^{271,273}Mt^{*}$$
$$^{90,92}Kr + ^{186}W \rightarrow ^{276,278}Ds^{*}$$

$$^{44}Ar + ^{232}Th \rightarrow ^{276}Hs^{*}$$
$$^{44}Ar + ^{238}U \rightarrow ^{282}Ds^{*}$$

Requirements

Beam properties

The highest possible intensity is the main requirement for these experiments. As the expected excitation functions are narrow, the energy resolution should be better than 1% and emittance should be no worse than with presently available beams (5π mm mrad or better). This aids beam suppression in the separator devices. Some **stable** beam operation will be necessary to perform calibration of the various detection systems with known activities.

In order to push to proton number greater than Z=108, further increases in beam intensity (i.e. towards 1 pμA) will be required.

Detection

The experiments will be centred around a highly efficient recoil separator or recoil mass spectrometer with a state-of-the-art focal plane detection system. The focal plane spectrometer will consist of various silicon, germanium and transmission detectors equipped with digital electronics and a time-stamping data acquisition system. The data acquisition system and analysis software should be as flexible as possible to allow temporal and spatial correlations between the various detector groups.

Theoretical support

A major unknown in these studies is the expected production cross-section to produce a particular nucleus using a certain reaction. Extensive theoretical work is required to predict production cross sections and inform the experimentalist in the choice reaction. This theoretical work should be backed up with data from experimental studies using stable beams.

Once new data are obtained for the heaviest elements, it can be used to constrain nuclear models and the predictions of e.g. the ordering and energies of single-particle states.

Further considerations

The radiation from scattered beam must be dealt with, especially in the target chamber area and in the beam dump of the separator. The level of radiation in the vicinity of the detection system must also be kept to a minimum to avoid random coincidences. Once interesting concept which should be explored is the recycling of the precious radioactive beam, which would normally be dumped after separation from the fusion products in the recoil separator device.

Optical spectroscopy of the heaviest elements

Abstract

Laser spectroscopic studies of the heaviest elements will be made at the focal plane of an efficient recoil separator device. The resonance ionization measurements will allow experimental determination of the location of atomic levels and nuclear ground-state properties. The experiments are strongly guided by input from theoretical predictions of atomic levels.

Keywords

Atomic levels, nuclear ground-state properties, laser spectroscopy

Physics case

Investigations of the atomic properties of the heaviest elements aim for a better understanding of the electronic structure in strong (nuclear) fields. Although QED is being well recognized as the fundament for all atomic and molecular interactions, the interplay of relativistic effects (owing to the Breit interaction) and the QED effects self-energy and vacuum polarization in heavy systems is by far not well understood.

If the hyperfine structure of suitable atomic transitions allows the determination of nuclear ground-state properties - such data will enable stringent tests of nuclear models applied to the heaviest nuclei, as well. Determination of ground-state spins in odd-mass nuclei will be extremely valuable in the construction and comparison of level schemes built from alpha-decay data.

Current laser spectroscopic investigations at No (Z=102) represent also a crucial test to extend resonance ionization up to rutherfordium (Z=104) and dubnium (Z=105). This nuclear charge (Z) selective method may then serve for definite identification of the neutron-rich final daughter nuclides ^{267,268}Rf and ^{267,268}Db from the decay chains assigned to the heaviest Elements 112, 114, 115, 116 and 118.

Observables

Isotope shift measurements and hyperfine spectroscopy will be performed on various isotopic chains. The experiments will reveal the location of atomic levels and allow the determination of nuclear ground-state properties such as deformation and spin.

Proposed experiment

The reactions to be used are similar to those described in the "In-beam spectroscopy of heavy elements" and "Synthesis and decay properties of the heaviest elements". The recoil separator device to be used is also the same. A buffer gas cell will be placed at the focal plane to stop reaction products. The products will then be selectively ionized with a collection of high-power lasers. On ionization, the ions will be transported by an electric field to a silicon detector, where they will be identified by their characteristic charged-particle decay properties.

Requirements

Beam properties

The beam properties required are much the same as for the synthesis and decay experiments. As the expected excitation functions are narrow, the energy resolution should be better than 1% and emittance should be no worse than with presently available beams (5π mm mrad or better). This aids beam suppression in the separator devices.

Detection

Effective separation of fusion evaporation products from the primary beam is a necessary prerequisite for the proposed experiments. The suppression of the primary beam has to be at least 10^{10}, thus a state of the art recoil separator is needed.

Laser spectroscopy :

- Buffer gas cell (UHV-set up) + optical resonator
- High repetition, high power Laser Systems

  e.g. Excimer Laser (1 kHz repetition rate, >100 mJ/pulse@353nm pumped dye lasers)
- PIPS Detectors

Theoretical support

The experiments rely heavily on the predictions of atomic levels from theory, which are used to guide the selection of laser frequencies. Experimental determination of the location of atomic levels in turn feeds back into these calculations. Any data obtained from hyperfine spectroscopy will be used to constrain and test nuclear structure theories.

Neutron capture cross sections of radioactive nuclei

Abstract

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 (α,γ) 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,γ) reactions) isotopically enriched radioactive targets have to be used for determining the reaction rates.

Keywords

Origin of the elements, nucleosynthesis, s-, r-, and p-process, reaction rates.

Physics case

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. [1]). The respective (n,γ) 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}Fe and ^{107}Pd.

^{60}Fe: The production of ^{60}Fe in massive stars depends strongly on the very uncertain ^{59}Fe(n,γ)^{60}Fe and ^{60}Fe(n,γ)^{61}Fe cross sections. The long-lived ^{60}Fe, with $t_{1/2}$=1.5·10^{6} yr has been detected in deep sea sediments [2] 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 γ-ray satellite INTEGRAL [3] via the decay of the daughter nucleus ^{60}Co. This will be important to constrain the ^{60}Fe output of supernovae. So far, no experimental data are available for the $^{59}Fe(n,\gamma)^{60}Fe$ cross section, whereas the available theoretical predictions between 1.8 mb and 3.4 mb deviate by almost 100%.

^{107}Pd: Spectroscopic observations of elements on the surface of a dozen very old, metal-poor halo stars (see e.g. [4]) 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 underproduced 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}Ag and ^{109}Ag are known with uncertainties of 3%. However, a large fraction of elemental Ag is produced by the radiogenic contribution of ^{107}Pd, which has a half-life of $6.5 \cdot 10^6$ years.

^{107}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}Fe, ^{26}Al, ^{41}Ca) [1]. So far, there is only one measurement of the neutron capture cross section of ^{107}Pd [5], which was performed with a fission product Pd sample with a very low (16%) enrichment in ^{107}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 10^{16} atoms only. Therefore, we propose to produce isotopically enriched samples by ion implantation of radioactive beams.

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Observables

Not applicable.

Proposed experiment

Implantation of radioactive nuclei in a thin carbon backing to produce isotopically enriched samples.

Requirements

Beam properties

For the production of isotopically enriched radioactive samples one needs:

- beam intensities of $>10^{10}$ ions/s in order to produce samples with $>10^{16}$ atoms in a reasonable time
- beam energies < 5 MeV/u
- beams with contaminants <10%
- a beam spot size <2 cm

The r-process path between the N=50 and N=82 shells

Abstract

A systematic study of the basic nuclear structure properties of neutron-rich nuclei on the r-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.

Keywords

r-process nucleosynthesis, nuclear mass, decay properties, shell structure far from stability

Physics case

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. 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.

Observables

Nuclear mass (S_n, and Q_β)
Half-life (β-decay $T_{1/2}$), β-delayed neutron emission probability (P_n)
Additional important observables: energies and J^π of excited states, ground-state deformation, neutron-capture rates

Proposed experiment

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):

$^{68(*)-74}$Fe,	$^{73-75}$Co,	^{78}Ni(*),	$^{79(*)-81}$Cu,
$^{80(*)-84}$Zn,	$^{81(*)-87}$Ga,	$^{84(*)-90}$Ge,	$^{87(*)-95}$As,
$^{90(*)-98}$Se,	$^{91(*)-101}$Br,	$^{96(*)-106}$Kr,	$^{101(*)-107}$Rb,
$^{102(*)-110}$Sr,	$^{105-115}$Y,	$^{108-118}$Zr,	$^{111-123}$Nb,
$^{114-124}$Mo,	$^{121-125}$Tc,	$^{124-126}$Ru,	^{127}Rh,
^{128}Pd,	^{129}Ag(*),	^{130}Cd(*),	^{131}In(*),
^{132}Sn(*).			

Nuclides marked with (*) have been already measured and will be used as benchmark cases.

Requirements

Beam properties

Low-energy beam of the Nuclear Astrophysics Sector of EURISOL (characteristics still to be defined)

Detection

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-up with various detection systems.

Theoretical support

Modern nuclear structure models for the nuclear mean field. 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.

Ground-state two-proton radioactivity

Abstract

Ground-state two-proton radioactivity allows for the study of nuclear structure beyond the proton drip line. In particular, the pairing force can be investigated and the sequence of single-particle levels as well as the j content of the nuclear wave function can be studied. In addition, the tunnelling process with a changing deformation can be subject of investigations.

Keywords

Two-proton radioactivity, exotic decay modes, nuclear pairing, single-particle levels

Physics case

Nuclear structure studies far from the valley of stability revealed a lot of new phenomena, which are not observed closer to the stability line. These studies allow for a deeper understanding of nuclear structure, as the concepts of its description are pushed to their limits.

One of the newly observed phenomena is ground-state two-proton radioactivity. This new nuclear decay mode was first predicted in 1960 to occur in very proton-rich even-Z isotopes, where the nuclear forces can no longer bind all protons. However, due to the Coulomb barrier, the protons are kept for a certain time in the nucleus to yield measurable half-lives. An additional requirement is that one-proton emission is energetically forbidden.

The first case of two-proton radioactivity fulfilling the requirements mentioned above was ^{45}Fe in 2002. Meanwhile ^{54}Zn and most likely also ^{48}Ni were observed as other two-proton emitters. Up to now, only the decay energies and the half-lives for two-proton decay, their branching ratios as well as the absence of beta particles in the decay could be established. Additionally, the decay of the two-proton daughters has been observed, serving as an additional proof of two-proton radioactivity. However, no direct observation of the two protons was attempted. These studies should be performed soon.

In order to study details of the two-proton decay process to extract information about pairing, the single-particle structure in the region of the two-proton emitters and other information, higher statistics is needed and other two-proton emitters have to be studied. In addition, details about the decay process have to be investigated by measuring the individual proton energies and their relative emission angle.

Observables

To identify new two-proton emitters, the decay energy, the half-life and the 2p emission branching ratio has to be measured. Additionally, the absence of beta radiation needs to be demonstrated.

To study the details of two-proton radioactivity, the individual proton energies and the proton-proton angle in the centre of mass need to be detected.

Proposed experiment

The known 2p emitters ^{45}Fe, ^{54}Zn, and ^{48}Ni need to be studied with increased statistical precision. Therefore, high-intensity primary ^{58}Ni beams at about 100-150 MeV/nucleon or proton-rich radioactive beams (e.g. ^{54}Ni and ^{62}Zn) are needed. Production rates of the order of a few per minute should be enough to significantly improve our knowledge about two-proton radioactivity.

New 2p emitter candidates are ^{59}Ge, ^{63}Se, ^{67}Kr, ^{71}Sr etc. To produce them, projectile fragmentation is the best tool. Therefore, high-intensity stable beams like ^{78}Kr or ^{92}Mo should be developed. Reaccelerated proton-rich radioactive species in the vicinity of the 2p candidates can also be used.

Requirements

Beam properties

High-intensity proton-rich stable or radioactive beams at about 100-150 MeV/nucleon

Detection

To produce the aforementioned isotopes 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 silicon detector telescope with a highly pixellated silicon-strip detector will be used to search for new two-proton emitters. To study the details of this decay mode, a high-resolution time-projection chamber can visualize the tracks of the individual protons and therefore give access to their individual energies and their emission angle.

Theoretical support

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.

β-delayed two-neutron emission

Abstract

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.

Keywords

Beta-delayed two-neutron emission, exotic decay modes, nuclear pairing, single-particle levels

Physics case

When moving further and further away from the valley of stability, the Q values for β decay increase more and more. Close to the drip line, β-delayed particle emission is observed. Even further away, β-delayed two-nucleon emission can be observed and studied. β-delayed two-proton emission has been observed experimentally for 9 different nuclei, but only the decay of ^{31}Ar has been studied to some extent. On the neutron-rich side, β-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 modelling of the astrophysical rapid-neutron caption process.

Observables

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 β decay scheme, γ radiation should also be observed.

Proposed experiment

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 centre of the detection set-up, the neutrons will be detected and their energy and angular correlation will be determined.

Requirements

Beam properties

High-intensity neutron-rich stable or radioactive beams at about 100-150 MeV/nucleon for fragmentation or deep inelastic reactions

Detection

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.

Theoretical support

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.

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

Abstract

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.

Keywords

Neutron drip line, shell structure, neutron correlations

Physics case

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 (unbound) 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.

Observables

The ground and low-lying excited states of $^{26-28}O$, as reconstructed from the ^{24}O fragments and coincident neutrons.

Proposed experiment

A high-energy beam of $^{28\text{-}30}$Ne will be reacted on a thick (~500 mg/cm^2) Be or C secondary reaction target. The unbound $^{26\text{-}28}$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 $^{26\text{-}28}$O will be reconstructed from the measured momenta of the fragments.

Requirements

Beam properties

$^{28\text{-}30}$Ne beams of intensities of 10^4 pps or more, with energies of ~100-150 MeV/nucleon.

Detection

Charged fragments will be detected using a large-gap, sweeper magnet/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 ~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.

Theoretical support

Improved shell-model calculations, both classical and in the continuum, of the low-lying structure of the $^{26\text{-}28}$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.

Mass of ^{78}Ni ground state

Abstract

Neutron-rich, doubly magic ^{78}Ni is a key nuclide on the neutron-rich landscape. Its mass is a fundamental observable that will test model predictions.

Keywords

Neutron-rich, mass, Penning trap, ^{78}Ni

Physics case

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}Ni will provide key tests of the most up-to-date model predictions. Here we address the measurement of its mass.

Observables

The mass will be measured, as part of a systematic mass measurement programme addressing the n-rich landscape.

Proposed experiment

The directly produced ISOL beam of ^{78}Ni will be used.

Requirements

Beam properties

About 20 ion/s of 50 keV ^{78}Ni are needed.

Detection

An advanced Penning trap system similar to the ISOLTRAP/ISOLDE set-up is needed (cf. MATS design at FAIR, or TITAN at TRIUMF).

Theoretical support

Mass model predictions are needed.

Magnetic moments of isomers in the ^{78}Ni region

Abstract

The neutron-rich, doubly magic nuclide ^{78}Ni, and neighbouring nuclides, are expected to have μs isomers arising from cross-shell excitations. Their magnetic moments will provide benchmark tests of shell-model predictions.

Keywords

Neutron-rich, magnetic dipole moments, TDPAD, ^{78}Ni region

Physics case

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}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.

Observables

The magnetic dipole moments will be measured by time-differential perturbed angular distributions (TDPAD) as part of a wider programme to characterize isomers in the ^{78}Ni region of the neutron-rich landscape.

Proposed experiment

Secondary fragmentation of a radioactive ^{81}Ga beam will be used.

Requirements

Beam properties

100 A.MeV ^{81}Ga is needed to produce, by fragmentation, 10^3 ion/s of ^{78}Ni, with about 10% in isomeric states. Beam pulsing, on a *μs* time scale, is needed.

Detection

A dipole magnet and Ge gamma-ray detectors are needed.

Theoretical support

Shell model predictions are needed.

Charge radius of ^{78}Ni

Abstract
Neutron-rich, doubly magic ^{78}Ni is a benchmark nuclide on the neutron-rich landscape. Its charge radius is a fundamental observable that will test model predictions.

Keywords
Neutron-rich, charge radius, laser spectroscopy, ^{78}Ni

Physics case

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}Ni will provide benchmark tests of the most up-to-date model predictions. Here we address the measurement of its charge radius, as part of a wider programme to determine, by laser spectroscopy, nuclear radii and moments in the ^{78}Ni region.

Observable

The charge radius will be measured, as part of a systematic programme addressing the n-rich landscape.

Proposed experiment

The directly produced ISOL beam of ^{78}Ni will be used.

Requirements:

Beam properties
About 20 ion/s of 50 keV ^{78}Ni are needed.
Detection
An advanced collinear laser spectroscopy system is needed (c.f. design at Jyväskylä, for example).
Theoretical support
Model predictions are needed.

^{44}Ti Abundance as a Probe of Nucleosynthesis in Core Collapse Supernovae

Abstract

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) be measured.

Keywords

Core collapse supernovae, nuclear abundances, ^{44}Ti, satellite gamma-ray observation

Physics case

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 synthesised ^{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.

Observables

Reaction rate near and within Gamow window
Spins, parities, energies and widths of low energy resonances

Proposed experiment

Direct measurement of the $^{44}Ti(\alpha,p)^{47}V$ reaction.

A previously attempted measurement (PRL 84 (2000) 1651) was unable to explore the astrophysically interesting energy regime. Extrapolation of the result to lower energies suggests the $^{44}Ti(\alpha,p)^{47}V$ reaction rate is significantly higher than previously expected (reducing the amount of ^{44}Ti synthesised), 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 $^{45}V(p,\gamma)$ reaction: $^{45}V(p,p)$ and (for example) $^{45}V(d,p)$.

Extremely limited previous data exist (PRL 87 (2001) 1325) and do not cover the relevant energy region. Shell model and isobaric analogue considerations (PRC 66 (2002) 015801) suggest several relevant states should be suitable for this technique

Requirements

Beam properties

Low energy (~0.5-2 MeV/u) beams of ^{45}V and ^{44}Ti. Beam currents in excess of 10^7 pps will be required.

Detection

Silicon charged particle arrays, similar to the Louvain-Edinburgh Detector Array.
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 $^{44}Ti(\alpha,p)$ measurement, with a thickness of $\sim10^{18}$ cm^{-2}.

Theoretical support

Hydrodynamical and network calculations to allow interpretation of results.
Shell model calculations to help identify states in ^{46}Cr.

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

Abstract

Study interior part of wave functions of nucleons and clusters 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.

Keywords

Mean field, single particle and collective degrees of freedom, spectroscopic factors, internal part of wave function, deep inelastic break-up.

Physics case

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.

Observables

Neutron and core energy or parallel momentum distributions. Absolute break-up cross sections. Angular correlations (n-core).

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.

Proposed experiment

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 60A.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 Phys. Lett. B459 (1999) 55, 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 (θ and ϕ) 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); γ 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 4π or the target γ rays.

The resolution for i) and ii) should be good enough to infer the invariant mass (excitation energy E*) of the projectile. The γ 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 γ 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 break-up 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.

Requirements

Beam properties

Well-focused, high intensity (10^5 pps), 50-80A.MeV, ^{38}Ne to ^{46}Ar or heavy Ni (depending on availability)

Detection

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 4π (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 γ-ray detectors. Coupling with a large gap spectrometer sweeper magnet would be highly desirable.

Theoretical support

Advanced shell model calculations, developments of break-up models including full kinematics, microscopic optical potentials for neutron rich nuclei.

Isospin dependence of correlations

Abstract

A key experimental study within the programme will be to explore how the spectroscopic factors and occupancy of the $3s_{1/2}$ proton orbital changes in the heavy neutron-rich Pb isotopes. The absolute occupancy of the $3s_{1/2}$ proton orbital of ^{208}Pb was measured to be only 70-80% relative to the IPSM. How does this occupancy change as neutrons are added to ^{208}Pb? One-proton removal reactions and (d,^{3}He) transfer reactions using beams of neutron-rich Pb isotopes from EURISOL will allow this important effect to be measured.

Keywords

Shell model, single particle degrees of freedom, spectroscopic factors, isospin.

Physics case

Despite the enormous success of the independent particle shell model (IPSM) in explaining many nuclear static and dynamic properties at low excitation energies, the concept of independent particle motion is only an approximation and effects will exist beyond the mean field level. This is a consequence of the structure of the underlying nucleon-nucleon (N-N) interaction. Nucleons interact via the strong force, described by Quantum Chromodynamics. While it is not yet possible to derive a realistic N-N interaction starting from QCD in this non-perturbative regime, the interaction is reasonably well known empirically.

Fits to N-N scattering data reveal a complicated character to the interaction, with a strongly repulsive central interaction at small inter-nucleon distances, strong tensor components at medium distances and long-range components. These features lead to properties of nuclear wave functions that are beyond what is describable in terms of an independent particle model. For example, the long-range component of the N-N force gives rise to correlations that usually make it necessary to explicitly take into account the mixing of many valence configurations. The inclusion of these residual interactions in the shell model (SM) allows a much more detailed understanding of nuclear structure to be reached and this model has been verified many times.

The short-range and tensor parts of the N-N interaction also have a very important, not to say dominating, influence without which not even nuclear binding can be explained. The consequences of these short-range correlations are that the momentum distributions of nucleons acquire a tail extending to very high momenta k, and at the same time, part of the strength, located in independent particle descriptions at low excitation energy E, is moved to very high excitation energies. Most experimental investigations are confined to rather low momenta and energies, i.e. to the region where the strength is dominated by the independent particle properties. In this region, the consequences of short-range correlations are indicated primarily by a depopulation of states in comparison to the predictions of independent particle models. According to several calculations for infinite matter and finite nuclei using different realistic N-N potentials, a depopulation of the order of 15 to 20% is expected.

Observables

Momentum distribution of the projectile like fragment. Gamma rays in coincidence for nucleon removal. Simultaneous detection of target recoils, projectile like fragments and gamma rays for transfer.

Proposed experiment

(i) One nucleon transfer reactions such as (p,d) or (d,^{3}He) in inverse kinematics with incident exotic beam energies of 5 – 30 MeV/nucleon. Arrays that allow the simultaneous detection of target recoils, projectile like fragments and gamma rays with high efficiency and resolution will be necessary. Ideally, beam intensities greater than 10^4 pps will be necessary.

(ii) One-nucleon removal reactions with incident exotic beam energies of 50 – 200 MeV/nucleon. The momentum distribution of the projectile like fragment should be measured in a high-resolution magnetic spectrometer. The excited states of the core can be tagged using gamma rays measured in a high efficiency, high resolution gamma-ray array. Beam intensities as low as 1 pps can be utilised.

Requirements

Beam properties

Beam intensities greater than 10^4 pps will be necessary. Beam energies of 5 – 30 MeV/nucleon for transfer and 50 – 200 MeV/nucleon for nucleon removal.

Detection

Detection of target recoils, projectile like fragments and gamma rays with high efficiency and resolution will be necessary. Polarised targets of H and D should be developed as then unambiguous measurements of the j-values of the orbitals can be made. Magnetic spectrometer.

High efficiency, high resolution, gamma-ray array. The gamma-ray array will need to have a granularity and/or position resolution capable of compensating for the Doppler shifts of the gamma rays emitted from the high-energy projectile-like fragment.

Theoretical support

Improved theoretical descriptions of the reaction mechanisms will need to be developed The absolute spectroscopic factors would be expected to reflect the isospin dependence of the occupancies as described above. However, to obtain the absolute occupancies from the measurements of the spectroscopic factors, an approach such as the CERES sum rule, applicable for proton occupancies, will need to be applied. This sum rule requires measurements of charge density differences obtained by elastic electron scattering to be available. Such measurements will be made by the ELISE eA collider, under construction at the new FAIR facility at GSI.

Systematics of Isoscalar Giant Resonances in Exotic Nuclei

Abstract

The study of the Isoscalar Giant Monopole Resonance (GMR) can give a handle on the nuclear matter equation of state through its link to the nuclear matter incompressibility. The measurement of the GMR and GQR in unstable nuclei remains a major experimental challenge due to low radioactive beam intensities and unfavourable conditions in reverse kinematics. We propose an experimental set-up based on the unique capabilities of active targets, such as MAYA, to measure GMR and GQR in exotic nuclei.

Keywords

Giant Monopole and Quadrupole Resonance, Nuclear Matter Incompressibility, Nuclear Matter Equation of State, Inelastic d and α *scattering*

Physics case

In addition to being of intrinsic interest like any other collective motion, the study of the GMR is especially important because it relates to the nuclear matter incompressibility K_∞. Since the breathing mode corresponds to small density variations, the monopole energy is a relevant experimental observable to constrain the effective force entering in microscopic calculations of the compressibility. In particular, studying this mode far from stability is expected to characterise the asymmetry energy term of the effective force.

The nuclear matter incompressibility is of fundamental importance in describing the nuclear matter: K_∞ is the curvature of the equation of state around the saturation point. It is also a basic parameter in calculations describing neutron stars and supernovae explosions.

Observables

The best probe of the GMR is inelastic scattering of deuterons or alphas. The excitation energy spectra of the studied nucleus and angular distribution must be observed to characterise the GMR and GQR.

Proposed experiment

To measure the GMR and GQR we propose to perform inelastic scattering of deuterons or alphas. It is well known that the Giant Resonance cross sections are peaked at zero degrees in the centre of mass frame. In reverse kinematics, it implies to detect deuteron or alpha at very low energies, over a large angular range. With respect to these experimental constraints an active target such as MAYA could be the key to measuring the GMR in unstable nuclei. Low energy recoil particles will be detected in the active target and for higher energy (E>2 MeV) escaping recoils ancillary detectors will be used outside the active volume. For normalization purposes the beam will be counted in a diamond detector for example after traversing the active target. The 3D-reconstruction of recoil trajectories in the active target will provide the kinematics of the inelastic scattering and will yield the excitation energy spectrum of the exotic nucleus and angular distributions.

Requirements

<u>Beam properties</u>

Beam around 50 A MeV with an intensity of at least 10^4 pps. Small angular divergence (<0.5°). Beam spot of a few mm diameter.

<u>Detection</u>

The key detector of the proposed experiment is an active target such as MAYA. MAYA is a time and charge projection chamber in which the detector gas is also the target. It ensures three main decisive features compared to a standard silicon detection set-up: a large angular coverage, a low energy threshold and a much thicker equivalent target. Nevertheless at very low energies (400 keV) some problems of particle identification and sparks with He gas remain. Some improvements of the MAYA active target are expected with

ACTAR, a new active target designed presently by the JRA ACTAR in EURONS.

Theoretical support

Improvement of effective interactions and mean field calculations far from stability.

Mapping of Single Particle Energies using Transfer Reactions

Abstract

Single particle energies can be mapped out using one-nucleon transfer reactions such as (d,p) or (p,d). This is the most direct way of measuring shell gaps far from stability and assessing the modification of magic numbers. A very efficient set-up for particle-gamma coincidences needs to be built.

Keywords

Single particle energies, shell gaps, magic numbers, transfer reactions, particle-gamma coincidences, silicon strip and germanium detectors.

Physics case

Shell gaps and shell ordering are expected to change when moving far from stability. Following their evolution is a major subject of Radioactive Beam physics, both today and in the future when more exotic nuclei will become accessible.

Observables

One nucleon transfer reactions such as (p,d) and (d,p) provide a direct measurement of single particle energies as long as a large fraction of the spectroscopic strength is observed. The observables are the excitation energies, angular distributions and hopefully analysing powers of all the levels populated. Such measurements give more precise information than indirect approaches such as mass measurements, 2^+ energies etc., but larger beam intensities are necessary.

Proposed experiment

The experiments will be performed in inverse kinematics where the radioactive beam impinges the target containing the probe, possibly plastic (CH_2 or CD_2) or preferably pure hydrogen or deuterium. Polarized targets would allow for very interesting analysing power measurements, distinguishing between J=l+1/2 and J=l-1/2 orbitals. The kinematics of the reaction (excitation energy and scattering angle) are determined from the angle and energy measurements of the recoiling light particle. Detection of the scattered projectile-like nucleus provides channel selection. In many cases an efficient coincident gamma-ray measurement is necessary to overcome the limited energy resolution of the particle detection.

Requirements

Beam properties

Beam between 10 A MeV for (d,p) and 30 A MeV for (p,d) with an intensity of at least a few 10^3 pps. Availability of isotopic and isobaric chains. Beam spot of 1-2 mm diameter would avoid the tedious beam tracking routine. Beam energy resolution not crucial. Time resolution better than 1ns.

Detection

Combined 4π particle-gamma array such as GRAPA described in detail the EURISOL RTD report (Appendix 5, section 5.2) is the ideal set-up specifically designed for such experiments, and possibly not so futuristic considering the EURISOL time-scale. Any watered down GRAPA (2π particle combined with 2π gamma detection or gamma detection with scintillators) would be adequate for many cases.

Theoretical support

Improvement of effective interactions and mean field and shell model calculations far from stability as well as improved direct reaction calculations and optical potentials would be useful. However, the experiments are of intrinsic interest and current reaction models are probably adequate for a first analysis.

Fundamental tests with low energy beta-beams

Abstract

Neutrino beams produced with low energy beta-beams are used to perform fundamental interaction studies, in particular a measurement of the Weinberg angle at low momentum transfer and a test of the Conserved-Vector-Current (CVC) hypothesis on the weak magnetism form factor.

Keywords

Beta-beams, weak interaction, Weinberg angle, CVC hypothesis

Physics case

The measurement of the Weinberg angle represents a crucial test of the Standard Model of the electroweak theory. Several measurements exist at different momentum transfer and are consistent with the expected running of the weak mixing angle. However, a recent measurement of the neutral- to charged-current ratio in muon anti-neutrino nucleon scattering at the NuTEV experiment disagrees with these results by about 3σ. A complete understanding of the NuTeV anomaly is still lacking. Probing the Weinberg angle through additional experiments with different systematic errors would be very useful.

Low energy beta-beams are neutrino beams in the 100 MeV energy range, produced by the decay of boosted radioactive ions circulating in a storage ring. Such beams could be used to carry out such a test, through scattering of neutrinos on electrons at $Q^2 = 10^{-4}$ GeV^2 in a water Cerenkov detector.

The Conserved-Vector-Current (CVC) hypothesis relates the weak to the electromagnetic currents and tells us, in particular, the values of the vector, pseudo-scalar and weak magnetism form factors. Several tests of CVC have been performed in the past. In particular, the CVC prediction on the vector form factor has been extensively studied in super-allowed nuclear beta-decays.

Verifying that the CVC hypothesis correctly predicts the weak magnetism term is of fundamental importance. So far, such a prediction has been tested in an experiment involving the beta-decay of Gamow-Teller transitions in mirror nuclei in the A=12 triad. A test based on neutrino-nucleon scattering at low momentum transfer would be particularly interesting. In addition to providing a test of the CVC hypothesis, such a measurement is of direct interest for astrophysics, as these terms play an important role in the dynamic of core-collapse supernova.

Observables

For the measurement of the Weinberg angle, the scattering of neutrinos on electrons should be measured. Keeping systematic errors as low as 10%, a measurement of the Weinberg angle with a precision of 10% could be within reach.

For the CVC test, the scattering of neutrinos on protons should be measured. The angular distribution is needed since it is more sensitive to the weak magnetism form factor than the number of events. If systematic errors are kept as low as 5%, a one year measurement of the weak magnetism term is possible at a 1σ level of 9% (with the ions boosted at $\gamma = 12$).

Proposed experiment

An (anti)neutrino beam should be produced by the decay of ^6He ions, boosted at γ = 7-14, and circulating into a storage ring. Preliminary calculations show that 2.7×10^{12} ions/s can be accumulated in the storage ring which has 1885 m total length and 678 m straight sections. A 1 kton water Cerenkov detector is located at 10 meters from the storage ring. The (anti)neutrinos impinging in the water detector will interact mainly with the protons, with the oxygen nuclei and the electrons. Since neutrino-electron scattering is forward peaked, such events can be selected by choosing an angular cut of $\cos\theta>0.9$. By selecting (anti)neutrino-proton events, the same apparatus can be used to perform the CVC test.

Requirements

Beam properties

A ^6He ion beam of 2×10^{13} ions/s is needed. This ion beam should be stored in a storage ring to get a pure (anti)neutrino beam of well-known flux.

Some characteristics of the storage ring need still to be studied (in particular the space-charge effects and the duty cycle).

Detection

A 1 kton water Cerenkov detector is used. Detailed background simulations are required to assess the finally achievable sensitivities.

Nuclear structure studies with low energy beta-beams

Abstract

Neutrino beams produced with beta-beams are used to study the isospin and spin-isospin nuclear response. In particular, information on the spin-dipole can be extracted if the ions are boosted at γ=7-14. Besides the intrinsic interest, a better knowledge of such states is important for open issues in nuclear astrophysics and for the search of new physics.

Keywords

Beta-beams, weak interaction, spin-isospin and isospin nuclear response, spin-dipole

Physics case

A precise knowledge of the nuclear isospin and spin-isospin excitations is crucial for our understanding of weak processes such as beta-decay, muon capture, neutrino-nucleus interactions or neutrinoless double-beta decay. Besides their intrinsic interest, gaining a precise description of such states constitute a crucial step to progress on open issues in astrophysics, like understanding the nucleosynthesis of heavy elements during the r-process, or in high energy physics, for the search of new physics, like the Dirac or Majorana nature of neutrinos.

So far, the best-studied cases are the isobaric analogue state (IAS) and the Gamow-Teller (GT) giant resonance. Information on these states is obtained in particular through beta-decay and charge-exchange measurements. A good description of these excitations is nowadays achieved using the shell model or the random-phase-approximation and its variants. However, the "quenching problem", namely the observation that the calculated GT transition amplitudes are always larger than the measured ones still remains an open problem. This is usually accounted for using an effective axial-vector coupling constant.

Little is still known for the states of higher multipolarity, such as the spin-dipole or the other multipoles, that might well be affected by a quenching problem, or require modifications of the effective interactions. Muon-capture and charge-exchange reactions have been used so far for their study. An important step further could be obtained using neutrino beams produced with low energy beta-beams. These beams, in the 100 MeV energy range, are produced by the decay of boosted radioactive ions circulating in a storage ring.

Observables

The charged-current scattering of neutrinos on nuclei needs to be measured.

Proposed experiment

An (anti)neutrino beam should be produced by the decay of (^{6}He)^{18}Ne ions, boosted at γ = 7-14, and circulating into a storage ring. Preliminary calculations show that (2.7x10^{12}) 0.5x10^{11} ions/s can be accumulated in the storage ring which has 1885 m total length and 678 m straight sections. A 1 kton water Cerenkov detector is located at 10 meters from the storage ring. The (anti)neutrinos impinging in the water detector will interact mainly with the protons and with the oxygen nuclei. The neutrino-oxygen events can be selected by doping with Gadolinium. Systematic studies on other nuclei can be performed by replacing the Cerenkov detector by detectors based on other nuclei, such as iron and lead.

Requirements

Beam properties

^{6}He and ^{18}He ion beams of 2x10^{13} and 0.5x10^{11} ions/s, respectively, are needed. These ion beams should be stored in a storage ring to get a pure (anti)neutrino beam of well-known fluxes. Some characteristics of the storage ring need still to be studied (in particular the space-charge effects and the duty cycle).

Detection

A 1 kton water Cerenkov detector is used. Detailed background simulations are required to assess the finally achievable sensitivities. The Cerenkov detector can be replaced by a lead- or iron-based detector, for example.

The density dependence of the symmetry energy

Abstract

The behaviour of the symmetry energy at sub-saturation densities will be explored through the study of selected isospin observables in mid-peripheral collisions of exotic nuclei. Differential observables between systems of similar mass and isospin ratios ranging from N/Z~1 to N/Z~1.7 will be constructed to experimentally disentangle isospin effects from isoscalar transport properties.

Keywords

Density functional theory, symmetry energy, effective interactions, neck decay, isoscaling, pre-equilibrium particles

Physics case

We want to address the question of the energy functional of asymmetric nuclear matter, and specifically constrain its isovector part, the symmetry energy. Indeed the density functional theory (DFT) through self-consistent mean field calculations (and their extensions) is probably the only possible framework in order to understand the structure of medium-heavy nuclei; the largest uncertainties on the energy functional concern the density dependence of its isovector, or symmetry part.

We expect important synergies on this issue with the Single Particle and Collective Properties subtask, and with the Ground State Properties subtask. Since extended mean field theories with a density functional constraint in a large density domain are a unique tool to understand the structure properties of neutron stars crusts, we also expect an important synergy with the Astrophysics subtask. To address this physics case we need to produce sub-saturation and super-saturation density matter through heavy ion collisions.

Observables

Observables include: Isospin imbalance ratios, neck composition, isoscaling, emission times of pre-equilibrium particles.

Proposed experiment

The symmetry energy cannot be directly accessed from data. However, the different $E_{sym}(\rho)$ functionals can be implemented in transport equations and confronted to transport observables. The asy-stiffness of the EOS rules the drift and diffusion of isospin, which lead to isospin equilibration (transfer to bound states) and emission (transfer to continuum states). Isospin equilibration is measured by the global isospin content of the QP in peripheral reactions, while isospin emission is measured by the isospin content of midrapidity fragments and pre-equilibrium particles. In order to focus on the isovector properties and minimize the theoretical as well as experimental uncertainties, we will compare systems of similar size and largely different N/Z from ~1 to ~1.7. To produce and detect low-density matter we need to use reaction mechanisms leading to the formation of a neck, and a 4π detection for impact parameter selection.

Requirements

Beam properties

Different isotopes of medium and medium-heavy beams from neutron poor to neutron rich (e.g. $^{56}Ni \rightarrow {}^{74}Ni$, $^{106}Sn \rightarrow {}^{132}Sn$) in an energy range 15-50 A.MeV.

Detection

- 4π and low threshold complete A and Z identification for IMF (FAZIA)
- Large acceptance spectrometer for mass identification of QP remnant
- High angular resolution $\Delta\theta<0.5$ LCP and neutron arrays for correlation measurements

Theoretical support

Transport calculations (BUU,SMF,QMD,AMD,FMD). We will need extensive simulations with different effective interactions. A strong effort is also needed at the theoretical level, initially to assess and improve the compatibility between the different codes, and on a longer timescale to improve the description of clustering in dilute quantum media.

Neutron-proton effective mass splitting

Abstract

The neutron-proton effective mass splitting at normal and supersaturation density will be explored through the study of differential flow observables in mid-peripheral collisions of exotic nuclei. High incident energies will be needed to overcome the flow balance energy and to reach high baryon density values. Symmetric collisions with global isospin ratios ranging from N/Z~1 to N/Z~1.7 will be needed to discriminate between the different theoretical predictions.

Keywords

Effective mass, Lane potential, transverse flow, elliptic flow, pre-equilibrium particles.

Physics case

The density functional theory (DFT) through self-consistent mean field calculations (and their extensions) is probably the only possible framework in order to understand the structure of medium-heavy nuclei; in particular the isovector part of the energy functional of asymmetric nuclear matter is still very poorly known. One of the key quantities characterizing this functional is the difference in the effective mass of protons and neutrons, which widely differs in the different theoretical approaches already at normal density. Experimental constraints on this quantity are essential for nuclear structure as well as for the structure of neutron stars crusts, therefore we expect important synergies on this issue with the Single Particle and Collective Properties, Ground State Properties, and Astrophysics subtasks.

The difference between the effective masses can be recast in the form of a microscopic optical Lane potential, which in turn determines the transport properties of intermediate energy fragmentation reactions. Intermediate energies are important to have high momentum pre-equilibrium particles and to test regions of high baryon (isoscalar) and isospin (isovector) density during the collision dynamics.

Observables

The main observables sensitive to the isovector momentum dependence of the mean field are: high p_t distributions of pre-equilibrium particles, differential (proton minus neutrons, tritons minus 3He) transverse and elliptic flow.

Proposed experiment

The different effective masses $m_n(\rho)$, $m_p(\rho)$ can be implemented in transport equations and confronted to transport observables. The momentum dependence rules the kinetic observables established in the entrance channel, namely the transverse momentum distributions of pre-equilibrium particles, and collective flows. To extract the isovector part one needs to measure differential quantities (proton minus neutron, or 3He minus t). To minimize the theoretical as well as experimental uncertainties it is essential to compare systems of similar size and largely different N/Z from ~1 to ~1.7. To measure flow observables we need complete 4π detection for a precise determination of the reaction plane and impact parameter selection.

Requirements

Beam properties

Different isotopes of medium and medium-heavy beams from neutron poor to neutron rich (e.g. ^{56}Ni $\rightarrow$ ^{74}Ni, ^{106}Sn $\rightarrow$ ^{132}Sn) in an energy range 50-100 A.MeV.

Detection

- 4π and low threshold complete A and Z identification for IMF (FAZIA)
- 4π neutron detector

Theoretical support

Transport calculations (BUU,SMF,QMD,AMD,FMD). We will need extensive simulations with different effective interactions. A strong effort is also needed at the theoretical level, initially to assess and improve the compatibility between the different codes, and on a longer timescale to improve the description of clustering in dilute quantum media.

Isospin dependent phase transition

Abstract

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.

Keywords

Phase transitions, limiting temperature, fluctuations, scaling, calorimetry, heat capacity, statistical properties, correlations.

Physics case

Nuclear matter is known to present at least two major phase transitions: a transition to the quark-gluon 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 modelled for the supernovae explosion process and the cooling dynamics of proto-neutron stars.

Observables

The main observables needed to characterize the transition and locate it on the phase diagram (ρ_n, ρ_p) are the energy threshold for fragmentation, temperature measurements, inclusive and exclusive charge scalings, IMF multi-charge 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.

Proposed experiment

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.

Requirements

Beam properties

Different isotopes of medium and heavy beams from neutron poor to neutron rich (e.g. $^{56}Ni \rightarrow {}^{74}Ni$, $^{106}Sn \rightarrow {}^{132}Sn$, $^{200}Rn \rightarrow {}^{228}Rn$) in an energy range 30-100 A.MeV.

Detection

- 4π and low threshold complete A and Z identification for IMF (FAZIA)
- 4π neutron detector
- High angular resolution $\Delta\theta<0.5$ LCP and neutron arrays for correlation measurements

Theoretical support

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.

Isospin fractionation and isoscaling

Abstract

Isoscaling is a well-established experimental technique to quantify the global fragment isotopic content. This is directly linked to the symmetry energy coefficient at the time of fragment formation. Studying isoscaling parameters in well-defined emission sources as a function of excitation energy, isospin content and fragment charge will allow to strongly constrain the symmetry energy of excited and diluted correlated matter.

Keywords

Isotopic distributions, isoscaling, symmetry energy, fractionation.
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Physics case

Fractionation is a generic feature of phase separation in multi-component systems; in nuclear physics it implies a different isotopic composition of coexisting phases for isospin asymmetric systems. Since an increased fractionation is expected if fragmentation occurs out of equilibrium, a quantitative study of fractionation will elucidate the as yet unclear mechanism of fragment production in excited and correlated quantum media. Moreover, if fractionation is associated with finite temperature, the first moments of the isotopic distributions give a direct measure of the temperature dependence of the symmetry energy in correlated matter at sub-saturation density with important consequences for the dynamical evolution of massive stars and the supernova explosion mechanisms. In particular, the electron capture rate on nuclei and/or free protons in pre-supernova explosions is especially sensitive to the symmetry energy at finite temperatures.

Observables

Fractionation can be directly measured from isotopic ratios of light particles and fragments from carefully selected space-time emission regions. Different effects can be disentangled with isoscaling observables concerning ratios of isotopic distributions measured in different reactions.

Proposed experiment

Different space-time fragments emission regions will be separated with collective observables and imaging techniques. The resulting isotopic distributions will be studied through isoscaling comparing sources of similar size and different N/Z in order to pin down isovector components. The same technique will be applied to distribution widths. The comparison of data with different asymmetries and similar centrality will allow quantifying fractionation, while the study with fragment size will give a measure of the temperature dependence of the surface symmetry term.

Requirements

Beam properties

Different isotopes of medium and heavy beams from neutron poor to neutron rich (e.g. $^{56}Ni \rightarrow {}^{74}Ni$, $^{106}Sn \rightarrow {}^{132}Sn$, $^{200}Rn \rightarrow {}^{228}Rn$) in an energy range 30-100 A.MeV.

Detection

- 4π and low threshold complete A and Z identification for IMF (FAZIA)
- 4π neutron detector
- High angular resolution $\Delta\theta<0.5$ LCP and neutron arrays for correlation measurements

Theoretical support

We will need extensive simulations of both dynamical (QMD,AMD,FMD,SMF) and statistical (SMM,MMM) approaches with different effective interactions and prescriptions for the finite temperature symmetry energy. A theoretical improvement of evaporation codes for side feeding corrections will also be needed.

In-source spectroscopy and production of isomeric beams with a laser ion source

Abstract

A laser ion source can be used not only as a tool to produce ISOL beams but as an instrument for spectroscopy in its own right. Charge radii and nuclear moments can be determined by scanning one of the laser wavelengths in a multi-step resonant ionization scheme over the range of the atomic hyperfine splitting. Since the technique is exploited at the ion source itself, the gain in sensitivity is considerable. Isotopes with half-lives as short as tens of milliseconds and production rates as low as one atom per second will come within reach at EURISOL.

Keywords

Laser ion source, in-source laser spectroscopy, charge radii, nuclear moments, isomeric beams

Physics case

The prospects of pushing charge radii and moment measurements to shorter lifetimes is dependent on the release profiles from the primary ISOL target that can be achieved, which are in turn contingent on the ion source design. Synergy with ion source development is hence essential, as rapid diffusion and effusion should be aimed for. While the feasibility of the technique has been demonstrated recently for neutron-deficient lead, bismuth and polonium beams at ISOLDE, the millisecond polonium isotopes at the neutron mid-shell N=104 among others could be targeted for in-source laser spectroscopy at EURISOL.

Implementation of Doppler-free two-photon spectroscopy, in which resonant ionization is achieved by two oppositely travelling photons of half the full wavelength such that the Doppler shift cancels to first order, will open up the technique to lighter elements with smaller electronic F factors. Proton emitters beyond the drip line in particular could come under investigation, as particle detection can provide a clear and background-free signature for identification.

Once the hyperfine pattern is known for an isotope and its isomeric states, selection of a resonance line by a narrow bandwidth laser allows isomeric beams to be extracted. Starting with the beta-decay of silver isotopes at ISOLDE, isomeric copper beams with a purity of 85% were obtained for post-acceleration and Coulomb excitation, allowing single-particle configurations to be probed.

Interest for isomeric beams also arises from the nuclear astrophysics community, for instance in determining the destruction rate of ^{26m}Al in stellar environments. The relevance of this resides in our understanding of the nucleosynthesis of ^{26}Al, the gamma-ray emission of which has been mapped in great detail throughout the Milky Way.

Observables

Charge radii and nuclear moments are measured by in-source laser spectroscopy. Energies of gamma-ray transitions and many other spectroscopic observables can be obtained for those experiments where isomeric beams are extracted.

Proposed experiment

Measurement of charge radii and nuclear moments of polonium isotopes could be done at and beyond the neutron mid-shell at N=104. These nuclei are inaccessible at present facilities.

Once demonstrated as a prototype elsewhere, Doppler-free two-photon spectroscopy could then bring many other elements across the nuclear chart within reach.

Selecting high-spin isomers of polonium by means of laser ionization and post-accelerating these at EURISOL would enable reaction studies such as single or double nucleon transfer to be performed. It would become possible to shed new light on how neutrons in specific orbitals stimulate the internal formation of an alpha particle, as the neutrons couple to the two protons outside the lead core.

Requirements

Beam properties

Use of the laser ion source will ensure relative high purity of the extracted beam.

Detection

A laser ion source is needed, combined with conventional alpha, beta, gamma, or possibly electron spectroscopy.

Theoretical support

The electronic F factors of the transitions that are scanned are not always available from literature. In these cases calculations need to be performed. Collaborations should be set up or extended towards a number of groups possessing this knowledge