Procon07

International Conference on Proton Emitting Nuclei and related areas

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Painel de azulejos do Palacio Fronteira

ABSTRACTS

International Conference on Proton Emitting Nuclei and related topics

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Book of abstracts

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The two potential approach to proton emission

Jim Al-Khalili *, Adrian Cannon, and Paul Stevenson

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Proton decay half-lives can be calculated reliably using the idea of simple tunnelling probabilities within a WKB model. Just as simple, but much more intuitive is the approach of Gurvitz and Kalbermann of splitting the tunnelling potential into internal (bound state) and external (scattering state) parts. This is referred to as the Two-Potential approach to the tunnelling problem. For spherical nuclei there is not much to choose between TPA and WKB, but to extract reliable spectroscopic information from the dripline nuclei of interest, these methods must be extended to deformed potentials. We outline our approach for the case of spherical nuclei starting from a mean field HF potential using the Skyrme interaction and outline a programme of work leading to an extended 3D TPA model for deformed nuclei.

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Toward the island of strong deformation in the lightest Po and Rn nuclei

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The results of the recent experiments to study alpha-decay of the new nuclides ^{186,187}Po and ^{193,194}Rn will be presented. The strong retardation of the half-lives of ^{186,188,190}Po isotopes relative to the expected linear behavior of the classical Geiger-Nuttall rule and evidence for strong ground state deformation of these isotopes will be discussed in the shape-coexistence approach.

The production cross-sections in this region of nuclei will be reviewed and a application of the projectile fragmentation method for such studies will be discussed.

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Triaxially deformed proton emitters

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One of the interesting questions in nuclear structure studies of deformed proton emitters, is the role played by triaxial deformation in the decay process. Proton radioactivity from nuclei with axial deformation is well understood [1, 2] within the nonadiabatic quasiparticle approach [3], and properties of the decaying state and nuclear deformation are identified, providing a consistent interpretation of all experimental data available. However, the influence of triaxial deformation on proton emission from some of these exotic nuclei, where such deformations are expected to occur, is not yet carefully analyzed.

We have generalized the nonadiabatic quasiparticle method, to include the triaxial degree of freedom, and performed exact calculations for proton emission from triaxial nuclei. Therefore, a proper formalism for triaxial proton emitters, is for the first time available, and takes fully into account the pairing residual interaction and the coupling to the daughter nucleus states. Applications were made for nuclei whose half lives for decay have been measured experimentally, like for example ^{161}Re [4] and ^{185}Bi [5]. The discussion of our model and results obtained, will be the subject of this work.

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Experimental systematics of the isomeric configurations in the neutron-deficient $N = 77$ odd-Z isotones

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The neutron-deficient N=77 isotones lie at the border between prolate and oblate deformation. In this region, three neutron orbitals $\nu \mathrm{s}_{1/2}$, $\nu \mathrm{d}_{3/2}$ and $\nu \mathrm{h}_{11/2}$, and three proton orbitals $\pi \mathrm{s}_{1/2}$, $\pi \mathrm{d}_{3/2}$, and $\pi \mathrm{h}_{11/2}$ are expected to be close to the Fermi surface. By measuring the decay properties of the isomers of these nuclei near the proton drip line the systematics of the wave functions can be determined.

We have investigated the systematics of the isomeric configurations of ^{140}Eu, ^{142}Tb, ^{144}Ho, and ^{146}Tm via x-ray, γ -ray, and charged particle spectroscopy at the Recoil Mass Spectrometer at the Holifield Radioactive Ion Beam Facility (ORNL). Half-lives and expanded decay schemes were developed for the 8^+ and 5^- isomers of ^{140}Eu, and ^{142}Tb. In the case of ^{144}Ho, no evidence of the decay of the 5^- state to the expected 1^+ ground state was observed. In the proton decay of ^{146}Tm, five proton transitions were confirmed from previous investigations [1]. Due to an improved setup and a factor of five higher statistics [3], we were able to definitively assign these transitions to two proton-emitting states with half-lives of 198(3) ms and 68(3) ms. By comparing the experimental data to calculations done with a particle-core vibrational model [2], we were able to assign the J^π of 10^+ and 5^- to the ^{146m}Tm and ^{146gs}Tm isomers respectively. In addition, we were able to place single particle neutron states in the daughter ^{145}Er.

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Two-proton radioactivity: Comparison experiment - theory

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With Fe45 and Zn54 and possibly Ni48, two to three ground-state two-proton emitters have been identified experimentally [1,2,3,4]. Three models are on the market which predict quantities measured by experiment [5,6,7]. The data allow a first comparison between experiment and theory. In this talk I will compare the experimental results to predictions from these theories. In addition, an outlook with respect to measurements of other two-proton radioactivity candidates will be given.

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Recent achievements in beta delayed particle studies

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The beta decay process allows for understanding the interactions and behaviour of the nucleons inside the nucleus. The process is well understood and the interpretation of the data yields a wide variety of spectroscopic information: level energies, spins, parities, widths and level densities.

Often the key nuclei to understand how such a complex system can be constructed from a few ingredients are very neutron or very proton rich. Such exotic systems allows isolating and amplifying specific aspects of the nucleonic interactions, and uniquely display the physics of loosely bound quantal systems governed by the strong interaction. Beta decay is mediated by the weak interaction, so it can also shed light on some fundamentals of weak interactions.

Going far from stability the difference in isobaric masses increases quadratically and the binding energy of the last nucleon decreases dramatically, the beta-delayed particle emission becomes dominant near the drip lines. The beta transitions feed unbound excited states and they are followed by delayed particle emission. The high efficiency for the charged particle detection makes the study of the beta delayed particles a unique tool to understand the nuclear structure of very rare species. The stability of the α-particle and the fact that ^{8}Be is unbound, makes multiparticle break-up to dominate the decay of very light nuclei. In the process of β-delayed multi-particle emission the nucleus breaks up into more than two subsystems. The main interest in β-delayed multi-particle emission is the fact that the mechanism of the break-up is not fully determined by conservation laws. Furthermore if the mechanism is sequential, as it seems to be in most of the cases, full kinematic experiments allow to determine the relative importance of the partial decay branches. These decay branches are critical to astrophysical questions from energy generation in stars, to the nature of the explosive phenomena in Universe as well as to nucleo-syntesis and origin of elements.

In this contribution recent achievements in particle decay studies will be presented. The different techniques developed to do high quality spectroscopy of very low produced exotic nuclei, will be revised.

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Search for diproton decay of ^{18}Ne excited levels after coulomb excitation

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At INFN Laboratori Nazionali del Sud in Catania we started an experimental program to search for the diproton decay of excited levels of 18Ne. 18Ne is produced by nuclear fragmentation on a 9Be target of a 20Ne beam delivered by our cyclotron. The 18Ne beam selection is performed by using the FRIBS setup[1]. The beam with an average energy of about 30 MeV/A is tagged using a double side silicon strip detector. A Pb target is used to induce coulomb excitation on 18Ne. The residual nucleus as well as the emitted fragments are detected in coincidence by an array of double and triple Silicon-CsI detector telescopes. The detection of all decay products allows a good measurements of the excited levels involved in the reaction. Preliminary results will be shown.

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Evidence for enhanced collectivity in Te-I-Xe nuclei near the $N = Z = 50$ double shell closure

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An important aspect for understanding the structure of nuclei far from stability is the evolution of collectivity with proton and neutron number. The region around the presumed doubly-magic self-conjugate ^{100}Sn nucleus is a unique regime since it is the only place on the Segré chart where the nuclei contain a sufficient number of particles (the level density is high enough) for pronounced collective excitations to appear and, at the same time, the $N = Z$ line coincides with an expected double shell closure. Gamma-ray transitions have been identified for the first time in the extremely neutron deficient nuclei ^{106,107}Te, ^{109}I and ^{110}Xe and the energies of the the lowest excited states in have been deduced. The experiments were performed at the K130 Cyclotron accelerator facility at the University of Jyväskylä, Finland using the JUROGAM γ-ray spectrometer in conjunction with the gas-filled recoil separator RITU and the GREAT decay spectrometer. The results establish a breaking of the normal trend of increasing first excited 2^+ and 4^+ level energies as a function of decreasing neutron number as the $N = 50$ major shell gap is approached for the neutron-deficient tellurium and xenon isotopes. A similar effect is found for the sequence of $h11/2^-$ bands in the iodine isotopic chain. This unusual feature is suggested to be an effect of enhanced collectivity, possibly arising from isoscalar $n - p$ interactions becoming increasingly important close to the $N = Z$ line. Results on ^{107}Te relevant for the astrophysical rp-process will also be discussed.

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Isomer studies for nuclei near the proton drip line in the mass 130-160 region.

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This talk will give an overview on the status of a programme of research which has focussed on using isomeric states to identify and tag weakly populated nuclei around the proton drip line. The work has been carried out at the University of Jyvaskyla in Finland using the RITU and GREAT spectrometers. The technique relies on correlating prompt decays at the target position with delayed decays from isomeric states at the focal plane of RITU. The tagging technique relies on detecting the delayed events in a low-background environment. Several new isomers have been identified and the talk will focus on the properties of these isomers and the new information obtained for the states above the isomers.

More recently we have modified the focal-plane setup to use a more efficient dual Multi-Wire Proportional Counter system. The first results with this setup will be discussed in addition to possible future developments to access properties of nuclei beyond the drip line.

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A new alpha-decaying high-spin isomer in the proton-unbound nucleus ^{158}Ta

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The recoil-decay-tagging (RDT) [1] technique has revolutionised experimental investigations of the single-particle structures near the proton drip line. In a RDT experiment using the JUROGAM and GREAT spectrometers in conjuction with the RITU gas-filled separator, excited states have been investigated in the proton-unbound nucleus, ^{158}Ta, for the first time.

We report the observation of a high-spin isomer in the N = 85 nucleus ^{158}Ta, which decays via competing alpha and E3 gamma-ray decay branches. We present the level scheme depopulating this 6 microsecond isomer and the levels built upon it. The implications for the evolution of single particle structures in the N=85 isotones close to the proton drip line will be discussed.

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Recent results at Argonne - Decay of the highly deformed proton emitter ^{121}Pr ⋆

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The decay of the highly-deformed proton emitter 121Pr will be described, as well as results from other proton decay experiments carried on at the ATLAS facility.

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Nuclear structure near the drip line using large gamma-ray detector arrays

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Big Ge-arrays like Euroball or Gasp have been built with the main purpose of studying high angular momentum phenomena in nuclei. When coupled with powerful ancillary detectors they became also excellent instruments to explore the properties of very exotic nuclei far from β-stability. A large fraction of the experiments has been therefore devoted to study both proton-rich and neutron-rich nuclei populated using stable beams provided by the Legnaro and Strasbourg accelerators. Nuclei lying close to the $N = Z$ line are of particular interest being a laboratory where collective excitations as well as fundamental properties of the nuclear force can be tested, like isospin symmetry and isospin breaking terms, proton neutron pairing, dripline effects. Due to their special symmetry they allow to test the impact of nuclear physics calculations on the prediction of the standard model of the electro-weak interaction. Isospin mixing probability can be determined using isospin forbidden γ transitions or alternatively through the investigation of the electromagnetic decay properties in mirror pairs.

We have investigated the high spin structure of even-even and odd-odd $N = Z$ nuclei in the $A \sim 70$ mass region. The recent observation of the excited states of ^{67}Se has also allowed to extract the Coulomb energy differences (CEDs) between isobaric analog states in the $A = 67$ mirror pair. Here the peculiar behavior of the CEDs can possibly be related to the contribution of the isospin breaking electromagnetic spin orbit term of the nuclear Hamiltonian.

High intensity beams of stable ions will also offer an interesting possibility to extend our knowledge of the nuclear structure both for proton rich and moderately neutron rich nuclei. The use of beams of unstable ions will finally allow the nuclear physics studies for the most exotic systems. New perspectives in the field will be opened by the use of second generation radioactive ion beam facilities. Allowing the production of beams of neutron rich nuclei, such facilities, complemented by new instrumentation (AGATA), will allow to investigate nuclear properties very far from the stability line as the evolution of magic numbers or the isospin dependence of the spin orbit splitting of the mean-field orbitals.

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Systematics of proton emission

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The experimental half-lives for proton emitters with charge numbers $Z > 50$, mainly taken from the compilation of Ref. [1], as a function of the Q-value are all mixed up and it is impossible from such a plot to deduce any systematic trend. However by subtracting the contribution of the corresponding centrifugal barriers and plotting the resulting reduced half-lives as a function of the Sommerfeld parameter $\chi = 2(Z-1)e^2/(\hbar v)$ [2] one obtains a striking order in the experimental points. It turns out that almost all experimental data lie on two straight lines, namely

$$\begin{aligned} &log_{10}\, T_{red} = a_k(\chi - 20) + b_k \ , \\ &\qquad a_1 = 1.31 \ , \quad b_1 = -2.44 \ , \quad Z \leq 68 \ , \\ &\qquad a_2 = 1.25 \ , \quad b_2 = -4.71 \ . \quad Z > 68 \ , \end{aligned} \tag{1}$$

where the reduced half-life is given by

$$T_{red} = T_{1/2} e^{-2\frac{l(l+1)}{\chi} tg\ \alpha} \ , \quad cos^2\,\alpha = \frac{Q}{V_c} \ , \tag{2}$$

and V_c is the Coulomb potential at the geometrical touching radius.

The standard errors are $\sigma_1 = 0.26$ and $\sigma_2 = 0.23$, respectivelly, corresponding to a mean factor less than two. The reduced half-lives are strongly correlated with the quadrupole deformations, estimated in ref. [3]. The sharp change of deformations from prolate to oblate values at the charge number $Z = 68$ suggests that the two lines correspond to different subshells, divided by this value.

This simple relation is the analog of the Geiger-Nuttall rule for proton emitters. It allows one to assign rather precisely the spin and parity of proton decaying states. The only quantities that are needed are the half-life of the mother nucleus and the proton Q-value. Since the decay probability is strongly dependent upon the orbital angular momentum l of the decaying proton, only properly assigned l-values will fit into the straight lines. This can, therefore, be a powerful tool to determine experimentally quantum numbers in rare nuclei.

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The tagged RIBs facility of LNS

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Radioactive Ion Beams (RIBs) at intermediate energy by the In-Flight method (Projectile Fragmentation) were successfully produced at the LNS since a few years ago (FRIBs project)[1] Different projectile fragmentation reactions have been studied to produce RIBs by using ^{12}C, ^{20}Ne, ^{40}Ar and ^{58}Ni projectiles at incident energies between 62 and 40 AMeV on ^{9}Be and ^{27}Al targets. Production rates of both neutron and proton rich RIBs up to Z= 28 have been measured. Transport up to 95% was measured along the LNS beam lines and individual RIBs rates up to 10^5 ions/sec were obtained on the reaction target for primary beam currents on the order of 500 enA. The leading idea of the FRIBs project was to tag, event-by-event, in A,Z energy and positions, each fragment, produced by the projectile fragmentation, after the selection operated by the LNS Achromatic Fragment Separator and before it interacts with the secondary target. The DE-ToF method was applied to identify each ion. The status and perspective of the project and an overview of research programs will be presented.

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Quasi-bound low energy tail of resonance

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Ground states of particle-unbound nuclei are seen as resonances. According to the Heisenberg's uncertainty principle, the shorter is the lifetime of the state the broader is the resonance. The Breit-Wigner function describes perfectly the shape of the resonance when energy-dependent partial-widths are used. In the low energy tail of a resonance, close to the particle-emission threshold, the partial-width for the emission of a charged particle through the Coulomb barrier is dramatically reduced. In this region of the resonance, the charged particle could be trapped inside the unbound nucleus. This idea will be discussed in more details and experimental aspects will be given.

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Decay studies of the neutron deficient ^{33}Ar and ^{32}Ar revisited

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Beta delayed particle emission is a powerfull tool to study nuclear structure near the drip-line. This is due to the combination of several factors. Near the drip line, the large difference in isobaric masses and the low binding energy for the last nucleon open up a large Q_β-window for particle emission. The high efficiency in the detection of the emitted particles, only limited by the solid angle, allows to determine the excited structure of the daughter nucleus if the final state is known, even for very rare species. This method has been applied in the last four decades to about two hundred nuclei known to be β-delayed proton emitters [1].

In a recent experiment done at the low energy line branch, IBE, of SPIRAL in GANIL (Caen, France) the lighter argon isotopes were studied. The experimental setup consisted of 6 DSSSD (Double Side Silicon Stripped Detectors) placed in a cubic geometry with the stopper foil in the center.Each DSSSD was backed by a silicon detector to detect high energy charged particles and betas. The cube was surrounded by 3 small EXOGAM clovers detectors.

Although detailed studies have been done of the decay of these light argon isotopes previously [2,3], we have decided to revisit these decays with the aim of exploring with high sensitivy the β-3p branch and search for correlated *p-p* emission in ^{31}Ar as well as possible 2p branch in ^{32}Ar. We are also interested in the study of the interplay of the proton and gamma partial branches in the levels close to the particle threshold for the three proton-emitters: $^{31-33}$Ar. Furthermore the high granularity of the set-up will allow to do particle-particle correlations to settle the spin of the excited states in the daughter nucleus. In this contribution we will present the results obtained for ^{32}Ar and ^{33}Ar decays.

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Nuclear structure studies of Bi isotopes near the proton drip-line

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Shape coexistence of a spherical ground state and low-lying deformed states has been established in neutron-deficient lead isotopes. Triple shape coexistence could even be observed in ^{186,188}Pb, with prolate and oblate excited 0^+ states being close in excitation energy. These deformed states have been interpreted as proton intruder configurations which are well-known to occur at rather low excitation energy in the A = 190 mass-region. Therefore the identification of the proton orbitals involved in such a process is necessary to better understand the origin of shape coexistence in this mass region. This information cannot be deduced from the study of 0^+ states in even-even lead isotopes because of the coupling of the proton pairs, but the orbitals involved can be investigated studying proton single particle states in neighbouring odd-A isotopes. This can be achieved by making nuclear structure studies on ^{189}Bi for example, which corresponds to a single proton added to the ^{188}Pb core. Preliminary results from an experiment on ^{189}Bi performed at the University of Jyväskylä with JUROGAM, RITU and GREAT, using the Recoil Decay Tagging (RDT) technique will be presented.

Observation of individual particles in the 2-proton radioactivity with a TPC

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Two decay modes were predicted for nuclei at the proton drip-line by Goldanskii[1] in the early 60's: the 1-proton radioactivity for odd-Z nuclei and the 2-proton radioactivity for even-Z nuclei. The first one was discovered experimentally in the 80's[2], while the 2-proton decay was observed for the first time in 2002 in the decay of 45Fe at GANIL[3] and GSI [4]. This was confirmed by a recent GANIL experiment [5], that also stated 54Zn as a precursor of this decay mode[6]. This new radioactivity may provide many experimental pieces of information about masses for nuclei beyond the drip-line, single particle levels sequence, tunnelling processes or the pairing interaction. The challenging goal for experimental two-proton studies is then to perform a more extensive analysis of the decay process by measuring energy and angular correlations between the two emitted particles. This should allow for a comparison with models taking into account the structure of involved nuclei and the decay mechanism. For this purpose, a Time Projection Chamber detector has been developed at CENBG. It has been used successfully in an experiment performed at GANIL in September 2006, leading to the first direct observation of individual protons emitted in the decay of 45Fe. The experimental set-up and the first results of this experiment will be presented.

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Recent progress in the theory of two-proton radioactivity and three-body decay

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The results of studies of two-proton radioactivity phenomenon in the framework of three-cluster hyperspherical model [1,2] are reviewed. We introduce the simplified semianalytical model for the precise calibration of the hyperspherical calculations and obtain the quasiclassical (R-matrix-type) formulae for decay widths [3]. We discuss the astrophysical applications of the two-proton decay theory; this is made for the reverse processes of the resonant two-proton radiative capture [4]. The questions of the soft E1 mode existence in proton rich nuclei and nonresonant two-proton radiative capture have also been studied [4]. The importance of correlation information for investigation of three-body decays is demonstrated on the example of the ^{5}H continuum [6]. Recent experimental results on the decays of ^{19}Mg [7], ^{45}Fe [8], and ^{94m}Ag [9] are considered from theoretical point of view. Prospects of the $2p$-radioactivity and three-body decay studies are discussed.

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Discovery of the new proton emitter ^{144}Tm

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Evidence for the proton decay of ^{144}Tm was found [1] in an experiment at the Recoil Mass Spectrometer [2] at Oak Ridge National Laboratory. The ^{144}Tm events were found in the weak p5n channel of the fusion reaction using a ^{58}Ni beam at 340 MeV on a ^{92}Mo target. The observed proton decay energies are 1.70 MeV and 1.43 MeV and the half-life $\sim$1.9 μs, making it the shortest lived observed ground-state proton emitter. The decay properties suggest proton emission from the dominant $l = 5$ πh$_{11/2}$ part of the wave function and from the small $l = 3$ πf$_{7/2}$ admixture coupled to a quadrupole vibration. The detection of this very short proton emitter was made possible by use of a Double Sided Silicon Strip detector connected to a fast Digital-Signal-Processing-based acquisition system [3]. The developments critical technical developments which enabled success of the experiment will be presented.

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Diproton emission from ^{17}Ne halo resonant states

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Fingerprints of entangled states of the two protons, from the decay of halo resonant states of ^{17}Ne have been studied. This study makes possible a way to discern the diproton emission from the other two proton emission mechanisms. In particular, we calculate the energy (E1=10.87 MeV) and the width (G1=3.82 MeV) of the first halo resonant state able of emitting diproton. For this purpose, the diproton was considered as a resonant state and its width (Gs=4.049 MeV) was estimated. An analytic expression for the angular proton-proton distribution was found (which reproduces rather well the form of the experimental results) in agreement with experimental results. We conclude that the first 17Ne excited state can not emit diproton and there are few ^{17}Ne excited states, having halo properties, able of emitting diproton.

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Capture reactions relevant to p-process nucleosynthesis

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The origin in the cosmos of the so-called p nuclei is one of the most puzzling problems to be solved by any model of heavy-element nucleosynthesis. The class of p nuclei consists of 35 proton-rich stable nuclei that are heavier than iron and cannot be synthesized by the two neutron-capture processes referred to as s and r process. To date, these nuclei have been observed only in the solar system. The reproduction of p-nuclei abundances on the basis of astrophysical processes occuring outside the solar system such as exploding supernovae (SNII) or He-accreting white dwarves with sub-Chandrasekhar mass, will enable us not only to understand the nuclidic composition of the solar system but also to further elucidate our fundamental picture of its creation.

So far, all the models of p-process nucleosynthesis are able to reproduce most of the p-nuclei abundances within a factor of 3, but they fail completely in the case of the light p nuclei. Due to the huge number of reactions involved in abundance calculations, the latter have to rely almost completely on the reaction cross-section predictions of the Hauser-Feshbach (HF) theory. It is therefore of key importance, on top of any astrophysical model improvements, to investigate the uncertainties in the nuclear data, and in particular in the nuclear level densities (NLD), nucleon-nucleus optical model potentials (OMP), and γ-ray strength functions entering the HF calculations.

In view of these problems, we have performed several in-beam cross sections measurements of proton- as well as α-capture reactions in the Se-Sb region at energies well below the Coulomb barrier. Our aim is to contribute to a cross-section database relevant to the modelling of the p process and to obtain global input parameters for HF calculations. This contribution reports on 25 (p, γ) and 9 (α, γ) reactions. Our results, as well as all other existing data, are compared with HF calculations using various microscopic and phenomenological models of the nuclear input (NLD, OMP). Several aspects of all the experiments performed so far, as well as plans for additional measurements, are presented. Finally, the question of whether there is sufficient experimental information to put constraints on the theory and draw final conclusions is discussed.

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Precise mass measurements of exotic nuclei - the SHIPTRAP Penning trap mass spectrometer

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The mass of an atomic nucleus contains the binding energy that brings the nucleus into existence. Its precise measurement gives access to many phenomena. A systematic investigation of the nuclear binding energy reveals nuclear structure and is a prerequisite for nuclear models. An independent and very precise determination of reaction enthalpies, i.e. Q-values, yields necessary data for fundamental tests as for instance the test of the CVC hypothesis and for reaction network calculations in nuclear astrophysics. Mass measurements of short-lived radioactive nuclei are provided by Penning trap mass spectrometers like SHIPTRAP with relative uncertainties between $1 \cdot 10^{-7}$ and $1 \cdot 10^{-8}$.

SHIPTRAP is installed after the Separator for Heavy Ion Products (SHIP) at GSI in Darmstadt. The radionuclei are produced in fusion-evaporation reactions at a few MeV/u energy. The reaction products are separated from the primary beam in the velocity filter SHIP. The energy of the reaction products is then degraded from around 100 keV/u down to a few 10 keV/u in a μm-thin titanium window before they are stopped in 50 mbar helium in a buffer-gas cell. After extraction from the buffer-gas cell, the radioactive ions are accumulated in a linear RFQ trap to prepare the efficient transfer to a Penning trap. The ions are then injected into a purification Penning trap for accumulation and mass selective cooling with a resolving power up to $m/\Delta m = 10^5$. After the transfer of the purified ion ensemble to a second (high-precision) Penning trap the ion cyclotron frequency $\nu_C = qB/(2\pi m)$ and hence their mass, is determined. This is done with a resolving power of up to 10^6, enough to separate low-lying isomeric states.

This presentation will summarize the recent results obtained at SHIPTRAP and their relevance for modern nuclear-physics subjects. One of the outstanding examples is the measurement of the ground-state proton emitter ^{147}Tm and its daughter ^{146}Er. This yields not only the proton separation energy by mass difference but for the first time an absolute mass value for these nuclei.

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High spin features of 3QP bands and the 3QP plus rotor model

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The high-spin features of the 3QP bands along with the role of the residual interactions on the splitting of the 3QP multiplets will be discussed, A 3QP plus Rotor model developed recently will be applied to explain the observed phenomena. An extension of the 3QP plus Rotor model and its applications, currently in progress, will also be discussed.

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Prompt proton decay in the vicinity of ^{56}Ni

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During the past 10 years, the prompt particle decay mode has been established in a number of nuclei in the vicinity of ^{56}Ni. In contrast to ground state proton emitters, which competes with the ordinary β^+ decay, the prompt particle emission competes with γ decay. Hence the typical time scale of prompt particle emission is 10^{-12}-10^{-15} s. This makes it possible to study them in prompt coincidence with preceding and subsequent γ rays emitted from the parent and daughter nuclei, respectively, in experiments using fusion-evaporation reactions. The prompt particle decay typically occur from highly or superdeformed initial states into spherical states in the daughter nucleus. The dramatic shape change resulting from the decay may affect the angular distribution of the prompt protons. This in turn could offer insights into quantum mechanical tunneling processes.

I will report on some recent results and ongoing efforts in the Nuclear Structure Group at Lund University to study the prompt particle decay. An experiment aimed at high resolution in-beam particle-γ coincidence spectroscopy was performed at Argonne National Laboratory, using GAMMASPHERE, parts of MICROBALL, the Neutron Shell, the Fragment Mass Analyzer, the Ion Chamber and the LuWuSiA. The Lund-Washington university silicon array (LuWuSiA) is a state-of-the-art charged particle detector consisting of eight ΔE - E silicon strip telescopes, which combined gives rise to 2048 pixels. Using LuWuSiA the goal is to determine the angular distribution of the prompt protons with respect to the individual spin axis of the emitting nucleus.

A discussion around the first observation of isomeric proton radioactivity produced in a fragmentation reaction will also be presented. This result arose from the so-called stopped beam campaign within the *Rare Isotope Investigations at GSI* (RISING) project. Here the newly established 10^+ isomeric state in ^{54}Ni was found to not only decay by $E2$ and $E4$ γ rays but also via proton decay into the daughter nucleus ^{53}Co.

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Mass measurements and proton binding energies near the $Z = N$ line below ^{100}Sn

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During the recent years, the Penning trap technology and IGISOL-technique were combined in the University of Jyväskylä for precision studies of atomic masses of short-lived exotic isotopes without target-ion source chemistry related restrictions [1].

Frequencies of radial eigenmotions in the Penning trap sum up to a cyclotron frequency which in the given magnetic field is mass dependent. By measuring periodically the cyclotron frequency of the unknown isotope and a well known reference ion, it is possible to deduce the mass of the unknown isotope with an accuracy in the range of a few keV.

One of the main JYFLTRAP projects aims to measure the binding energies of nuclei located in the expected region of the rp-process [2] and p-process [3] paths. These measurements include $^{80-83}$Y, $^{83-86,88}$Zr and $^{85-88}$Nb. ^{84}Zr has been measured for the first time. The obtained data have considerably improved S_p and Q_{EC} values for astrophysically important nuclei [4]. Recently we have also measured heavier neutron-deficient isotopes from molybdenum to palladium. These results will be discussed and an outlook for further similar studies will be given. In addition, these results are discussed in comparison with other spectroscopic information and theoretical studies. We will also compare our results with the recent Atomic Mass Evaluation [5] and selected mass predictions used in astrophysical calculations [6].

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Probing the limit of nuclear existence: Proton emission from ^{159}Re

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The observation of the new nuclide ^{159}Re provides important insights into the evolution of single particle structure and the mass surface in heavy nuclei beyond the proton drip line. This nuclide, 26 neutrons away from the nearest stable rhenium isotope, was synthesised in the reaction $^{106}Cd(^{58}Ni, p4n)$ and identified via its proton radioactivity using the RITU gas-filled separator and the GREAT focal plane spectrometer.

Comparisons of the measured proton energy and decay half-life with values using the WKB method indicate that the proton is emitted from an $h_{11/2}$ state. The implications of these results for future experimental investigations into even more proton unbound nuclei using in-flight separation techniques are considered.

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Fine structure in proton emission form the deformed ^{141gs}Ho and ^{141m}Ho states

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Proton emission from ground- and isomeric states in nuclei creates a powerful tool for nuclear structure studies. The measured proton energy and partial half-life confronted with the modelling of the emission process allow us to deduce the angular momentum of the emitted proton and to identify active components of the parent wave function.

An observation of proton emission from an odd-Z, even-N mother nucleus to the 0^+ ground-state and to the 2^+ first excited state in the daughter nucleus (called a fine structure) offers additional information on the decay process. The energy of the 2^+ state in the daughter nucleus yields the information on the nuclear potential tunnelled by the proton, in particular it's deformation. In addition, since at least two different wave function components have to be involved to populate the levels with spin difference of ΔI=2, such observation is probing the structure of the emitter wave function.

Two cases of fine structure in proton emission from odd-Z, even-N nuclei are known from literature. For both emitters, the highly deformed ^{131}Eu (quadrupole deformation β_2 ≈0.3)[1] and the transitional nucleus ^{145}Tm (β_2 ≈0.18)[2], only the decay of the ground-state was reported.

The first observation of fine structure in proton emission from two states in the same odd-Z, even-N deformed nucleus will be presented. The decay properties and structure of 7/2-[523] ^{141gs}Ho and 1/2+[411] ^{141m}Ho will be analyzed. The experimental data are suggesting a revision of the modelling of proton emission process.

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Studies of the excitation functions near ^{100}Sn

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Establishing the limits of bound nuclei is one of the most compelling problems in nuclear physics. Exotic nuclei at the limits are produced at very small rates, so the optimization of the production cross section is of utmost importance.

The region of proton- and α-emitting nuclei above the doubly magic ^{100}Sn, close to the N=Z line and proton drip-line, is exceptionally interesting. One can investigate there the correlations between neutrons and protons filling the same single-particle orbits leading, e.g., to an enhancement of the α-preformation probability [1]. The observation of an ultimate superallowed α-decay of ^{104}Te to ^{100}Sn will require the production of ^{108}Xe or ^{112}Ba in a 4n channel of fusion-evaporation reaction involving ^{54}Fe and ^{58}Ni projectiles and targets.

The excitation function for producing ^{109,110}Xe and ^{109}I in a fusion-evaporation reaction was mapped using the Recoil Mass Spectrometer at HRIBF (ORNL). The 3n, 2n, 1p1n, 1p2n and 2p1n evaporation residues of the reaction ^{54}Fe+^{58}Ni$\rightarrow$^{112}Xe were investigated looking for the maximum yield as a function of the impinging beam energy. The identification of the reaction products was achieved through the observation of their unique proton or α-decay. The number of decay events, corrected for the total efficiency, allowed us to determine the cross sections. Additionally, we performed calculations using the code HIVAP [2] with updated mass tables [1,3,4] for several nuclei in the ^{100}Sn region. The data on the cross sections for ^{109,110}Xe and ^{108,109,110}I will be discussed in comparison with the calculations.

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Identification of the ^{109}Xe → ^{105}Te → ^{101}Sn alpha-decay chain

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The region of alpha emitting nuclei above ^{100}Sn is a fertile area to investigate possible enhanced correlations between neutrons and protons filling the same single-particle orbits and a variety of experiments have been conducted to look for evidence of such effects (e.g. [1]). Such correlations could lead to the observation of superallowed alpha decay as an approach is made toward the N = Z line [2].

The isotope ^{109}Xe and the following alpha-decay chain ^{109}Xe → ^{105}Te → ^{101}Sn were identified [3] at the HRIBF at ORNL. Recoil and decay signals were analyzed using a digital data acquisition system based on XIA DGF modules [4]. The large recoil pulses were analyzed on-board, while 25-microsecond-long images of decay pulses below 9 MeV were stored for further analysis. This novel data acquisition technique allowed for the resolution of the two overlapping alpha particles signals into two separate energies even when there was less than 1 μs separation between decay events.

The identification of ^{105}Te (the lightest mass α-radioactivity identified to date) and ^{109}Xe marks the closest approach to the N = Z line above ^{100}Sn. The half-life and Q_α value for ^{105}Te were used to determine the reduced α-decay width, δ^2. The ratio $\delta^2_{^{105}Te}/\delta^2_{^{213}Po}$ of 2.7 ± 0.7 indicates the superallowed character of the α-emission from ^{105}Te. Additionally, fine structure in the millisecond alpha decay of ^{109}Xe to ^{105}Te was identified and the energy difference between the $\nu d_{5/2}$ ground state and the $\nu g_{7/2}$ first excited state was determined to be 150 ± 13 keV in ^{105}Te. Prospects for reaching the superallowed alpha decay chain ^{108}Xe→^{104}Te →^{100}Sn will also be discussed.

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Two-proton simultaneous emission from ^{29}S

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The phenomena of two-proton emission are extensively studied in recent years. The nucleus ^{29}S which the last two proton locates in $2s_{1/2}$ orbit may exist such exotic behavior. Our previous experiment shows that the total reaction cross section of 29S+28Si has abnormal large value. It indicates that the last two proton occur a diffuse distribution in ^{29}S. In order to investigate the phenomenon of two-proton emission, a new experiment was performed at HILF-RIBLL of Institute of Modern Physics, Lanzhou. Secondary beams of 29S with energy of 46.8 MeV/u were produced by the projectile fragmentation of an ^{36}Ar primary beam on a Be target at 80.4 MeV/u, and were delivered to the secondary ^{12}C target with thickness of 0.29 mm. Four silicon strip detectors followed by a CsI+PIN detector array were placed behind target to detect the energies and positions of the outgoing fragments. Most of the heavy fragments stopped in the last silicon detector. Coincide with the ^{28}P and ^{27}Si fragments, the 1p and 2p events which stopped in the CsI detectors were clearly identified. The 1p and 2p remove cross sections for ^{29}S are 3.15+-0.32 b and 1.85+-0.20 b, respectively, and 1p remove cross section for ^{28}P is 2.13+-0.22 b. They are in good agreement with the previous results. Among the 2p coincident events, we found a strong correlation between two protons. More detail analyses are still in progress. At present, the primary results represent the signature of 2He cluster emission from ^{29}S.

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In-beam γ-spectroscopy of proton emitters ^{117}La and ^{151}Lu

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^{117}La is the lightest nucleus from the region of highly-deformed proton emitters. Its proton decay was first studied at INFN Legnaro, two proton lines were reported and assigned as the g.s. ($E_p = 783(6)$ keV, $t_{1/2} = 22(5)$ ms) and an isomer ($E_p = 933(10)$ keV, $t_{1/2} = 10(5)$ ms) proton decays, respectively [1]. Later an independent investigation was performed at the ANL but only the g.s. proton decay ($E_p = 806(5)$ keV, $t_{1/2} = 26(3)$ ms) was confirmed [2]. In the present study ^{117}La was produced in the ^{64}Zn(^{58}Ni,$p4n$) reaction at beam energy of 305 MeV. The proton energy was calibrated carefully with the method applied in [3]. About 300 g.s. protons, more than three times the statistics in previous experiments, were observed, but no evidence for the isomeric proton was found. The energy was extracted to be 812 (3) keV, in agreement with the previous ANL results, while the half-life was extracted to be $t_{1/2} = 20.1(2.5)$ ms. More than 20 γ-transitions have been identified in coincidence with the g.s. proton, the intensities are highly fragmented, the strongest peak having only about 15 counts. The configuration for the proton emitting state is discussed based on the systematics of band structures in heavier odd-A La isotopes $^{121-127}$La.

^{151}Lu was the first case of ground state proton decay discovered in 1981 [4]. Gamma-transitions in ^{151}Lu were first identified at Oak Ridge [5] with the RDT method, but no $\gamma - \gamma$ coincidence was established. In the present wok ^{151}Lu was produced in the ^{96}Ru(^{58}Ni, $p2n$) fusion evaporation reactions at a beam energy of 265 MeV. The prompt γ-rays observed in the Oak Ridge experiment were confirmed, their $\gamma - \gamma$ coincidence relationships were measured, and a level scheme is established.

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Multiple particle emission after ^{11}Li β-decay: exploring new decay channels

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Light nuclei have been studied intensively as they are good laboratories to understand nuclear structure. In particular the halo structure have caught the interest of nuclear physicists during the last two decades and many reaction experiments have been done to highlight their structure and identify candidates. The halo structure of a state can affect beta decay in two aspects. Firstly the diminished overlapping with the daughter state due to the extension of the halo can reduce the transition rates and secondly the halo particle can decay more or less independently from the core, giving equivalent decay pattern for both the halo nucleus and the core nucleus [1].

We report here on the experiment carried out at the ISOLDE-PSB facility at CERN dedicated to compare the beta-strength patterns of the halo nucleus ^{11}Li and its core ^{9}Li. Considering that at the drip-line the decays are very complex, in order to correctly assign the feedig to the high excited states from the measured spectra it is necessary to disentangle the multiple particle break-up channels. The analysis presented here concentrates in the channels from high excited states involving charged particles. In the case where three particles are emitted the detection of two of them in coincidence and the use of momentum and energy conservation allows to reconstruct the energy of the missing particle. Therefore, the complete decay mechanism can be studied in these cases.

This method gave recently firm values for spin and parity of the mirror levels in ^{9}Be and ^{9}B at about 12 MeV with widths around 0.4 MeV [2, 3]. In this work the charged-particles plus neutrons channels following ^{11}Li beta-decay are studied. Previously [4] the decay of the high excited states in ^{11}Be (E*>10 MeV) was established to occur through phase space break-up into ^{6}He-α-n (three body) and 2α-3n (five body) channels. Our new data (of higher statistics and larger angular coverage) show that the suggested pure phase-space break-up cannot explain the structures observed in the coincidence data. Two new decay channels, one of them involving ^{5}He-^{6}He gs resonances and the other involving ^{7}He(gs), are introduced to explain these discrepancies.

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Theoretical aspects of proton emission from deformed nuclei

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One of the most challenging topics of research in nuclear physics, is the creation in the lab of exotic nuclei with proton or neutron excess, reaching the limits of stability of matter beyond which a nucleon is no more bound. The proton drip–line has been mapped extensively in the region of low and intermediate nuclear charges, and the discovery of proton radioactivity in nuclei lying beyond the proton drip-line, played a crucial role in these studies. Protons can be emitted from the ground state and from isomeric excited states of the parent nucleus, and fine structure for decay to excited states of the daughter nucleus was also observed.

Important nuclear structure aspects can be learned from proton decay, since it is a probe for small components of the wave function of the decaying state, and helps to determine the deformation and angular momentum of the parent nucleus. The theoretical description of proton emission from spherical and deformed nuclei has been addressed by various authors, in order to interpret the experimental observables.

A review of the various theoretical approaches, and achievements in understanding the structure of exotic nuclei at the limits of stability, will be the purpose of this talk.

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On the alpha decay of ^{109}I and its implications for the proton decay of ^{105}Sb

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Nuclei with Z>50 near the doubly magic ^{100}Sn form an island of alpha and proton emission. The island's existence directly reflects the strong double shell closure N=Z=50 and the presence of the proton drip line. The odd-Z isotopes in this region are especially fascinating as both alpha and proton decay may occur. To date alpha decay has been observed in $^{108,110-113}$I and ^{114}Cs, while their neighboring nuclei ^{109}I and ^{112,113}Cs are proton emitters. The nuclide ^{105}Sb was also reported to be a proton emitter [1], but despite many attempts applying various techniques the result for ^{105}Sb has not been confirmed in any direct measurement, yet the deduced binding energy was included in widely used mass tables.

In an experiment at the Recoil Mass Spectrometer of the HRIBF, Oak Ridge National Laboratory, the alpha decay of ^{109}I was searched for and observed with a minuscule branching ratio. The measured alpha decay energy of ^{109}I provided an indirect and independent determination of the proton separation energy in ^{105}Sb. The result is about 130 keV larger than the previous value of -491±15 keV. The data and their consequence for the termination path of the astrophysical rapid proton capture process will be presented and discussed.

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Imaging nuclear decays with optical time projection chamber

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A novel type of gaseous ionization detector - Optical Time Projection Chamber - developed to study rare nuclear decays will be presented. In the OTPC tracks of charged particles ionizing a counting gas are recorded by optical imaging of the light generated by electrons multiplied in the amplification structures of the detector. By combining an electron drift-time profile measured by a photomultiplier and a CCD camera image, it is possible to reconstruct three-dimensional trajectories of particles, to measure their energies and charge.

The capabilities of the OTPC detector will be demonstrated by examples of various nuclear decay modes observed. Beta-delayed proton emission from ^{13}O, two-alpha break-up of ^{8}Be, triple-alpha decay of ^{12}C excited states as well as beta-delayed two proton decay of ^{43}Cr and two-proton radioactivity of ^{45}Fe will be presented.

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Search for two-proton radioactivity of ^{19}Mg in tracking experiments at GSI

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The results of the search for two-proton radioactivity of the ground state ^{19}Mg at the Projectile Mass Separator (FRS) at GSI will be presented. The ^{19}Mg ground state is predicted by the realistic three-body model to have a half-life in the 0.5–700 ps time interval which overlaps with the decay-time range accessed at FRS. The ^{19}Mg decay in-flight populated in a reaction of neutron knock-out from ^{20}Mg was detected in triple ^{17}Ne$+p+p$ coincidence with a newly developed detector array consisting of four large-area micro-strip silicon detectors. The detectors measured the positions of hits of two protons and heavy-ion residue, allowing to reconstruct all product trajectories and respective coordinates, e.g., reaction vertexes, life-time distribution and proton-proton correlations. Evidence for ^{19}Mg $2p$ decay will be considered.

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B($E1$) strengths and isospin symmetry in ^{67}As and ^{67}Se, results and theory

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In a recent experiment at Argonne National Laboratory, new spectroscopic information was obtained for the mirror pair ^{67}As and ^{67}Se via the measurement of the lifetime of analogue $9/2^+_{\mathrm{I}}$ excited states. The $9/2^+_{\mathrm{I}}$ states de-excite in both nuclei to lower lying $7/2^-_{\mathrm{II}}$, $7/2^-_{\mathrm{I}}$ and $5/2^-_{\mathrm{I}}$ states via two $E1$ and one $M2$ transitions. The nuclei of interest were populated via the fusion evaporation reaction of ^{32}S on ^{40}Ca, and selected by the combination of Gammasphere, Microball and the Neutron Wall arrays.

If isospin symmetry holds, and in the long wavelength limit, $E1$ transitions in mirror nuclei should be purely isovector and show equal reduced strengths. Differences in the mirror B($E1$) strengths were indeed observed in the analogue $E1$ transitions in ^{67}As and ^{67}Se, probably due to the interference between the isovector term and an induced isoscalar term. Interestingly, this difference arises only in the pair of $E1$ transitions de-exciting to the $7/2^-_{\mathrm{II}}$ state. This observation suggests the presence of isospin mixing only in one of the $E1$ transitions and may be related to the structure of the excited states involved. These new findings will be discussed with reference to recent shell model calculations [1], and to theoretical predictions of isospin mixing [2].

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Probing single particle structures beyond the proton drip line

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Decay spectroscopy provides important insights into the structure of nuclei beyond the proton drip line. Indeed for the most exotic species it is often the only way of deducing information on the proton and neutron single particle states. Recent work using the GREAT spectrometer coupled to the RITU separator at Jyvaskyla has revealed new insights into these changing structures, which have profound ramifications for the observable limits to nuclear existence.

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First observation of ^{19}Na states by inelastic scattering

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Low-energy states of the ^{19}Na proton-drip nucleus have been investigated by resonant elastic and inelastic scattering in inverse kinematics at the RIB facility at Louvain-la-Neuve, Belgium. We have used a 66 MeV ^{18}Ne beam and a proton-rich (CH2)n target. Recoil protons were detected at forward angles by using a ΔE-E system, the so-called CD-PAD detector [1]. The resonant elastic scattering technique have already been applied to study the ^{19}Na nucleus [2,3]. In this experiment, we have mostly concentrated on the ^{18}Ne+p inelastic scattering. The energy spectra from inelastic protons, which leave the ^{18}Ne nucleus in its first excited state at 1.887 MeV, exhibit the level structure of ^{19}Ne in the excitation energy region from 2.5 up to 3.5 MeV. In this talk, absolute elastic and inelastic ^{18}Ne+p cross sections will be presented and the analysis of the ^{19}Ne level properties, performed in the framework of the R-matrix model, will be discussed.

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Spectroscopy of the lightest nuclei in the Lanthanide region

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One of the most exciting subjects in contemporary nuclear physics is the study of nuclei at the limits of stability with respect to particle emission. Recently, there has been an intensive experimental activity in measuring the proton decay and a large variety of proton emitters were observed in the region of heavy nuclei with $50 < Z < 82$. Very recently the proton radioactivity from ^{117}La [1], ^{121}Pr [2], ^{131}Eu and ^{141}Ho [3] has been identified. The proton decay rates deviates significantly from calculations assuming spherical configurations, thus indicating the onset of large deformations in the drip line nuclei below Z=69. However, a detailed study of the structure of these nuclei can only be performed by means of γ-ray spectroscopy using large detector arrays coupled with efficient light charged particles detectors, since the cross section for their population with the presently available stable beams are very low. In order to establish the lowest single-particle excitations close to the point of the predicted [4] maximum deformation in this mass region (N,Z=64), we have studied the structure of the $^{122}La_{65}$, $^{123}Ce_{65}$ and $^{127}Nd_{67}$ nuclei using the ^{40}Ca+^{92}Mo reaction. We report preliminary results on only one of the nuclei of interest populated in the reaction, ^{122}La. The data analysis is in progress, and we hope to identify new excited states also in the other nuclei at the limit of stability, ^{123}Ce and ^{127}Nd, that are also unknown from the spectroscopic point of view.

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Decay spectroscopy of ^{45}Fe

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We have developed a new type of detector which combines a gaseous time projection chamber with the digital photography technique and can record tracks of heavy ions and their charged decay products in three dimensions. We have applied this detector to the decay study of ^{45}Fe — the first nucleus for which ground-state two-proton radioactivity was observed [1,2]. Results of this study will be presented. Clear images of two protons ejected from stopped ^{45}Fe ions represent direct and unambiguous experimental proof of this decay mode. Additionally, we demonstrate that beta decay branch of ^{45}Fe leads to various particle emission channels including two-proton and three-proton emission. The preliminary results on the angular correlation between emitted protons will be shown.

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Charged-particle channels in the β-decay of ^{11}Li

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The ground state of the ^{11}Li nucleus has the most pronounced two-neutron halo structure identified so far. The investigation of its properties is hindered by the difficulty of producing beams of ^{11}Li ions; so far, high energy beams have mostly been used, requiring to make assumptions on the reaction mechanism in order to extract the relevant information. The β-decay process, on the other hand, offers a reliable probe since it is well understood and provides direct information on the overlap between the mother and daughter states. In the specific case of ^{11}Li, of particular interest is the deuteron emission channel $^{11}\text{Li} \xrightarrow{\beta} {}^{9}\text{Li}+\text{d}$, since this decay essentially occurs in the halo and can probe its properties. This mode was identified in the past [1], but it was not disentangled from the ^{8}Li+t channel. The deuteron emission channel in the β-decay of ^{11}Li has received new attention in a recent theoretical work [3].

We report on a new measurement performed using the implantation technique described in [2], that allowed us separating the various decay channels of ^{11}Li.

For the first time, a pure beam of ^{11}Li nuclei was produced and post-accelerated at the ISAC facility in TRIUMF. The beam had an energy of 1.5 MeV/nucleon and intensities up to 1000 particles per second. The nuclei were implanted in a finely segmented silicon detector, where their decay was observed. The channels of interest were identified through the subsequent decay of the unstable ^{9}Li and ^{8}Li daughters. We obtained the branching ratios of the different channels with a precision better than 10%, and the energy spectra for the emitted particles (deuterons and tritons).

The results will be presented, along with a discussion on the implications for the halo structure of the ^{11}Li ground state.

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Proton-rich nuclei in nuclear astrophysics

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The stable isotopes which we observe on Earth are to a large extent produced in Nature via a 'detour' through unstable nuclei. The path leading through proton-rich nuclei is the so-called rapid-proton capture process, where, starting from carbon, nitrogen and oxygen through successive capture of protons and alphas followed by beta decay nuclei up to the mass 100 region can be produced. In order to understand the reaction path and the conditions at various astrophysical sites cross sections, masses and half-lives of unstable nuclei have to be measured. I will describe recent experiments in these areas and what they can teach us about the conditions which exist on the surface of white dwarfs and neutron stars.

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First observation of excited states in ^{137}Gd

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The γ-ray decay of excited states have been observed for the first time in the highly neutron-deficient nucleus ^{137}Gd, which lies 15 neutrons away from the nearest stable isotope. The transitions form a rotational band, thought to be based upon a single quasi-neutron orbital. The band decays via low-energy γ-ray transitions to a 484±68 ns isomeric state, which is subsequently observed to decay via a 177-keV γ-ray. Comparison of the experimental results to theoretical calculations show that the most likely interpretation for this rotational band is that it is the favoured signature of the $\nu h_{11/2}$ band.

The experimental work was carried out at the University of Jyväskylä Accelerator Laboratory, Finland, utilising the Recoil-Isomer Tagging technique. The focal plane spectrometer, GREAT, was used in conjunction with the Recoil Ion Transport Unit (RITU) and the JUROGAM HPGe array.

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Static and dynamic aspects of covariant density functional theory for proton rich nuclei ⋆

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Covariant Density Functional Theory (CDFT) provides a fully microscopic and universal description of nuclei in the vicinity and far from the valley of stability. Its static version is Relativistic Hartree Bogoliubov (RHB) theory. It allows the determination of the proton drip line and the investigation of proton emitters, in particular the calculation of the proton separation energies, the quantum numbers of the corresponding proton levels and their spectroscopic factors. We find good agreement for experimentally known proton emitters in medium heavy nuclei and we predict new possible proton emitters. With the same parameters the dynamic features of nuclei with large proton excess can be investigated by Relativistic Quasiparticle Random Phase Approximation (RQRPA). New collective modes are predicted, where the proton skin oscillates against the core with equal proton and neutron number.

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One-proton and two-proton radioactivity of the (21^+) isomer in ^{94}Ag

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The (21^+) isomer of the lightest known isotope of silver, ^{94}Ag, has properties that are unmatched in the entire nuclear chart. It is characterised by a long half-life of 0.39(4) s [1] , a high spin [2], a large excitation energy of 6.7(5) MeV [4] and the occurrence of β-delayed γ-ray [2] and proton [3] emission as well as direct one-proton (1p) and two-proton (2p) radioactivity. The experiment was performed at the GSI on-line mass separator by using ^{58}Ni(^{40}Ca,p3n) fusion-evaporation reactions. Protons were recorded by means of silicon detectors while germanium crystals served to 'tag' on known γ-ray transitions in the respective decay daughter. The cross-section for producing the 2p radioactivity in the fusion-evaporation reaction was found to be about 350 pb [6]. By comparing the experimental partial half-lives of the two 1p-decay modes with WKB estimates, very small spectroscopic factors of 1x10^{-6} and 3x10^{-6} were deduced [3]. The experimental data on 2p decay include proton-proton energy correlations A total of 19 such events were observed to fulfil a triple condition set on two ^{92}Rh γ-transitions and on the 2p sum-energy in the range of 1.8 - 1.95 MeV. These results are interpreted in comparison with predictions obtained from the break-up model [4]. The observed proton-proton correlations seem to be consistent only with ^{94}Ag decaying through a simultaneous 2p emission process. The experimental results on the 2p half-life and on the proton-proton energy correlation are interpreted as indicating a very large, prolate deformation of the parent nucleus, with the emission of protons occurring either from the same or from opposite ends of the 'cigar' [4]. Plans for continuing this experiment, which for the first time identified 1p and 2p radioactivity to occur from one and the same nuclear state and represents the first observation of proton-proton correlations in 2p radioactivity, will be discussed.

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Towards the studies of new proton emitters below ^{100}Sn at Oak Ridge

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Over thirty nuclei have been identified to date as ground-state proton emitters. All these proton radioactivities are located between the elements of Z=53 Iodine and Z=83 Bismuth. For the proton-rich nuclei above Z=83 the alpha decay channel starts to dominate over proton emission making the observation of new proton radioactivities less likely. However, for the elements below Z=50, proton emission should win the competition with beta decay soon after crossing the proton drip line. So far only three excited states in nuclei with $Z < 50$, ^{53m}Co, ^{54m}Ni and ^{94m}Ag, were reported as proton-emitting isomers. These meta-stable states have apparently a very small fraction of the wave function active for proton emission. Observation of ground-state proton radioactivities in the region below ^{100}Sn would help verify and understand better the evolution of the nuclear potential and the structure of states involved in the decay process.

An analysis of the predicted proton separation energies will be presented. It suggests that the decay of nuclei like ^{93}Ag, ^{89}Rh, ^{85}Tc, ^{81}Nb and ^{76}Y are likely to be dominated by proton emission. These exotic nuclei can be produced in fusion-evaporation or heavy-ion fragmentation reactions. Proton half-lives around a few microseconds can be expected for most cases, which creates a challenge for the observation of decay.

The production of the exotic nuclei in fusion-evaporation and fragmentation reactions, and the respective detection techniques for observing very rare and fast particle decays will be compared. HRIBF (Oak Ridge) developments such as a fast rotating target will be presented. High beam currents can be used and this increases the production rates of new proton-rich nuclei in fusion-evaporation reactions. Combined with a very selective Recoil Mass Spectrometer [1], Microchannel Plate Detectors [2] and digital electronics [3, 4] it enhances our potential to discover new proton emitters.

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Spectroscopic studies of proton unbound iridium nuclei and their neighbours.

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Odd-A nuclei around proton dripline below lead are rich laboratories for the study of single particle structures. Moving away from the Z=82 and toward to the N=82 shell closures the intruder $\pi h_{11/2}$ and $\pi i_{13/2}$ orbitals play an important role in the structure of these, usually forming isomeric states at relatively low excitation energies with respect to the ground state. The nuclei are produced via fusion evaporations and high spin states are strongly populated favouring the intruder orbitals. As the fusion/fission ratio in this region is relatively high, it is now possible to perform in-beam gamma ray and decay spectroscopy simultaneously. The University of Jyväskylä presently hosts the JUROGAM array and the GREAT spectrometer at the target and focal plane of the gas-filled separator RITU, respectively. This combination allows in-beam γ-ray spectroscopy to be performed down to a cross section limit of tens of nanobarns, when the RDT technique is employed.

A brief overview of technical developments and the latest results of in-beam and decay studies performed for the proton unbound $^{166-170}$Ir isotopes and the structures along alpha decay chains of very neutron deficient odd-A Pt isotopes will be presented.

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Extreme γ-ray spectroscopy: single-neutron states in ^{101}Sn and rotation of the proton emitter ^{145}Tm

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In-beam γ-ray studies of nuclei with a large proton excess are faced with ever decreasing cross sections and large backgrounds due to strong less exotic reaction channels. However, many of the nuclei along the proton drip line α decay, proton decay or emit β-delayed particles. This offers an efficient and very selective tag for prompt γ-rays and has been known as the Recoil-Decay Tagging (RDT) method. RDT has been extensively used with the Gammasphere array of Compton suppressed Ge detectors coupled with the Argonne Fragment Mass Analyzer. Recently, despite a very small cross section of about 50 nb and a long half life of $\sim$2s, protons emitted following the β decay of ^{101}Sn were used to identify γ-ray transitions in ^{101}Sn. As a result, the energy splitting between the neutron $g_{7/2}$ and $d_{5/2}$ orbitals outside the ^{100}Sn core was deduced. This result will be compared with predictions of Hartree-Fock calculations using modern nucleon-nucleon interactions. The structure of light Sn isotopes will be also discussed in the framework of the shell model in light of the new results. Another state-of-the-art example is the observation of a rotational ground-state band in the ^{145}Tm fast proton emitter, which decays with a half live of only $\sim 3\mu$s. In this experiment, coincidences between the proton decay to the 2^+ excited state in the daughter nucleus and the 2^+ to 0^+ γ-ray transition were also measured, which constitutes the first direct proof of proton decay fine structure. Based on the data the possibility of a triaxial shape in ^{145}Tm will be considered.

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High-energy Coulomb breakup of proton-dripline nuclei as a tool to study radiative-capture reactions of astrophysical interest

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Baur et al. [1] suggested about 20 years ago that high-energy Coulomb dissociation (CD) could be used to investigate the time-reversed process, radiative capture, for unstable nuclei where the direct capture reaction is difficult or impossible to perform. At GSI, we have run a series of CD measurements involving the proton-halo nucleus ^{8}B which plays a major role in solar-neutrino physics. We could show that for this case CD and direct proton capture yield the same result [2]. Theoretical guidance is necessary, however, to make sure that contributions of different electromagnetic multipolarities and nuclear dissociation processes are well under control. Recently, we have complemented the LAND/ALADIN experimental apparatus at GSI with new Si microstrip detectors and proton-drift-chambers to continue similar studies with radioactive beams from the fragment separator FRS at GSI. The first case of astrophysical interest to be studied will be the CD of ^{27}P, which has been studied at lower energies at RIKEN [3]. Another case will be the 2-proton breakup of ^{17}Ne to investigate radiative two-proton capture on ^{15}O, a process which could modify the reaction flow of the rp-process [4].

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α-^{36}Ar clustering and triaxiality in ^{40}Ca

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The ground state of ^{40}Ca is typical doubly closed-shell structure. However, many configurations exist in the low-lying states. Normal-deformed (ND) band built on $J^\pi = 0_2^+$ (3.35 MeV) was suggested that have α-^{36}Ar cluster structure with macroscopic model [1] and it was supported with ^{36}Ar(^{6}Li,d)^{40}Ca reaction [2]. In the experiment, α-^{36}Ar higher-nodal band are observed. ND state are suggested that have triaxial shape. [3] α-^{36}Ar clustering and triaxiality are reproduced with semimicroscopic cluster model [4]. Superdeformed (SD) band built on $J^\pi = 0_3^+$ (5.21 MeV) were discovered recently [5]. The band is suggested to have ^{12}C-^{28}Si-like structure. [6] ^{40}Ca have been studied with microscopic studies recently. [6–8] However, there is no full microscopic study to reproduce triaxiality and α-^{36}Ar clustering in ND band.

We have studied clustering and triaxiality in ^{40}Ca using Antisymmetrized Molecular Dynamics (AMD) + Generator Coordinate Method (GCM), where AMD is full microscopic framework. The GCM basis are calculated by energy variation with two kinds of constraints for obtaining mean-field-type structure and cluster structure, respectively [9]. Superposing mean-field-type structure, α-^{36}Ar structure and ^{12}C-^{28}Si structure, we reproduced ND, SD and α-^{36}Ar higher-nodal band and the electric transition strength $B(E2)$. We found that ND and SD state contain α-^{36}Ar and ^{12}C-^{28}Si cluster structure component, respectively. α-^{36}Ar higher-nodal band was obtained due to excitation of inter-cluster motion between α and ^{36}Ar cluster in ND state. Furthermore, we found that ND and SD band are triaxial shape and both have $K^\pi = 2^+$ side band due to triaxiality.

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Detector and electronic developments for low energy multi particle break-up studies

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The study of excited states of unbound light nuclei includes the simultaneous detection of several charge particles emitted with very low energy. This puts sever constrains on the detection system to be used. In the case of the detectors, high segmentation is needed to be able to detect several coincident particles, very thin dead layers to reduce the cut-of energy in combination with thin detectors to minimize sensitivity to beta and neutral particles. Further heavy particles are easily stopped in the delta E detector why in many cases identification of mass has to be done by pulse shape analysis. The high segmentation of the detectors leads to experiments with an increased amount of electronic channels. For very dedicated experiments integrated electronic chips can be prepared, but in many cases where the detector set-ups are frequently being changed, one still have to rely on more traditional electronic circuits, of course though with a relatively high packing ratio. Still one can further improve the situation using multiplexing of the signals. Detector and electronic developments made in parallel to experimental studies of multi particle break-up of excited states will be discussed.

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Unbound states of neutron-rich oxygen isotopes ⋆

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Fast beams of rare isotopes produced by in-flight separation from projectile fragmentation or fission have been very effective and productive for studying properties of nuclei far from stability. Fast beams have the farthest reach to study very short-lived, neutron-rich nuclei. New experimental techniques are continuously being developed to improve the sensitivity of fast beams and to measure new observables not accessible at the present time. For example, two-proton knock-out reactions have proven to be a sensitive tool to study shell closures far from stability. These direct reactions rely on the knockout of valence protons leaving the remaining nucleons largely undisturbed. We have shown that the direct knockout of inner-shell protons will selectively populate excited neutron-unbound states in neutron-rich nuclei. Fragment-neutron coincidence measurements were recently performed to measure the ground state of ^{25}O and excited states in the dripline nuclei ^{23}O, and ^{24}O.

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Probing the nuclear structure of odd-Z nuclei at and beyond the proton drip line above lead

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The falling trend of the excitation energies as a function of decreasing neutron number has been discovered to occur for the $(\pi i_{13/2})13/2^+$, $(\pi f_{7/2})7/2^-$ and $(\pi s_{1/2})1/2^+$ single particle states in odd-A isotopes heavier than lead [1–7]. These nuclei can be produced in heavy ion induced fusion evaporation reactions but when proton drip line is probed the production cross sections falls to sub-μbarn level. Low production yields, the existence of intruder states and shape coexistence in trans-lead nuclei makes it a challenging domain for spectroscopic studies. In Jyväskylä these nuclei has been studied extensively for several years. Today both delayed focal-plane spectroscopy and prompt in-beam spectroscopy are employed by using the state- of -the-art JUROGAM-RITU-GREAT system. In the present work an overview of the spectroscopic studies performed for the odd-A bismuth, astatine, francium and actinium isotopes will be given.

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Rare decay modes associated with high-spin isomers

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The spin degree of freedom adds an extra dimension to the exploration of decay mechanisms, and isomers offer special opportunities. In this talk, the different isomer decay modes will be discussed.

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Measurements of proton unbound states for explosive astrophysical scenarios

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The talk will review recent results and techniques that are enabling the study of important astrophysical resonances relevant for novae and X-ray burster scenarios. Particular emphasis will be placed on the interface between the nuclear structure of proton-rich nuclei and their influence on astrophysical reaction rates.

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Experimental study on beta-delayed proton decay in the rare-earth region near the proton drip line

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Experimental study on beta-delayed proton decay in the rare-earth region since 1970s has been briefly reviewed. In particulary, the related publications given by IMP, Lanzhou, China over the last 10 years have been summarized, which deals with the experimental observation of beta-delayed proton decays of nine new nuclides and two new isomers in the rare-earth region near the odd-Z proton drip line as well as five nuclides in the mass 90 region with N$\sim$Z by utilizing the proton-gamma coincidence technique in combination with a He-jet tape transport system. In addition, the experimental results were compared to the theoretical predictions of some nuclear models, resulting in the following conclusions. (1) It was found that most of the studied rare-earth nuclei were highly deformed with β_2 around 0.3. (2) The experimental assignments of spin and parity for the drip-line nuclei ^{142}Ho and ^{128}Pm could not be well predicted by any of the nuclear models. Nevertheless, the configuration-constrained nuclear potential-energy surfaces calculated by means of a Woods-Saxon-Strutinsky method could reproduce the assignments. (3) ALICE code overestimated by one or two orders of magnitude the production-reaction cross sections of the nine studied rare-earth nuclei, while the HIVAP code overestimated them by approximately one order of magnitude. (4) The experimental half-lives for ^{85}Mo, ^{92}Rh, as well as the predicted "waiting point" nuclei ^{89}Ru and ^{93}Pd were 5 to 10 times longer than the macroscopic-microscopic model predictions of Möller et al. These data considerably influenced the predictions of the mass abundances of the nuclides produced in the rp process. Finally, the perspective on searching the beta-delayed proton decay towards the even-Z proton drip line around the rare-earth region in near future at IMP has been simply introduced.

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Proton skin in neutron-deficient nuclei studied via interaction cross-sections at relativistic energies

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Precision measurements of the interaction cross-sections (σ_I) at relativistic energies $\sim$1 AGeV allow us to derive nuclear matter radii [1]. Since nuclear matter radii are directly related to the density distributions, the measurements of σ_I are a good tool to search for unusual nuclear structures. One of the most important features of unstable nuclei is the existence of neutron and proton skin structure. A clear evidence for neutron skin has been found in neutron-rich Na isotopes [2] where neutron skin thickness increases with the neutron number monotonically. Some nuclear theories, for example relativistic mean field approach, can reproduce this tendency and even predict the existence of proton skin in neutron-deficient nuclei. However, little was known for proton skin experimentally.

We have systematically performed the precision measurements of σ_I for unstable nuclei using the fragment separator FRS at GSI. Nuclear effective root-mean-square matter radii of light nuclei have been successfully determined [3]. Among them, argon and krypton isotopes can provide quantitative information on proton skin, since their charge radii of $^{32-40}$Ar [4] and $^{72-80}$Kr [5] have been determined by optical isotope-shift measurements. In addition, neutron-deficient Kr isotopes close to the $N = Z$ line attract a particular interest in their structures such as large deformation and shape coexistence.

In this contribution the systematics of the matter radii and their skin will be presented together with the experimental details and data analysis. Particular emphasis may be on the recent experiment for the krypton isotopes.

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Coulomb dissociation of the proton-rich nuclei ^{23}Al and ^{27}P and their astrophysical implications

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The astrophysically important two reactions, ^{22}Mg(p,γ)^{23}Al and ^{26}Si(p,γ)^{27}P, were investigated by the Coulomb dissociation of the proton-rich nuclei ^{23}Al and ^{27}P. These reactions are relevant to the reaction sequence in the rp-process, and experimental information on these reactions has been desired. Through the measurement of the Coulomb dissociation of the unstable nuclei ^{23}Al and ^{27}P, which correspond to the inverse reactions and are more efficient than the direct reaction measurement, the resonant capture via the excited states in ^{23}Al and ^{27}P were studied. The experiments were performed at RIPS in RIKEN. The RI beams of ^{23}Al and ^{27}P at energies of several tens MeV/nucleon bombarded a lead target. The breakup products, ^{22}Mg+p and ^{26}Si+p, were measured in coincidence. By the invariant mass method, the relative energy spectra were obtained and then the cross sections and corresponding radiative widths were determined. The dominance of the resonant capture over the direct capture, competition of the capture reactions with the beta decays, and comparison with the theoretical calculations are discussed.

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