EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Constraining the neutron star crust via mass measurements

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Abstract

We propose mass measurements of the most neutron rich nuclides in the region *A*~100 and *Z*~36, taking advantage of the most advanced mass measurement and target ion source techniques at ISOLTRAP and ISOLDE. This mass region is of particular interest to probe mass models used in the calculation of the composition of neutron stars at finite temperature.

Requested shifts: 16 shifts in 1 run on HRS.

Motivation

Neutron-star crust

Neutron stars are residues from gravitational core-collapse (type-II) supernovae. About two thousand neutron stars have been observed in the Milky Way and Magellanic Clouds (mainly as radio pulsars) and orders of magnitude more are expected to exist. Among the detected neutron stars, about 5% evolve in a binary system (binary pulsars, X ray bursts…). Type-II supernovae are at the origin of approximately one half of the stable nuclei with A > 60 through the rapid neutron-capture process (the so-called r-process) [1]. The merging of binary neutron stars is an alternative scenario to the type-II supernovae scenario. In order to improve the understanding of the formation and dynamical evolution of neutron stars, as well as their internal structure and composition, combined efforts on theoretical, observational and experimental sides are needed. Experimental nuclear physics measurements in particular play a unique role in the determination of outer and inner crust properties.

The outer crust of a neutron star is a Wigner-Seitz lattice of nuclei immersed in a homogeneous electron background. The only unknown in the equilibrium condition defining the structure of such a system is given by the mass of neutron rich isotopes. The equilibrium with respect to weak processes implies that stellar matter becomes increasingly neutron rich in going from the atmosphere to the core of the star. Dripline nuclei are therefore predicted to be abundantly produced within the depths of the outer crust. The composition, equation of state, and mechanical as well as thermal properties crucially depend on the masses of these nuclei which are not yet experimentally accessible. In particular, in the density region $10^{-4}<\rho<10^{-3}$ fm^{-3} (corresponding to the inner part of the outer crust) the atomic number of the neutron star constituents can vary from Z=34 to Z=44, depending on the model adopted for the nuclear mass (NuDat data base, microscopic-macroscopic droplet models, relativistic or non-relativistic density functionals [2,3,4,5]). In the isotopic region of interest, the energy landscape predicted by modern energy functionals is extremely complex and includes many quasi-degenerate minima, the implication being that changes in nuclear masses of the order of a hundred keV can drastically modify the predicted composition. As a consequence, high-precision mass measurements as close as possible to the dripline constitute essential constraints in reducing the uncertainties of the mass model. For binary neutron-stars, the nucleosynthesis path crucially depends on the accretion dynamics towards the more massive object. This, in turn, depends on the excited configurations of the neutron-star crust at finite temperature, where an even larger set of isotopes can be populated, and once again crucially depends on the mass and, to a lesser extent, on the density of states.

Recently, the implementation of the experimental mass value of ^{82}Zn, measured at CERN ISOLDE with the ISOLTRAP setup, in the neutron-star model allowed to constrain the crust composition profile: a change in position of ^{80}Zn and the replacement of its successor ^{82}Zn by ^{78}Ni or ^{79}Cu were observed [6-7].

Temperature dependent composition

Neutron stars are created with typical temperatures above 10 MeV. They cool down first by emitting neutrinos and then by gammas during hundreds of thousands years [8]. The study of neutron-star cooling is a subject of intense research in the astrophysical community, and it is known to be strongly related to the thermal properties of the crust. In particular, new information on the cooling rate came recently from the observation over ten years of a young neutron star (330 y), a remnant of the Cassiopeia A Supernova, by the Chandra X ray observatory [9, 10]. The composition of the outer crust will give insights to the dynamics of the cooling mechanism since it provides a way to infer the heat capacity. Fig. 1 presents the composition as calculated [2] for different temperatures and different cells at the frontier between the outer and inner crust of the neutron star. Temperatures and densities are varying respectively from 500 keV to 1.5 MeV ($0.6\cdot10^{10}$ to $1.7\cdot10^{10}$ K) and from 10^{-4} to $4\cdot10^{-4}$ fm^{-3} ($1.7\cdot10^{11}$ to $6.6\cdot10^{11}$ g/cm^3). The pairing effect is quite important even at these energies and the even – even isotopes are the most abundant nuclides. As can be seen, the effect of the temperature is to bring the nuclides of the crust closer to stability. Such an effect is more pronounced for cells in the depth of the outer crust. For these calculations, experimental, as well as extrapolated masses are taken from [11]. When extrapolations are not available, an analytical parametrization with parameters fitted from the Sly4 energy density functional is used [12]. In the density and temperature domain shown in the figure, this functional calculation is needed as the extrapolated masses from [11] do not cover the whole (N,Z) relevant domain. Concerning level densities, experimental data are taken when available for the ground state degeneracy; a parametrized back-shifted Fermi-gas formula fitted on the whole neutron resonance experimental information on the low-lying excited states is used for the excited states [13]. Finally, free nucleons present at finite temperature are included within the self-consistent density functional approach, with the same Sly4 effective interaction as for the exotic clusters.

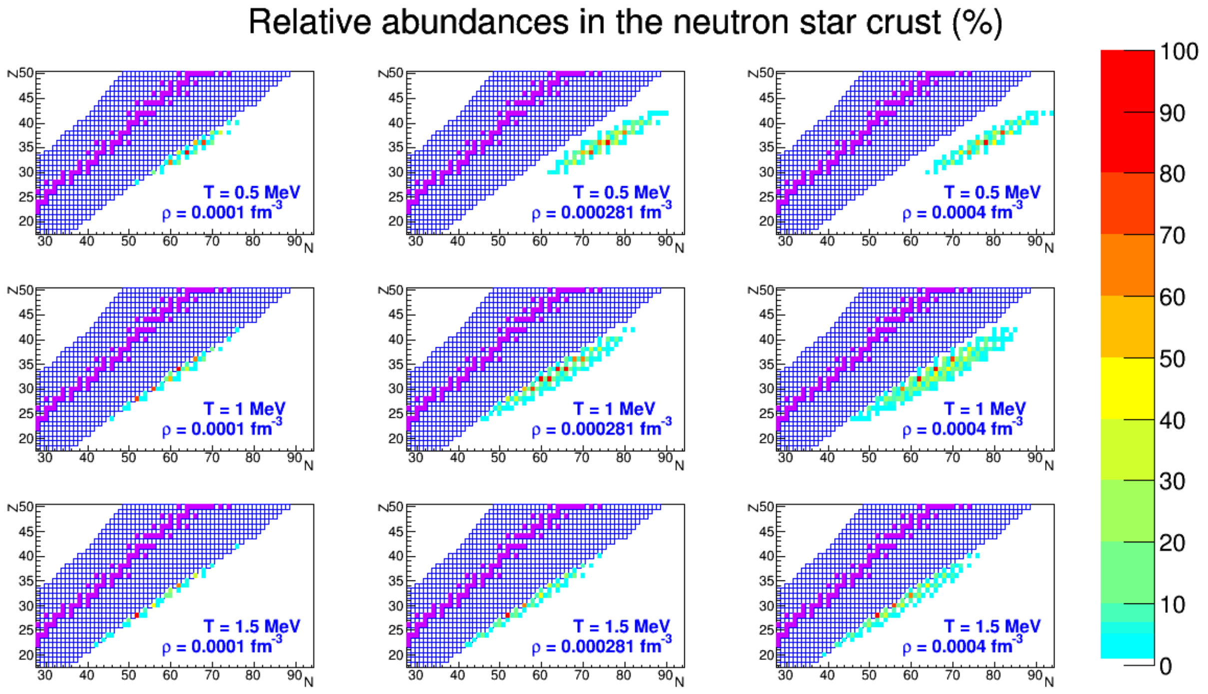

Figure 1: Composition of the outer crust as a function of temperature and density [5].

Experimental objectives

We propose to perform mass measurements of the most exotic neutron-rich Ge, Se and Kr isotopes with the ISOLTRAP experiment [14-16]. The long-term aim is to put more constraints on the mass model predictions of the different dripline isotopes of Ge, Se, Kr, Sr, Zr, Mo, Ru, Pd, Cd, Sn which compose the depth of the outer crust [4]. Apart from the Penning-trap mass-spectrometry technique, which has been used over two decades [14], the ISOLTRAP setup can now additionally use a multi-reflection time-of-flight mass spectrometer (MR-ToF MS) for mass measurements with an uncertainty below 10^{-6} [15, 17]. Both types of measurements are proposed for the nuclides of interest. The proposed experimental program would also benefit from recent target and ion source developments.

The mass region around A=100, Z=36 has been approached by several setups using Penning-trap mass spectrometry. It is shown in Fig. 2, together with the predictions of abundances of nuclides for a temperature of 500 keV and a density of 10^{-4} fm^{-3}. Mass measurements in this region were mostly motivated by the study of the N=50 shell gap far away from stability towards ^{78}Ni, and the study of the large deformation appearing for N>60 and Z>36. Masses of the neutron rich Kr [18,19], Rb and Sr [20,21] were measured by ISOLTRAP and TITAN at TRIUMF, while JYFLTRAP has been harvesting masses of Ga, Ge, As, Se [22] and Sr, Y, Zr, Nb [23-25]. Measurements of very neutron rich $^{100\text{-}102}$Sr and $^{100\text{-}102}$Rb isotopes were very recently done using the Penning-trap and MR ToF MS techniques at ISOLTRAP [26], and are still under analysis. This astrophysics proposal aims at extending these measurements to the most neutron rich isotopes of Ge, Se and Kr accessible at ISOLDE, of particular interest for the neutron star crust composition.

The krypton isotopic chain was also proposed to be the boundary of the quantum phase transition at N = 60 in agreement with the body of experimental data measured so far (see [19] and references therein). As discussed in [21], a mean-field configuration of large prolate deformation is predicted to emerge in the krypton isotopic chain at a larger neutron number than in the chains with *Z* > 36. Whether a transition to a ground-state dominated by this configuration eventually takes place in the krypton chain depends on the fine interplay between the (oblate and prolate) mean-field configurations, as well as the mixing between them. Mass measurements of the more neutron rich krypton isotopes are necessary to delineate the region of deformed *A* ≈ 100 nuclei.

Beam-time request

While the Ge and Se beams need to be developed, the ISOLDE database [27] quotes promising yields up to ^{99}Kr using the old MK7 FEBIAD ion source. With the newly developed VD7 ion source, an improvement factor of 2-4 is expected on the tabulated yields. An anode body in Ta instead of Mo could be used, as it was previously done with VD7, to avoid the contamination of the ^{100}Kr isotopes by a beam of a few pA of ^{100}Mo. Beyond *A*=98, the isotopes of interest combine low yields and short half lives, so that using Penning-trap mass spectrometry in this region will be difficult. It is therefore proposed to use the MR-ToF MS for the most exotic masses.

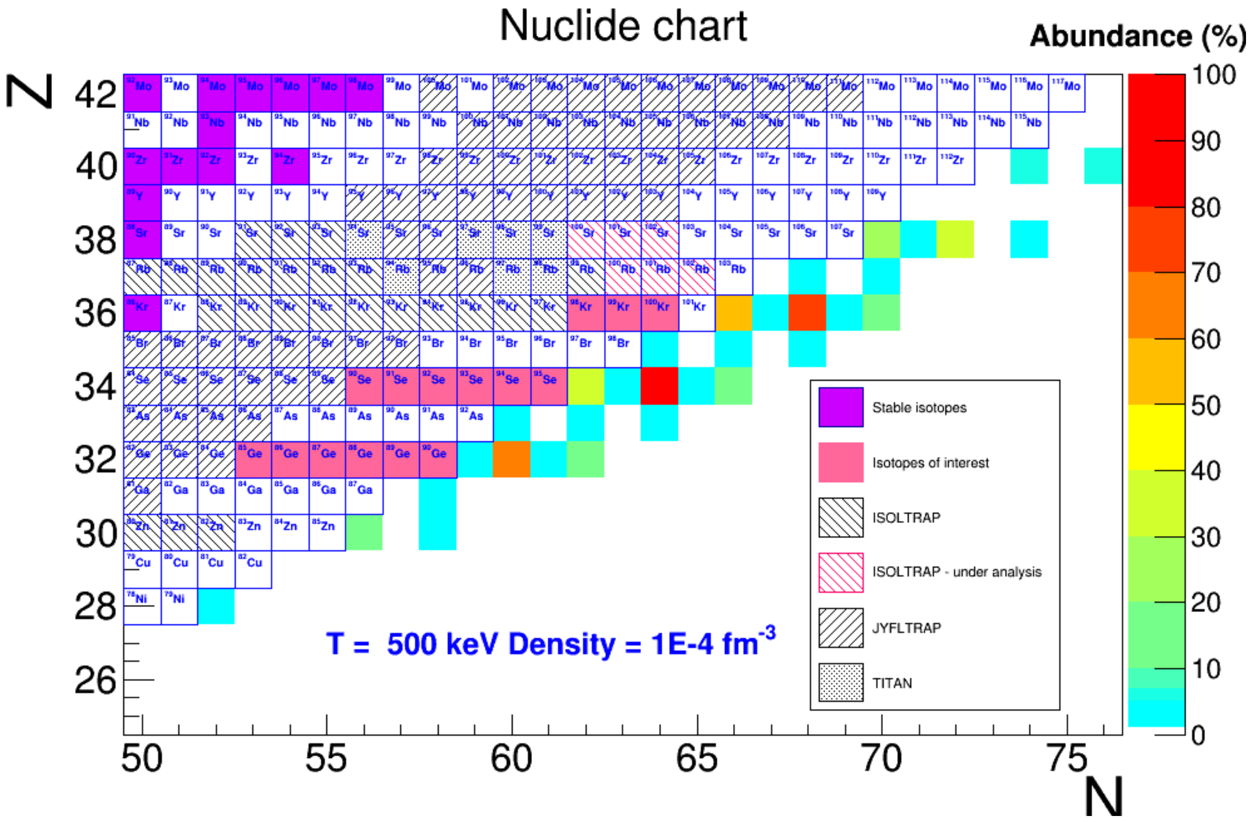

Figure 2: Region of interest. Nuclides whose mass was already measured by Penning-trap mass spectrometry are hatched. The color scale presents the relative abundance of nuclides predicted for a temperature of 500 keV and a density of 10^{-4}fm^{-3}.

Table 1 presents for the Kr isotope the yields quoted in [27], and the proposed technique. The precision required to constrain the mass models for the neutron star crust composition is of the order of 50 keV. In the right hand column, the measurement time is estimated according to the technique proposed. In the case of a Penning trap measurement, formula (4) of ref [28] has been used, assuming that 1000 ions are needed to perform a reasonable measurement, and an overall efficiency of 10^{-3} for the ISOLTRAP spectrometer. In the case of an MR-ToF MS measurement, the time was estimated based on the statistics which were required to reach the accuracies obtained during the $^{52-54}$Ca mass measurements [17] and beam times from 2014. For MR-ToF MS measurements, apart from the data collection some additional time is required for identifying reference isotopes from the on-line beam, using the precision Penning trap (typically one shift per isotope). This time is included in the request. The preparation time is related to the optimization of the plasma-source parameters, ISOLTRAP trapping cycles (considering the charge-exchange losses in the buffer gas environment of the preparation traps) as well as the beam purification approach (which depends on the specific beam content). These optimizations can only be performed on-line. We ask for beam time on the HRS, in order to remove potentially abundant contamination which could be resolved by the separator.

In Tab. 1 the potential yield improvement related to the use of VD7 instead of MK7 has not been taken into account. 12 shifts are requested for the mass measurements of the $^{97-99}$Kr isotopes. In the case of the most exotic ^{100}Kr nuclide, no yield has yet been measured. We request 2 shifts for identification, yield measurement and target ion-source optimization, and 2 additional ones for an eventual mass measurement if it is found that the yield is high enough. The newly tested, micro-structured, carbon nanotube UCx could be a good alternative to the standard UCx target. Such a target was recently tested in the frame of ENSAR (Actilab JRA), providing high yields of short-lived K and Rb isotopes. It would be particularly suited to the production of short half-life isotopes of interest in this proposal.

A	Element	Half life (ms)	δm (keV)	Yield (ions/μC)	Method proposed	Measurement time (UT=8h)
97	Kr	62.2	130	6500	Penning//MR-ToF	6
98	Kr	42.8	300#	470	Penning//MR-ToF	
99	Kr	40	500#	9	MR-ToF	4
100	Kr	12	400#	-	MR-ToF	2 (+2)
		Kr beamtime		**Preparation**		2
				Total (UT)		**16**

Tab. 1: List of isotopes of interest. Present precisions on masses (δm) are from reference [29]. # means that the masses are extrapolated rather than measured. The yields are from [27]. The right hand column gives the time proposed for the different mass measurements.

Compared to the Kr isotopes, the most neutron rich Ge and Se beams suffer from longer release times and a strong contamination of Rb from the VD5 ion source. The Ge and Se isotopes of interest for this proposal are presently out of reach using the standard UCx targets and FEBIAD ion source. We therefore ask for target – ion source R&D in a letter of intent submitted in parallel to this proposal.

Perspectives

This experiment would constitute the first step of a mass measurement campaign linked to the study of neutron stars at the SPIRAL2-S3 facility. Using the benefits of the intense uranium beam delivered by the heavy-ion source of the SPIRAL2, accelerated to around 6 MeV/u by the LINAC, very exotic neutron rich Zr, Mo and Ru isotopes could be produced through fission reactions of the projectiles on a thin carbon target unit. The reaction products of interest would be thermalized and neutralised in a buffer gas cell (REGLIS3 device). They will be transported toward the exit hole by the gas flow and evacuated through a de Laval nozzle. The coupling with a narrow-bandwidth, high-power, high-repetition rate, pulsed laser system will assure the selective and efficient ionization of the atoms of interest. Placed at the exit of the gas cell, a series of radiofrequency quadrupoles will capture the photo-ions and guide them to the low-pressure zone thereby achieving good emittance of the produced beam prior to its injection into the PILGRIM mass spectrometer (MR-ToF MS). The S3-LEB (using the PILGRIM MR-ToF MS) setup would give access to shorter-lived isotopes mass measurement with respect to the IGISOL (double Penning trap) facility. The expected mass accuracies accessible with such technique, around 30 keV, will be sufficient to probe efficiently the mass model (HFB / Skyrme HF) calculations.

Summary of requested shifts:

As indicated in Tab. 1 we request 16 shifts for the mass measurements of the most neutron rich Kr isotopes. Among these, 2 are dedicated to the yield measurement of ^{100}Kr, and 2 additional ones are conditioned by this latter. The Ge and Se beams of interest in this proposal are presently out of reach using the standard UCx targets and FEBIAD ion source. We therefore also ask, in a separate letter of intent, for dedicated R&D on very neutron rich ISOL Ge and Se beams.

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Appendix

Description of the proposed experiment

The experimental setup comprises: ISOLDE central beam line and ISOLTRAP setup. The ISOLTRAP setup has safety clearance, the memorandum document 1242456 ver.1 “Safety clearance for the operation of the ISOLTRAP experiment” by HSE Unit is released and can be found via the following link: https://edms.cern.ch/document/1242456/1.

Part of the Choose an item.	Availability	Design and manufacturing
ISOLTRAP setup	☒ Existing	☒ To be used without any modification