

# EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

## Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee

### Ge and Se beam developments for constraining the neutron star crust via mass measurements

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### Abstract

We ask for the development of very neutron rich Ge and Se beams to perform mass measurements in the region  $A \sim 100$  and  $Z \sim 36$ , taking advantage of the most advanced mass measurement techniques at ISOLTRAP. This mass region is of particular interest to probe mass models used in the calculation of the composition of neutron stars at finite temperature. At present these Ge and Se neutron rich beams both suffer from a large alkali contamination, and from release times which are not compatible with the half-life of the isotopes of interest ( $< 1s$ ).



# 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  $10^{-4} < \rho < 10^{-3} \text{ fm}^{-3}$  (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 [2-5]). 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  $^{82}\text{Zn}$ , 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  $^{80}\text{Zn}$  and the replacement of its successor  $^{82}\text{Zn}$  by  $^{78}\text{Ni}$  or  $^{79}\text{Cu}$  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 ( $0.6 \cdot 10^{10}$  to  $1.7 \cdot 10^{10}$  K) and from  $10^{-4}$  to  $4 \cdot 10^{-4} \text{ fm}^{-3}$  ( $1.7 \cdot 10^{11}$  to  $6.6 \cdot 10^{11} \text{ g/cm}^3$ ). 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.

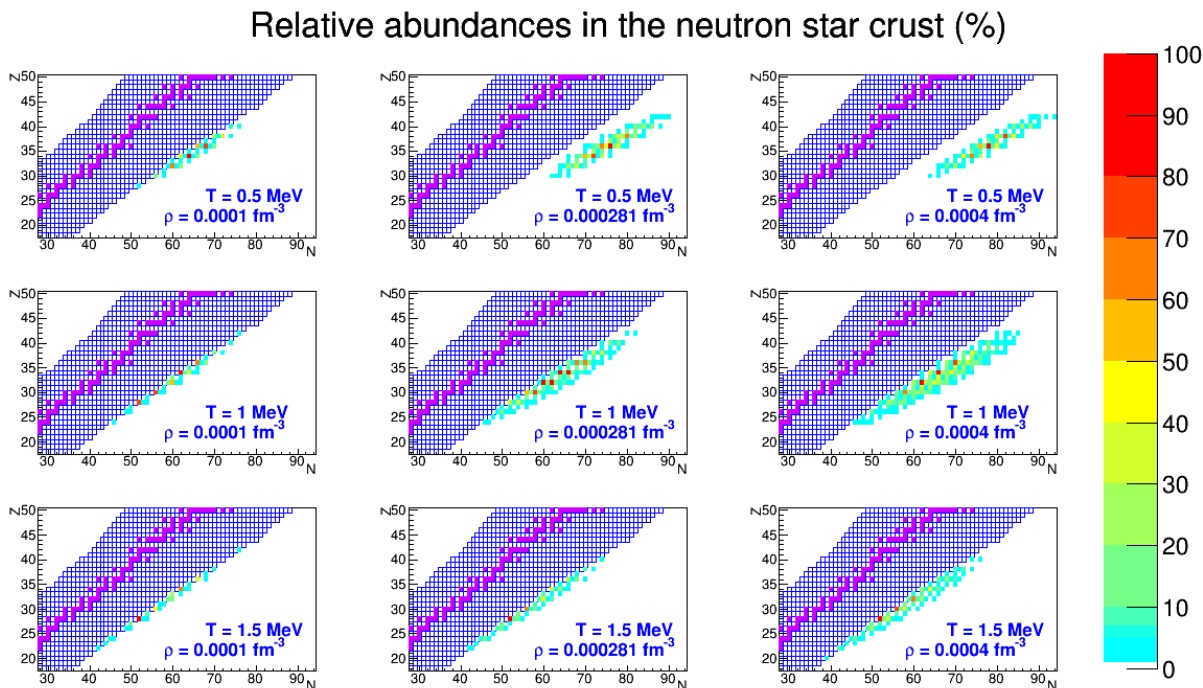


Figure 1: Composition of the outer crust as a function of temperature and density [5].

## 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<sup>-3</sup>. Mass measurements in this region were mostly motivated by the study of the  $N=50$  shell gap far away from stability towards  $^{78}\text{Ni}$ , 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  $^{100-102}\text{Sr}$  and  $^{100-102}\text{Rb}$  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.

## Ge and Se neutron rich beams

While the ISOLDE database [27] quotes promising yields up to  $^{99}\text{Kr}$  using the old MK7 FEBIAD ion source, the Ge and Se beams need to be developed. The Kr beams have been asked for in parallel in a separate proposal. 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 FEBIAD MK5 or VD5 ion source. The shortest half lives quoted in [27] for these elements are 4.6s for  $^{82}\text{Ge}$  and 5.3s for  $^{87}\text{Se}$ , with respective yields of  $7 \cdot 10^4$  ions/ $\mu\text{C}$  from an UCx target and  $5.6 \cdot 10^4$  from a Ta target. The MR-ToF MS requires a few ions per second at minimum for a mass measurement. It can purify a beam whose contamination is 3 orders of magnitudes more abundant than the beam of interest [17]. Even with these performances, the region of interest in Fig. 2, where half-lives are well below 1s and are often only estimated, would not be accessible for mass measurements with a standard UCx target and an old MK5 ion source.

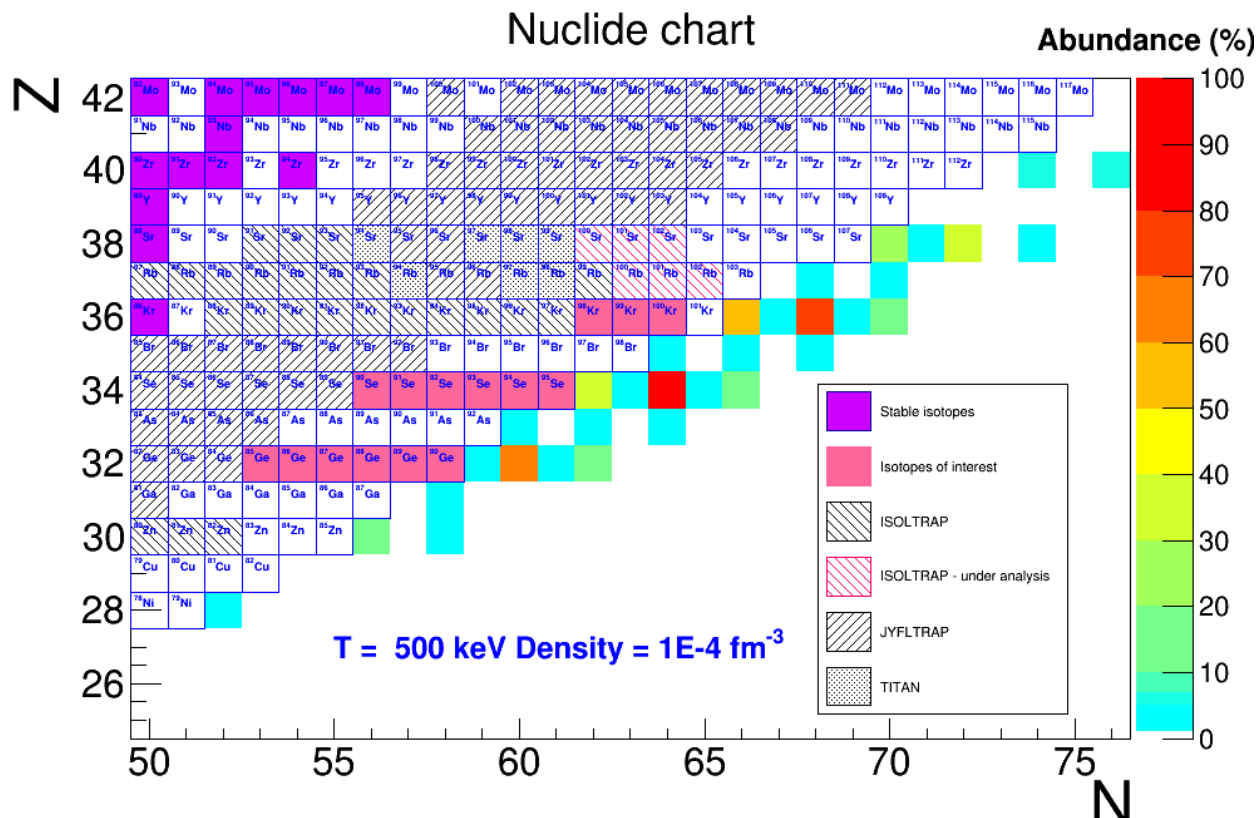


Figure 2: Region of interest. Nuclides whose mass was already measured by Penning-trap mass spectrometry are hatched. The color scale presents the relative abundance of nuclides predicted for a temperature of 500 keV and a density of  $10^{-4} \text{ fm}^{-3}$ .

Molecular beams (eg  $\text{GeS}^+$ ,  $\text{SeF}^+$  or  $\text{SeCO}^+$ ) have been used in the past to tackle the contamination problem. The formation of molecules can additionally speed up drastically the effusion process [28]. Here it is proposed to test new target ion source combinations which would permit the production of short half-life Ge and Se isotopes with improved beam purity. The production of pure beams of Ge and Sn from sulphide molecules has already been tested (see eg [29]). Such a method will be further investigated for the production of neutron rich Sn at HIE-ISOLDE coupling the VD5 ion source with a carbon nanotube, micro-structured target, which has been recently tested in the frame of the ENSAR Actilab JRA. Improved yields of short-lived isotopes of K and Rb were already obtained from such a target. It is proposed here to extend these tests to the neutron rich Ge isotopes. Alternatively to the

molecular formation and ionization in VD5, a laser ionization scheme recently tested for the development of neutron deficient Ge isotopes could be possibly used [30]. For the production of short-lived Se isotopes, it is proposed to test the coupling of a ThOx target with a hot VD5 source to form SeCO<sup>+</sup> molecules. SeCO<sup>+</sup> were successfully used for producing neutron deficient Se isotopes from ZrO<sub>2</sub> targets (see eg [31]).

For the Ge and Se yield measurements, the MR-ToF MS of ISOLTRAP could possibly be used. Such a setup offers a unique identification technique. A sensitivity on the order of 1 ion per second has already been demonstrated. It would therefore be particularly suited to the proposed beam development.

## Perspectives

These mass measurements 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.

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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	<input checked="" type="checkbox"/> Existing	<input checked="" type="checkbox"/> To be used without any modification