Access to proton and neutron radial distributions using Δ resonance excitation in isobar charge-exchange reactions

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Abstract

We propose a novel technique to prove in the same experiment proton and neutron radial distributions by measuring the cross section for Δ resonance excitation in isobar charge-exchange reactions. Using inverse kinematics we can isotopically identify the isobar charge-exchange channels at the FRagment Separator (FRS). Moreover, the high resolving power of the FRS allows to separate the quasielastic and resonant charge-exchange processes in the longitudinal momentum distribution of the recoiling projectile residue. According to the Glauber multiple-scattering theory the cross sections for the isobar proton and neutron pickup processes will provide a probe sensitive to the neutron and proton radial distributions in nuclei. In this first experiment we propose to investigate the excitation of the Δ resonance in nuclei with different neutron excess (Sn isotopes) and try to relate these measurements to the proton and neutron radial distributions.

1 Motivation

The nuclear symmetry energy is an important ingredient in the description of properties of proto-neutron stars. The equation of state, the proton fraction and the pressure are strongly affected by the density dependence of the symmetry energy in nuclear matter [1]. Present predictions for the symmetry energy vary substantially (28-38 MeV) and experimental constraints from finite nuclei are required. At supranormal densities ($\rho > \rho_o$), the proton-neutron diffusion in heavy ion reactions is used [2] while at sub-saturation densities ($\rho < \rho_o$) collective excitations (GDR or SDR) or static properties (masses or neutron-skin thicknesses) of nuclei provide constraints to the symmetry energy [3]. Unfortunately, for most of these processes the relation between the observables and the symmetry energy is model dependent, being the neutron-skin thickness one of the observables more directly related.

Several techniques are being used to determine proton and neutron radii. Proton radii can be accurately determined from electron scattering or isotope shifts in laser

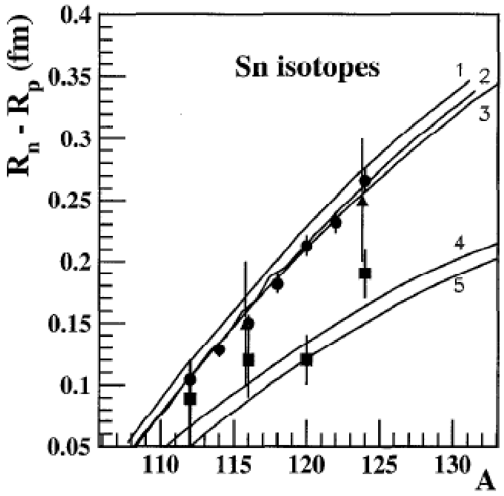

Figure 1: *Neutron-skin thickness of Sn isotopes obtained from GDR and SDR measurements (full circles), antiprotonic atoms (full triangles) and (p,p) reactions (full squares), compared to Hartree-Fock calculations with forces using different symmetry energy values (see Ref. [11] for details).*

spectroscopy [4], although for the moment only the latter can be used with exotic nuclei. The situation in determining the neutron or matter radii is much worse. Several techniques are based on strong probes, hadron [5] or π^- [6] scattering, antiprotonic atoms [7] and more recently antiproton annihilation [8, 9]. Parity-violating electron scattering [10] and collective excitations in nuclei (GDR and SDR) [11] are also used. However, for most of these techniques, the determination of the neutron radius is model dependent and they do not provide conclusive results on the magnitude of the symmetry energy as shown in Fig.1. Here we propose a novel technique allowing to prove in the same experiment the proton and neutron radial distribution of nuclei with half-lives longer than 300 ns.

2 New method for proton and neutron r.m.s radii determination.

The method we propose is based in the excitation of the Δ resonance in isobar charge-exchange reactions. According to the Glauber scattering theory, the relative probability for the two possible processes in isobar charge-exchange reactions, proton (N,Z)⟶(N-1,Z+1) and the neutron (N,Z)⟶(N+1,Z-1) pickup, is determined by the radial distribution of neutrons and protons in the nuclei.

Above the pion production threshold the charge-exchange process takes place

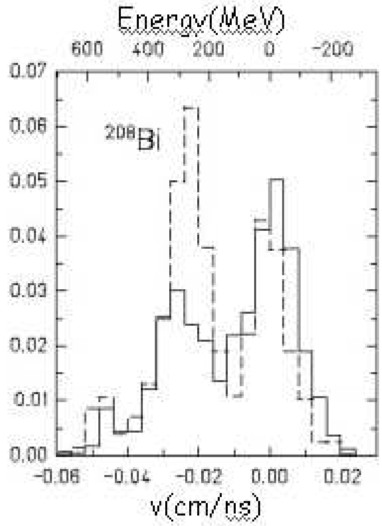

Figure 2: *Velocity distribution in the frame of the projectile of* ^{208}Bi *produced in proton pickup reactions induced by* ^{208}Pb *projectiles on a proton target at 1 A GeV obtained with the FRagment Separator [18].*

not only through the quasi-elastic channel but also through the Δ resonance excitation. While the quasi-elastic charge-exchange depends on the Gamow-Teller transition strengths of the nuclei involved [12], the probability for the latter process is well established by the inelastic nucleon-nucleon cross section and the probabilities for exciting the different Δ isobars and their decays given by the isobar model [13]. This reaction channel corresponds to a single nucleon-nucleon collision leading to the excitation of a Δ resonance decaying into a π^+ or π^- escaping from the nucleus.

The relation between pion production and the nuclear shape was proposed long ago [14] and the relative production of π^- and π^+ has even been used to characterise the difference between proton and neutron radial distributions in halo nuclei [15, 16]. Here we do not propose to measure the pion production but to identify the projectile momentum downshift produced by the Δ resonance excitation in isobar charge-exchange reactions investigated in inverse kinematics. This momentum downshift due to the Δ resonance excitation was observed by Greiner long ago [17] and more recently by Kelic [18] at the FRagment Separator (FRS) at GSI, as shown in Fig. 2.

Therefore, we propose to use the FRS to identify both isobar charge-exchange channels, the proton and neutron pickup, and determine from the momentum analysis of the final residues the cross sections of the resonant processes, as demonstrated in Fig. 2. The same experiment will also allow to easily determine the total absorption cross sections of the incoming projectiles providing additional information on the r.m.s matter radius. According to preliminary Glauber calculations describing these reactions, a measurement of the cross section of the Δ resonance excitation in both isobar charge-exchange channels with an accuracy of 10% will allow us to determine proton and neutron r.m.s. radii with a sensitivity of 0.05 fm.

The technique we propose here could be subject of a full experimental program to be initiated at the present FRS and continued at the future Super-FRS at FAIR. However, in this first experiment we want to demonstrate the feasibility of the technique, in particular investigate the excitation of Δ resonances in nuclei with different neutron excess and the sensitivity we obtain to the proton and neutron radial distributions. To this aim we propose to measure the Δ resonance excitation in isobar charge exchange reactions in several Sn isotopes. We will use two beams, ^{124}Sn and ^{112}Sn, allowing to prove the method with stable nuclei, small beam emittance and high statistics. We will then produce two secondary beams, ^{118}Sn and ^{106}Sn, fragmenting the stable ones. In order to investigate the role of the target nature we propose to use two targets H_2 and ^{12}C. Finally, we also require two energies per beam, 500 and 1000 A MeV, since we expect a sensitivity to different regions of the nuclear surface with the energy due to the evolution of the total inelastic nucleon-nucleon cross section.

3 Experimental setup

In Fig. 3 we depict the experimental setup we propose for this experiment. In order to investigate the charge-exchange reactions with the stable beams, ^{124}Sn and ^{112}Sn, we will transport these beams until the intermediate image plane of the FRS where we will place the charge-exchange targets, H_2 and ^{12}C. The residues will be analysed in the second section of the FRS. The time of flight between scintillators SC2 and SC4, the magnetic rigidity from the position measurements with the TPCs at the final image plane and the energy-loss measurement in the ionisation chamber (MUSIC2), also at the final image plane, will allow us to unambiguously identify the isobar charge-exchange channels with typical resolutions $\Delta Z/Z \approx 7\ 10^{-3}$ and $\Delta A/A \approx 2.4\ 10^{-3}$. The momentum analysis of the residues obtained from the magnetic rigidity will be used to isolate the resonant reactions.

To investigate the experimental feasibility with unstable nuclei, the primary beams, ^{124}Sn and ^{112}Sn, will be transported until the entrance of the FRS where we will locate a Be fragmentation target to produce ^{118}Sn and ^{106}Sn, respectively. The forward emitted fragmentation residues, in particular ^{118}Sn and ^{106}Sn, will be magnetically selected by the first section of the FRS. For their isotopic identification we will equip this section of the FRS with a 3 mm thick plastic scintillator (6x15 cm^2) placed at the first image plane (SC1 in figure 3), and a fast ionisation chamber at the intermediate image plane (MUSIC1). The SC1 scintillator, together with the SC2 scintillator will provide the time-of-flight measurement of the fragments on a flight path of 18 m. This measurement together with the magnetic rigidity obtained from the dipoles of the first section of the FRS and the TPCs chambers at the intermediate image plane of the spectrometer will provide the A/Q identification. The additional measurement of the

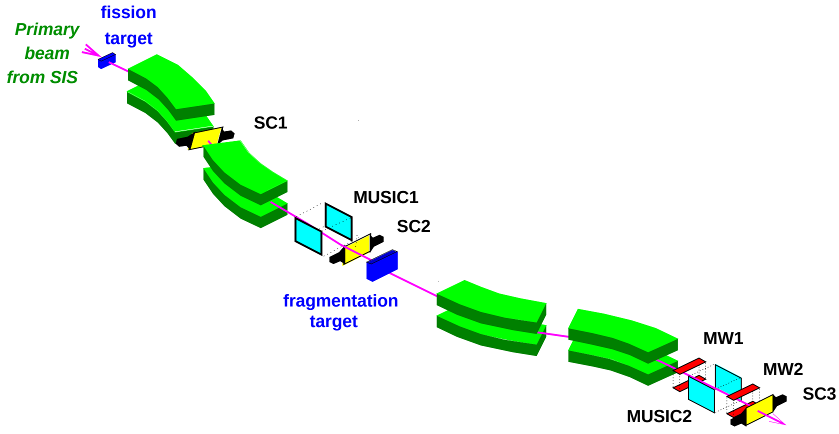

Figure 3: *Proposed experimental setup*

energy loss of the transmitted fragments in a fast ionisation chamber located at the second image plane of the FRS will provide their atomic number and the full isotopic identification of the fission residues. The proposed ionisation chamber MUSIC1 is able to determine the atomic number with a resolution around $\Delta Z/Z \approx 5\ 10^{-3}$ and an acquisition rate of 100 KHz [19]. This acquisition rate ensures the complete identification of all residues transmitted till the intermediate image plane of the FRS. Assuming an absolute time resolution of 150 ps and the magnetic-rigidity resolution of the FRS ($\Delta B\rho/B\rho \approx 3\ 10^{-4}$) one can expect a mass resolution around$\Delta A/A \approx 4.5\ 10^{-3}$. This resolution for the mass 135 is equivalent to the one obtained around the mass 240 with the standard 35 m flight path of the second section of the FRS.

The fully identified ^{118}Sn and ^{106}Sn fragments will impinge onto the charge-exchange targets located at the intermediate image plane of the FRS. As already explained, the charge-exchange residues will be then isotopically identified in the second section of the spectrometer.

4 Beam time request

We request two stable beams, ^{124}Sn and ^{112}Sn (with an estimated difference in neutron-skin thickness between 0.1 and 0.2 fm), two energies per beam (500 A MeV and 1000 A MeV) and for some cases we will use two charge-exchange targets, H_2 and ^{12}C. To validate the experimental separation of the resonant channel with secondary beams, we will use these stable beams to produce other Sn isotopes by fragmentation, ^{118}Sn and ^{106}Sn, respectively. For each of the four Sn isotopes we will measure the total absorption cross section as well as cross sections of the isobar neutron and proton pickup processes. In order to minimise the statistical uncertainty we will require few thousand events per measurement.

Table 1: Beam time request

Main beam time			
projectile	1^{st} FRS section	2^{nd} FRS section	beam time
^{124}Sn (500 and 1000 A MeV)	FRS calibrations		1 day
^{124}Sn (500 and 1000 A MeV)	^{124}Sn	^{124}Sn, ^{124}Sb, ^{124}In	1 day
^{124}Sn (500 and 1000 A MeV)	^{118}Sn	^{118}Sn, ^{118}Sb, ^{118}In	3 days
^{112}Sn (500 and 1000 A MeV)	FRS calibrations		1 day
^{112}Sn (500 and 1000 A MeV)	^{112}Sn	^{112}Sn, ^{112}Sb, ^{112}In	1 day
^{112}Sn (500 and 1000 A MeV)	^{106}Sn	^{106}Sn, ^{106}Sb, ^{106}In	3 days

Total requested beam time	
^{124}Sn (500 and 1000 A MeV)	5 days
^{112}Sn (500 and 1000 A MeV)	5 days

According to preliminary estimates and previous measurements [20] the expected cross section for the Δ resonance excitation in isobar charge-exchange reactions in nuclei with a neutron-skin thickness of 0.2 fm is is around 0.5 mb for the proton pickup channel and 20 μb for the neutron pickup. The required statistics for these channels can be obtained with the stable Sn isotopes in a few hours measurement. All proposed measurements with two energies and two targets could be done with 1 day of beam time. However, for the unstable beams the neutron pickup channel will require around 1 day per energy and half additional day per energy for the total absorption and proton pickup channels. Limiting this case to one target we will need 1,5 days of beam time per energy (3 days). Our final request including 1 day per beam for the FRS calibration is summarised in table 1

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