IL NUOVO CIMENTO **39 C** (2016) 401
DOI 10.1393/ncc/i2016-16401-0

Colloquia: IWM-EC 2016

Exciting baryon resonances in isobar charge-exchange reactions

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received 10 January 2017

Summary. — Isobaric charge-exchange reactions induced by different tin isotopes have been investigated at GSI. The high-resolving power of the FRS spectrometer made it possible to separate elastic and inelastic components in the missing-energy spectra of the ejectiles. The inelastic component was associated to the in-medium excitation of nucleon resonances such as the Delta and Roper resonances. These data are expected to contribute to better understand the in-medium properties of baryon resonances but also to investigate the abundance of protons and neutrons at the nuclear periphery.

1. – Introduction

Charge-exchange reactions are unique probes to investigate spin-isospin excitations in nuclei. The broad range in energy that can be covered with these reactions makes it possible to induce charge-exchange processes through nuclear (Gamow-Teller, spin-dipole, spin-quadrupole, ...) [1] or subnuclear (nucleon resonances) [2] excitations. During the 80's, subnuclear charge-exchange reactions were extensively investigated at Saturne (France) by measuring the ejectile missing energy spectra in relativistic heavy-ion charge-exchange reactions [3]. One of the main results of this research program was the observation of a downward shift of the mass of the delta resonance attributed to in-medium modifications of the baryon resonances.

The in-medium properties of baryon resonances such as the $\Delta(1232)$ or the Roper ($N^*(1440)$) resonance are also of importance for the understanding of three-body forces

[4,5] or the not fully solved problem of the missing Gamow-Teller strength [6]. Moreover, the excitation of baryon resonances in heavy-ion (p,n) and (n,p) reactions has also been proposed to explore the radial distribution of protons and neutrons in nuclei [7].

To investigate baryon resonances in asymmetric nuclear matter we used isobaric charge-exchange reactions induced by relativistic beams of stable and unstable projectile nuclei. These reaction channels guarantee that with a large probability the charge-exchange process is mediated by a quasi-free nucleon-nucleon collision. In the case of inelastic nucleon-nucleon collisions the excited nucleon resonances, produced in the overlapping region between projectile and target nuclei, decay by pion emission. To preserve the initial number of nucleons in the projectile remnant, pion decay should not induce any sizable excitation energy in the projectile, leaving then this nucleus without any further interaction. Due to the strong absorption of the pion, we can then conclude that these reactions must be very peripheral.

In this paper we will describe the experiment we performed at GSI using beams of stable (^{112}Sn and ^{124}Sn) and unstable (^{120}Sn and ^{110}Sn) tin isotopes to induce isobaric charge exchange reactions. We will detail the experimental technique and set-up and we will present preliminary results.

Projectile residues were identified and momentum analysed using the zero-degree magnetic spectrometer FRagment Separator (FRS) [8]. The momentum resolution of this spectrometer was proved to be sufficient to clearly identify the elastic (Gamow-Teller) and inelastic (nucleon excitations) components in the missing-energy spectra of projectile residues in isobaric charge-exchange reactions [9].

2. – The experiment

2·1. *Experimental technique and set-up.* – The experiment was performed at GSI (Germany) where the SIS18 synchrotron delivered beams of ^{112}Sn and ^{124}Sn with energies between 400 and 1000 A MeV and intensities around 10^8 ions per second. High-resolution measurements of the missing-energy spectra of the ejectiles produced in isobaric charge-exchange reactions induced by these primary beams were obtained by using thin targets of carbon, polyethylene, copper and lead from the target station located at the entrance of the fragment separator. Secondary beams of ^{122}Sn, ^{120}Sn and ^{110}Sn were produced fragmenting the primary beams of ^{112}Sn and ^{124}Sn in a beryllium target also located at the entrance of the spectrometer. The secondary beams were identified and separated with the first section of the fragment separator. Targets made of carbon and polyethylene were placed at the intermediate image plane and the isobaric charge-exchange residues identified in the second section of the spectrometer. In this case and due to the lower intensities of the secondary beams, around 10^3 ions per second, thicker targets were use to obtain a minimum statistics in the measurements.

The fragment separator (FRS) is a zero-degree high-resolving power spectrometer with a typical resolving power of $B\rho/\Delta B\rho \approx 1500$, a momentum acceptance of $\Delta p/p \approx 3\%$ and and angular acceptance around the central trajectory around 15 mrad. The FRS is an achromatic spectrometer made of two symmetric stages with a dispersive intermediate image plane [8]. The spectrometer can be used in a single and a two-step reaction modes. In the first case the reaction target is placed at the entrance of the FRS and the complete spectrometer is used to separate and identify the projectile residues (see, *e.g.*, [10]). In the two-step reaction model the target used to produce the secondary beams is placed at the entrance of the spectrometer and the secondary beams are identified and separated with the first section of the FRS (see, *e.g.*, [11]). The reaction target

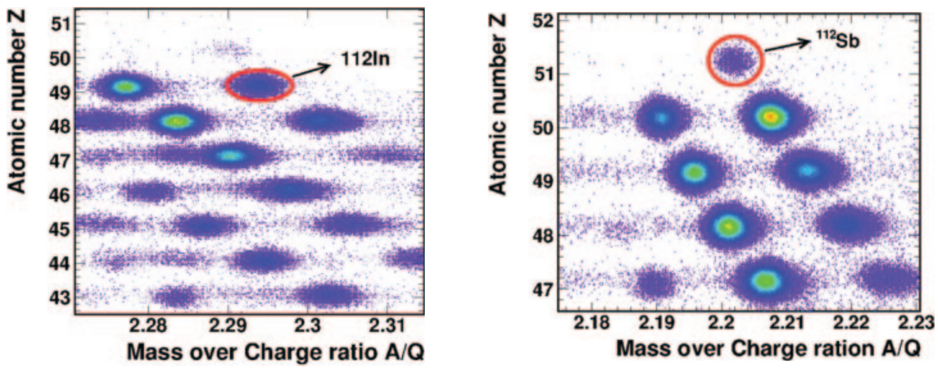


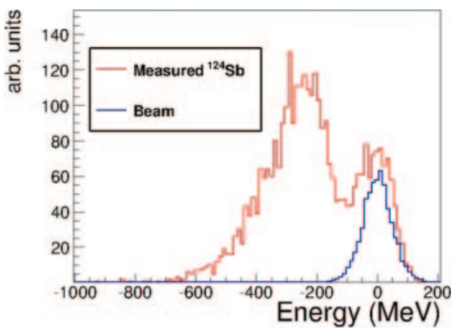
Fig. 1. – Identification matrices of the two isobar charge-exchange channels, (p,n) in the left panel and (n,p) in the right panel, which are produced in reactions induced by ^{112}Sn projectiles impinging a carbon target at 1000 A MeV.

is thus located at the intermediate image plane and the reaction fragments identified with the second section of the FRS. In both modes projectile residues are identified by measuring the $B\rho$, velocity and energy loss of the projectile residues using high-resolution time-projection chambers for tracking, scintillator detectors for time-of-flight and multi-sampling ionization chambers for energy loss. These measurements also allow for the accurate determination of the longitudinal momentum of the reaction products.

2˙2. *Observables*. – With the measurements provided with the FRS we could define two important observables for the characterization of the isobar charge-exchange reaction, the cross section of the process and the ejectile missing energy spectra. Cross sections were accurately determined from the yields of the final reaction residues obtained in the corresponding identification matrices, as the one shown in fig. 1, the number of scattering centres per surface unit in the target and the number of incoming projectiles determined with a secondary electron monitor placed at the entrance of the FRS. The measured yields were corrected by several factors accounting for the dead time of the acquisition system, fraction of atomic charge states in the final fragments, optical transmission through the FRS and secondary reaction in the target or any other layer of matter along the beam line. A detailed description of the method can be found in ref. [12].

The second observable we used in this work is the missing energy spectra of the recoiling projectile residues. This observable was obtained from the measured longitudinal momentum of the residual nuclei transformed into the reference frame defined by the velocity of the incoming projectiles in the middle of the reaction target. Kelic and collaborators already determined this observable at the FRS for ^{208}Bi residuals produced in isobaric (n,p) reactions induced by ^{208}Pb projectiles impinging hydrogen and deuterium [9]. In these measurements the separation between the elastic and inelastic components in the charge exchange reaction were shown.

In the present experiment we improved the resolution using more precise position measurements for tracking ($\approx 200\,\mu$m), optimizing the FRS optics and, the most important, by reducing angular and energy straggling using thinner targets. In fig. 2 the red line in the left panel represents a typical spectrum of the recoiling energy of ^{124}Sb residual fragments produced in isobaric (n,p) reactions induced by ^{124}Sn projectiles impinging into a carbon target. In this spectrum we observe two clear components, a peak



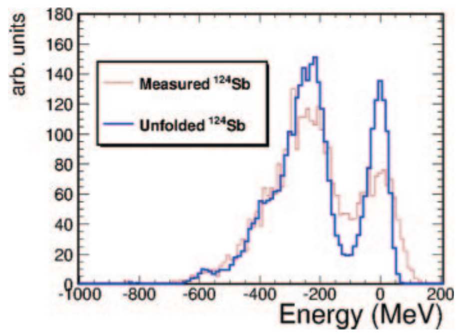


Fig. 2. – Left panel: missing energy spectra of the ^{124}Sb residual fragments produced in isobaric (n,p) reactions induced by ^{124}Sn projectiles impinging in a carbon target.

corresponding to residual nuclei having the same energy as the incoming projectiles, and a second peak for an energy loss around 300 MeV. We associate these two components to elastic spin-isospin nuclear excitations and to the excitation of the Delta resonance.

We additionally improved the resolution of the measured missing energy spectra by unfolding the response of the experimental setup. This response function was defined as the missing energy spectra measured for the unreacted projectiles. Those nuclei were measured in its hydrogen-like charge state in the same magnetic tuning of the FRS used for the measurement of the (p,n) channel, as shown in the left panel of fig. 1. This response function is depicted by the blue line in the left panel of fig. 2. The unfolding procedure used in this work is based on the Richardson-Lucy method with a regularization technique to optimize the stability of the solution against statistical fluctuations [13]. The result of the deconvolution is represented by the blue line in the right panel of fig. 2. As can be observed, the deconvolution clearly improves the separation between the elastic and inelastic charge-exchange components but also enhances some structures in the inelastic component that we will discuss in the next section.

3. – Results

Using the setup described in the previous section we could determine the cross sections and missing-energy spectra of projectile ejectiles issued in isobaric charge-exchange reactions ((p,n) and (n,p)) induced by several tin isotopes (^{110}Sn, ^{112}Sn, ^{120}Sn and ^{124}Sn) accelerated at 400, 700 and 1000 A MeV impinging on CH_2, C, Cu and Pb targets. The combined measurements with CH_2 and C targets made it possible to investigate the reactions induced by protons.

In fig. 3 we report the unfolded missing energy spectra obtained in isobaric charge exchange reactions, (p,n) (left column) and (n,p) (right column), induced by ^{112}Sn projectiles at 1000 A MeV on protons, carbon, copper and lead. In all spectra we observe a clear separation between the elastic and inelastic components of the charge exchange reaction except for the (p,n) channel with protons. In this case, charge conservation forbids the elastic process. In reactions induced on protons the inelastic peak seems to be dominated by a single structure with a mean missing energy around 300 MeV that we associate to the excitation of the Delta resonance in these charge-exchange reactions.

The missing-energy spectra measured in isobaric charge exchange reactions induced on targets heavier than proton show clear substructures in the inelastic component. The

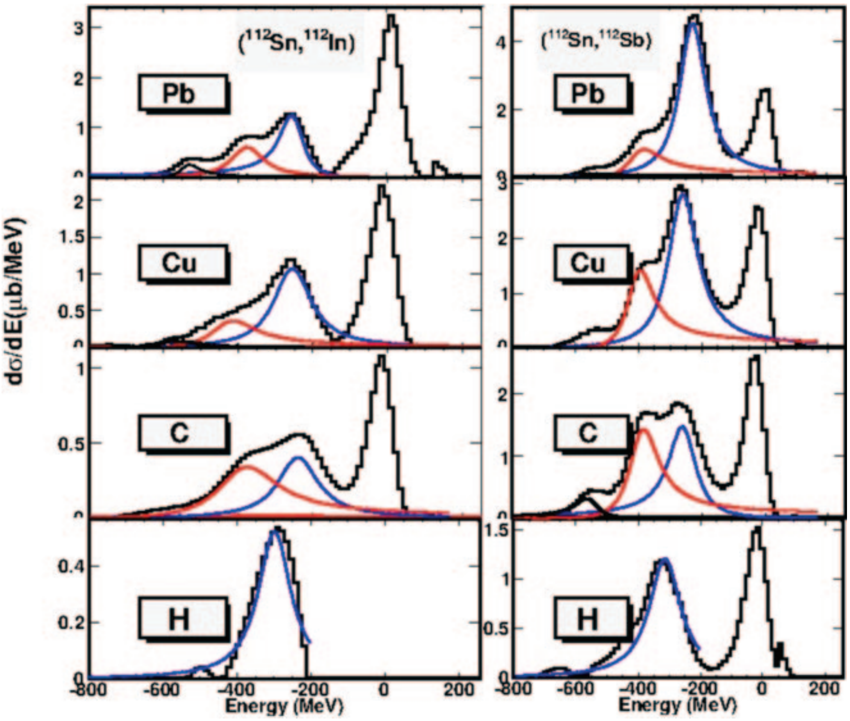


Fig. 3. – Missing energy spectra of the ejectiles measured in isobaric p,n (left panels) and n,p (right panels) induced by ^{112}Sn projectiles on different targets.

dominant structure at 300 MeV seems to correspond to the excitation of the Delta resonance. A second structure is clearly observed around 450 MeV, that we tentatively identify as the Roper resonance. A third structure can also be seen in many cases, although it could not be unambiguously identified. The main structures of the inelastic component in the missing-energy spectra were fitted to generalized Breit-Wigner functions just to guide the eye.

The reduction of these structures in the inelastic component for reactions investigated at lower projectile energies supports our identification of the different nucleon resonances in this isobaric charge exchange reactions. Indeed we observe the disappearance of the structure associated to the Roper resonance at projectile energies below 700 A MeV and the one corresponding to the Delta resonance below 400 A MeV.

The cross sections associated to the elastic and inelastic components of the isobaric charge-exchange process show a clear dependence with the target used to induce the reaction. As expected, the cross sections increase with the size of the target nucleus. We also observe that the cross section of the elastic channel increases for (p,n) reactions with the mass of the target, but not really for the (n,p) ones. This evolution could be understood as a consequence of the relative abundance of protons and neutrons at the target nuclei periphery. Such conclusion can be illustrated with the cross sections obtained with the lead target. In this case, the larger abundance of neutrons at the periphery enhances elastic (n,p) reactions in the target, and therefore the complementary (p,n) reactions in the projectile.

4. – Conclusions

Isobaric charge-exchange reactions induced by several stable and non-stable tin isotopes on different targets, and at energies between 400 and 1000 A MeV have been investigated at GSI. The experimental setup allowed us to measure the cross sections of these processes, but also to determine the missing-energy spectra of the corresponding ejectiles. Due to the large kinetic energies of the projectiles and the high-resolving power of the magnetic spectrometer FRS we could clearly identify in the missing-energy spectra the elastic and inelastic channels corresponding to nuclear spin-isospin and nucleon resonances excitations, respectively. Moreover, we implemented an unfolding method to further improve the resolution of the missing-energy spectra.

The unfolded spectra not only showed a better separation between the elastic and inelastic components but also enhanced additional structures in the inelastic channel. These structures were associated to the excitation of different nucleon resonances. The dominant structure located at a value of the missing energy around 300 MeV was assigned to the Delta resonance. A second structure corresponding to a missing-energy value around 400 was tentatively identified as the Roper resonance. An additional structure for a missing energy around 550 MeV clearly appears in many of the investigated reactions although its identification is still under investigation. Such an effect can be illustrated with the lead target. Since lead has a larger abundance of neutrons at the periphery, (n,p) reactions in the target, and therefore (p,n) in the projectile, will be more probable.

The preliminary results presented in this paper show the potentiality of these measurements. A forthcoming analysis of the missing-energy spectra will allow us to characterize the in-medium excitation of nucleon resonances in terms of its mean mass and width. On going model calculations of these processes benchmarked with the measures cross sections will provide information on the relative abundance of protons and neutrons at the nuclear periphery of the colliding nuclei. Moreover these kind of analysis could be extended with non stable projectiles giving access to the properties of nucleon resonances in asymmetric nuclear matter and the evolution of the relative abundance of protons and neutrons along long isotopic chains.

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