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Experimental study of neutron-rich nuclei near the $N = 82$ closed shell using the $^{96}_{40}$Zr + $^{124}_{50}$Sn reaction with GASP and PRISMA-CLARA arrays

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Abstract.
In this contribution an experimental study of the deep-inelastic reaction $^{96}_{40}$Zr+$^{124}_{50}$Sn at 530 MeV, using the GASP and PRISMA-CLARA arrays, is presented. The experiments populate a wealth of projectile-like and target-like binary fragments, in a large neutron-rich region around $N \geq 50$ and $Z \approx 40$. Preliminary results on the study of the yrast and near-yrast states for ^{95}Nb will be shown, along with a comparison of the experimental yields obtained in the experiments.

Keywords: "Shell Model", "Neutron-Rich Nuclei", "Deep Inelastic Reactions"
PACS: 29.85.-c, 21.10.-k, 23.20.Lv, 25.10.+s, 21.60.Cs

INTRODUCTION

The region of nuclei approaching $N \geq 50$ between the semi-magic $Z = 40$ and the magic $Z = 50$ numbers is a very interesting area of study for both, nuclear structure and nuclear astrophysics. For nuclear structure, the possibility to explore shell and subshell closures in a large neutron-rich region permits to characterize the evolution of nuclear collectivity; for astrophysics, the region provides a unique opportunity to increase our knowledge on nuclei in the path of the *r*-process in nucleosynthesis [1].

During the last decades successful experimental studies of neutron-rich nuclei have been conducted using deep inelastic reactions in conjunction with dedicated experimental arrays, such as the PRISMA-CLARA [2, 3] setup at Legnaro National Laboratory, Italy. With this array a clear identification of the sub-products of deep-inelastic reactions is possible due to the large acceptance of the PRISMA magnetic spectrometer, and its use in combination with the high-resolution γ-ray detector CLARA in thin target experiments.

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The PRISMA-CLARA array provides an excellent ion discrimination, due to the powerful combination of the charge-mass selection techniques working in coincidence with the detection of the γ-ray decay from the subproducts of the reaction. Results from a thin target PRISMA-CLARA experiment can be complemented with thick target experiments, which produce high γ-ray multiplicity, using highly efficient γ-ray arrays such as GASP. The combination of the clear identification of sub-products of PRISMA-CLARA, with the possibility to obtain γ-ray angular correlations with the GASP array, allows to obtain pivotal information for a complete characterization of the nuclear states.

In this contribution, the current efforts to perform an experimental study of the yrast- and near-yrast states of neutron-rich isotopes in nuclei between and near the semi-magic $Z = 40$ (Zr) and the magic $Z = 50$ (Sn) will be reported. Two experiments, using multi-nucleon transfer reactions, initiated by a beam of 6 MeV/u ^{96}Zr ions incident on targets of ^{124}Sn, were performed using the PRISMA-CLARA and GASP arrays. In the following sections a description of the experiments, details of the differences in the yield production, and preliminary results on the level scheme of $^{95}_{41}$Nb will be presented.

EXPERIMENTAL PROCEDURE

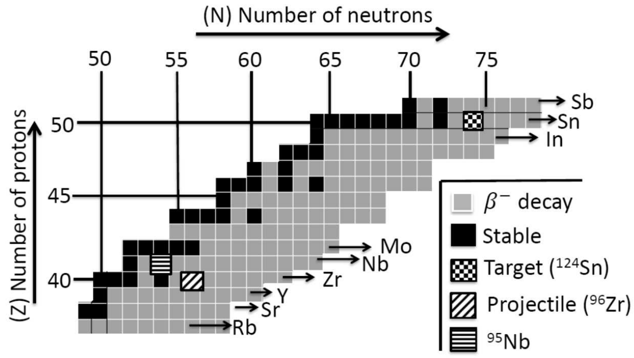

FIGURE 1. Chart of nuclides in the region of interest. Nuclei relevant for this contribution are indicated by arrows.

The region of interest was populated through the reaction $^{96}_{40}\mathrm{Zr} + ^{124}_{50}\mathrm{Sn}$ at a beam energy of 530 MeV. The binary reaction produces species that maintain some resemblance to the initial products, i.e., a couple of nuclei are produced, one similar to the projectile, the so called projectile-like product, and another one similar to the target, the target-like product. Fig. 1 shows the relevant area of the chart of nuclides for this work. This region is located in the neutron-rich side below the magic number $Z = 50$ and at the right of the magic number $N = 50$. The stable ^{124}Sn (target) and the ^{96}Zr (beam) have the largest number of neutrons in the set of stable nuclei of their own isotopic chains.

Two experiments have been performed at the Legnaro National Laboratory (Italy), the first one using the PRISMA-CLARA array with a thin target and the second one using the GASP setup with a thick target. These experiments will be briefly described below.

PRISMA-CLARA experiment

In the PRISMA-CLARA experiment a ^{96}Zr beam, with an energy of 530 MeV, on a thin target of 300 μg/cm^2 of ^{124}Sn was utilized. The ^{124}Sn on the target was enriched to 94.6% and had a carbon backing of thickness 40 μg/cm^2. The PRISMA-CLARA setup allows a clear identification of the projectile-like fragments thanks to the use of charge-mass discrimination techniques. Gamma rays from the target-like and projectile-like nuclei are detected with the help of the CLARA detector array which made use of 25 Compton-suppressed Ge detectors. The γ-rays from projectile-like nuclei are emitted in-flight, thus, a Doppler-shift correction is needed for the correct identification of γ-rays from this type of products. PRISMA and CLARA are linked at a laboratory grazing angle of 38°. Additional details about the specific characteristics of the setup can be found in Refs. [2, 3].

The PRISMA-CLARA experiment allows the clear identification of γ-rays belonging to an specific isotope, but the reaction yield was insufficient to allow the production of $\gamma\gamma$- and $\gamma\gamma\gamma$-coincidence matrices, from which reliable level schemes could be constructed. This was the main motivation to carry out a thick target experiment using the Compton supressed Ge multi-detector array GASP [4].

GASP experiment

In the GASP experiment a beam of 576 MeV on a thick target composed by a layer of ^{124}Sn with a thickness of 8 mg/cm^2, supported on 40 mg/cm^2 of ^{208}Pb, was utilized. The beam energy was selected to obtain around 530 MeV at the middle of the ^{124}Sn target layer. The use of a thick target makes the projectile-like fragments to be stopped inside the target. GASP is an array of 40 Ge-detectors, each one equipped with BGO Compton suppressor detectors. GASP detectors are distributed in eleven (11) rings nearly covering a 4π solid angle. Additional details of the array can be found in Ref. [4].

RESULTS: YIELDS OF THE REACTION

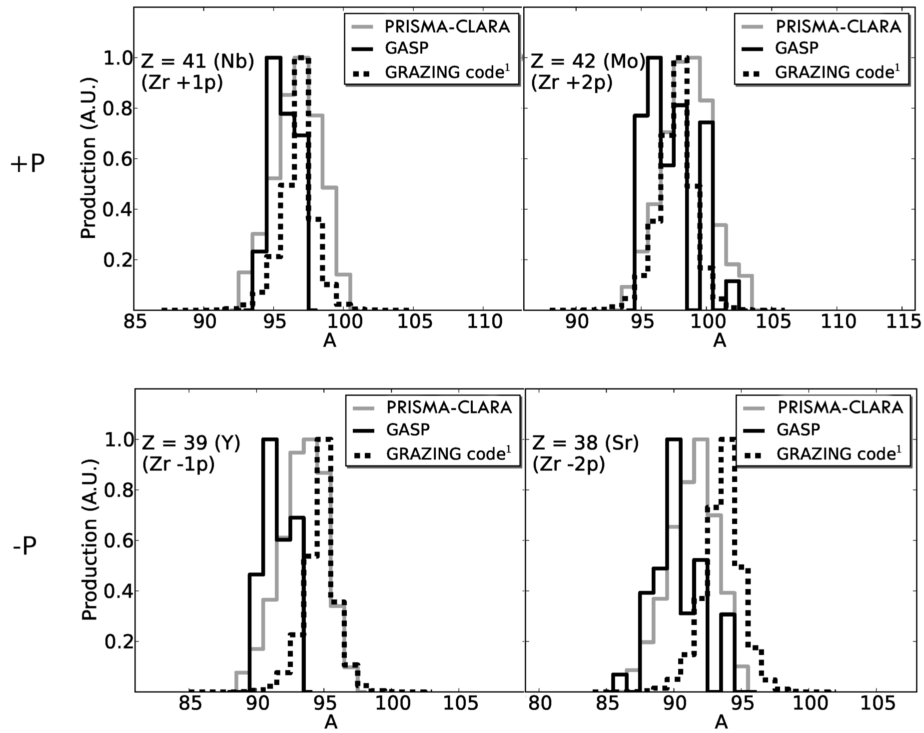

FIGURE 2. Yields of the reaction for some of the projectile-like products. To allow the comparison of the experimental results, PRISMA-CLARA and GASP, with the calculations using the GRAZING code, the largest yield production for the experiments and the calculations in each isotopic chain were normalized to one. Figures in the upper part correspond to the isotopes produced when the projectile, $^{96}_{40}$Zr, captures one or two protons in the reaction. Figures in the lower part represent the production of the isotopes which are obtained when the projectile loses one or two protons.

In the PRISMA-CLARA experiment the yields of the reaction are provided in a clean and direct way by the PRISMA magnetic spectrometer. In the GASP experiment the determination of the yields is carry out by fitting a superposition of Gaussian curves to the total spectrum of the experiment and taking, where possible, the intensity corrected by efficiency of the transitions which go to ground state for each nucleus. Fig. 2 shows the projectile-like yields of the reaction in both experiments, as well as a comparison with the production of the expected yields in a pure deep inelastic reaction at a grazing angle which was calculated using the code GRAZING [5].

Fig. 2 shows that there is a shift between the centers of PRISMA-CLARA and GASP experiments. The mass distribution from the GASP experiment is shifted to the left, the less neutron-rich side, with respect to the PRISMA-CLARA distribution. PRISMA-CLARA provides a cleaner discrimination of neutron-rich nuclei with its outstanding selection of binary reactions, in this case deep-inelastic transfer reaction, while the GASP experiment cannot perform such discrimination, and detects γ rays from all the possible reactions for a thick target experiment. The distributions shown by PRISMA-CLARA present a good qualitative agreement with the grazing code predictions, especially regarding the isotopes that capture protons from the beam, Nb ($Z = 41$) and Mo ($Z = 42$).

The differences between the results of PRISMA-CLARA arrays and the GASP setup is a clear example of the power of the PRISMA-CLARA for the selection of neutron-rich channels of the reaction, due to its very good $A/\Delta A$

discrimination.

PRELIMINARY RESULTS ON THE LEVEL SCHEME OF ^{95}Nb

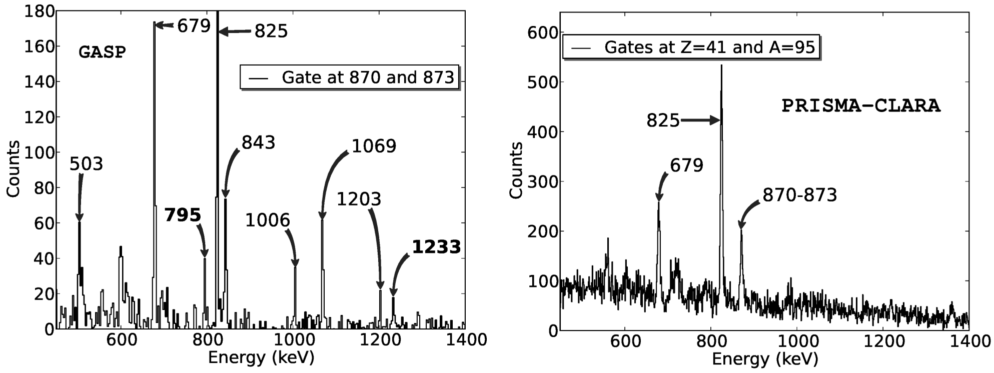

FIGURE 3. At left double-gated spectrum from the GASP experiment. The double gate was performed at γ-ray energies of 870 keV and 873 keV. γ-rays energies at 795 and 1233 keV are new lines added to ^{95}Nb level scheme, in this work. At right Spectrum from PRISMA-CLARA experiment with gates at $Z = 41$ and $A = 95$.

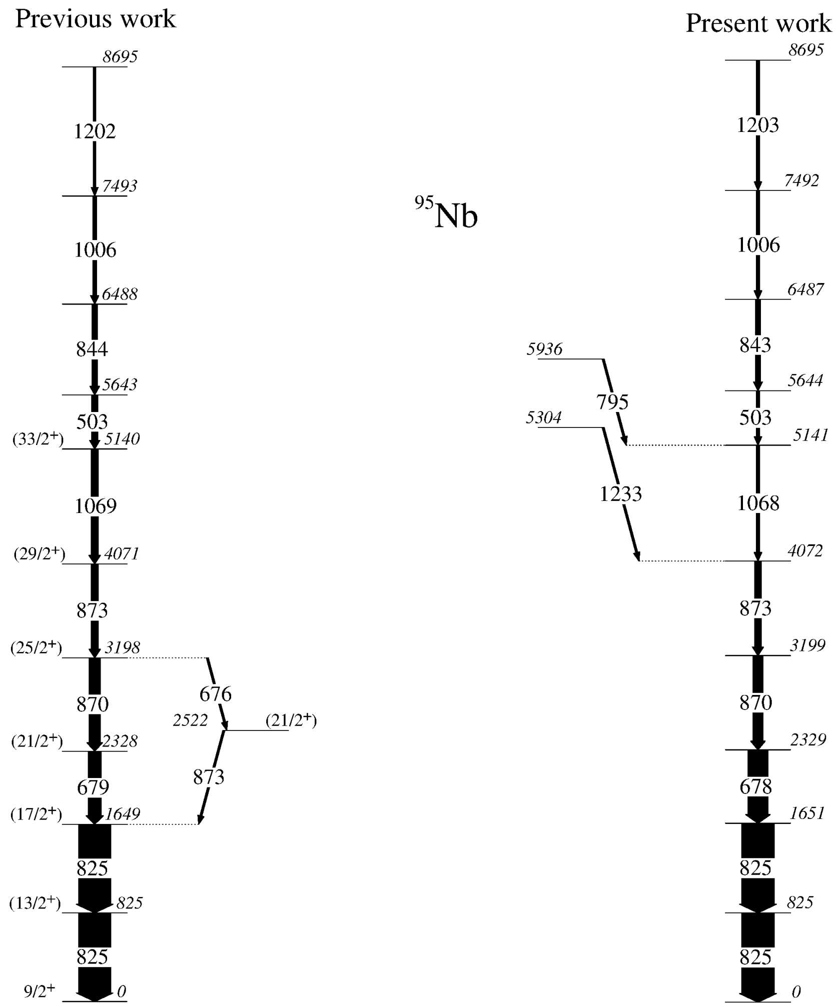

FIGURE 4. Right: Level scheme as proposed in the present work. Left: Level scheme proposed in Ref. [6].

As it was stated previously, the GASP experiment allows the construction of $\gamma\gamma\gamma$-coincidence matrices. Fig. 3 shows the double-gated spectrum at 870 keV and 873 keV which belong to the ^{95}Nb level scheme. In this spectrum, all transitions in the level scheme of ^{95}Nb can be seen, as well as two more peaks at energies of 795 keV and 1233 keV.

The PRISMA-CLARA results do not allow the identification of these two lines because of their low intensity. Gamma rays emitted from the partner nucleus and neighbor nuclei were checked to ensure that the γ-rays belong to ^{95}Nb. We propose to place the γ-rays in the positions shown in Fig. 4.

Figure 4 shows the preliminary level scheme proposed in this work, neither spins nor parities have been assigned. Two new transitions with energies of 1233 keV and 795 keV were added. Transitions with energies at 676.2 and 872.6 proposed in Ref. [6] were not observed in this work. The intensities of the γ-rays at 843 keV and 503 keV are the same between the range of uncertainty, a possible reason for this could be the existence of an isomeric state at $E = 5644$ keV. Additional studies are needed to confirm or rule out the existence of this isometric state.

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