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Experimental study of the $^{95}_{41}$Nb level scheme using the $^{96}_{40}$Zr + $^{124}_{50}$Sn reaction with the GASP and PRISMA-CLARA arrays

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In this contribution an experimental study of the excited states of ^{95}Nb, produced by means of the deep-inelastic reaction $^{96}_{40}$Zr+$^{124}_{50}$Sn at 530 MeV using the GASP and PRISMA-CLARA arrays, is presented. Results on the study of the yrast and near-yrast states for ^{95}Nb are presented. Angular correlations were performed to determine the spins and parities of some levels. The experimental results obtained are compared with predictions by shell model calculations.

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1. Introduction

Neutron-rich nuclei in the region A $\sim$ 100 approaching $N \geq 50$, between the semi-magic $Z = 40$ and the magic $Z = 50$ numbers, are of interest due to the possibility of studying shell closures and sub-closures. These nuclei lie on the pathway of the rapid neutron capture process (r-process) [1], so there is also an astrophysical interest in the structure of such nuclei. Experimental studies of neutron-rich nuclei in this region have been conducted during the last decades using deep inelastic reactions with experimental arrays, such as the PRISMA-CLARA array at Legnaro National Laboratory, Italy. Due to the large angular acceptance of the PRISMA magnetic spectrometer, and its use in conjunction with the high-resolution γ-ray detector array CLARA, in thin target experiments, a clear identification of the sub-products of the reaction is possible. More detailed spectroscopy information can be obtained if partner thick target experiments are performed using highly efficient γ-ray arrays, such as GASP [2]. The latter may allow to obtain pivotal information for a complete characterization of excited nuclear states.

A typical PRISMA-CLARA experiment has a clear isotope identification but with the setback of a low yield production. The GASP array provides a good γ-ray detection efficiency. The combination of both experimental arrays produces a powerful tool to study the nuclear structure of nuclei in the region.

The desired neutron-rich region is difficult to access with fusion-evaporation reactions using stable nuclear beams. Instead, deep inelastic binary reactions have been successfully utilized in recent years. The reaction presented in this contribution was initiated by a beam of $^{96}_{40}$Zr incident on a target of $^{124}_{50}$Sn. Here a study of the $^{95}_{41}$Nb level scheme constructed from the data obtained of PRISMA-CLARA and GASP experiments is presented. The region of interest of this work can be located in the chart of nuclides in Fig. 1 where the location of the beam, the target and the ^{95}Nb nuclei has been highlighted.

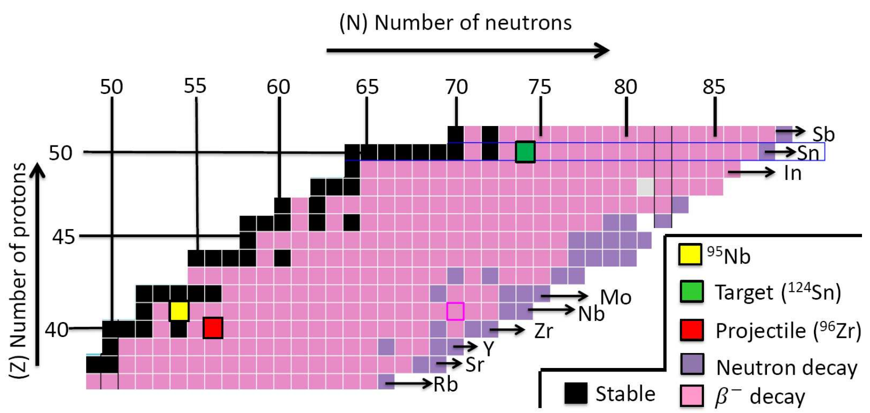

Figure 1: Chart of nuclides in region of interest. The target, $^{124}_{50}$Sn and the beam $^{96}_{40}$Zr are highlighted as well as the ^{95}Nb nucleus.

In the next section a description of the experiments is shown. In section 3 the level scheme obtained in this work is compared by the previous one obtained by Bucurescu et al. [3]. Finally, in section 4, a comparison of the experimental results with predictions from shell model calculations is exposed.

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2. Description of the experiments

Both experiments were conducted with a beam of $^{96}_{40}$Zr incident on a target of $^{124}_{50}$Sn. The beams at Legnaro were initially accelerated by the Tandem and finally by the linear accelerator ALPI.

In the PRISMA-CLARA experiment [4, 5] a thin target was utilized in order to allow the projectile-like fragments to reach the spectrometer PRISMA. A thick target was utilized in the GASP experiment [2]. It made the projectile-like fragments to stop inside the GASP multidetector array. A complete description of the experiments was made in a previous work [6]. A summary of main experimental details of both experiments is shown in Table 1.

$^{96}_{40}$Zr + $^{124}_{50}$Sn		
	PRISMA-CLARA	GASP
Target ($^{124}_{50}$Sn) thickness (mg/cm^2)	0.3	8
Thickness of the backing target (mg/cm^2)	0.04 of ^{12}C	40 of ^{208}Pb
Beam energy (MeV)	530	570 [a]
Number of working detectors	25/25	38/40

Table 1: Target thickness and beam energy of the PRISMA-CLARA and GASP experiments.

[a] The beam energy at the middle of the $^{124}_{50}$Sn target was 530 MeV.

3. ^{95}Nb level scheme

Figure 2 shows the double-gated spectrum at 870 keV and 873 keV showing transitions that belong to the ^{95}Nb level scheme. These data are from the GASP experiment.

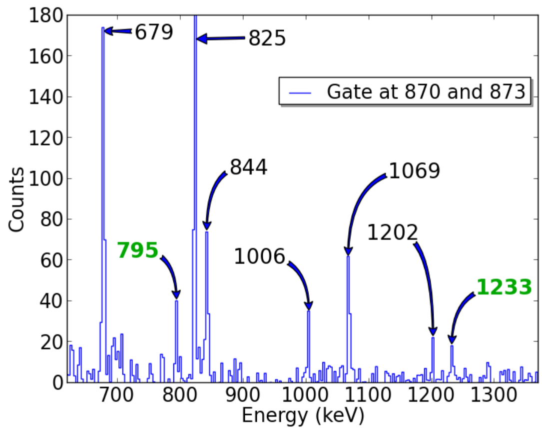

Figure 2: Double-gated spectra from the GASP experiment. The double gate was performed at γ-ray energies of 870 keV and 873 keV. Gamma-ray energies at 795 and 1233 keV are new lines added in this work to the ^{95}Nb level scheme.

From this spectrum most of the lines in the level scheme proposed in the most recent work on excited states of ^{95}Nb nucleus [3] can be seen, as well as two more peaks at energies 795 keV and 1233 keV. From Fig. 2 it can be seen that the intensity of these lines is lower than that of the other lines in the spectrum.

The data from the PRISMA-CLARA experiment confirm that most of the transitions in Fig. 2 belong to the ^{95}Nb nucleus. However transitions emitting γ-rays at energies of 795 and 1233 keV were not observed in PRISMA-CLARA experiment, because of their low intensity. These two transitions were not observed by Bucurescu et al. in a recent work [3]. These two lines could be emitted by the partner nucleus of ^{95}Nb $\left(^{125}\text{In}\right)$ as well as its neighbors or they could also be new transitions found for the ^{95}Nb nucleus. However the γ-rays emitted from the partner nucleus and neighbor nuclei were checked to ensure that the γ-rays at energies of 795 and 1233 keV belong to ^{95}Nb. The proposed ^{95}Nb level scheme in this work is presented in Fig. 3 alongside with the previous level scheme poposed by Bucurescu et al. [3].

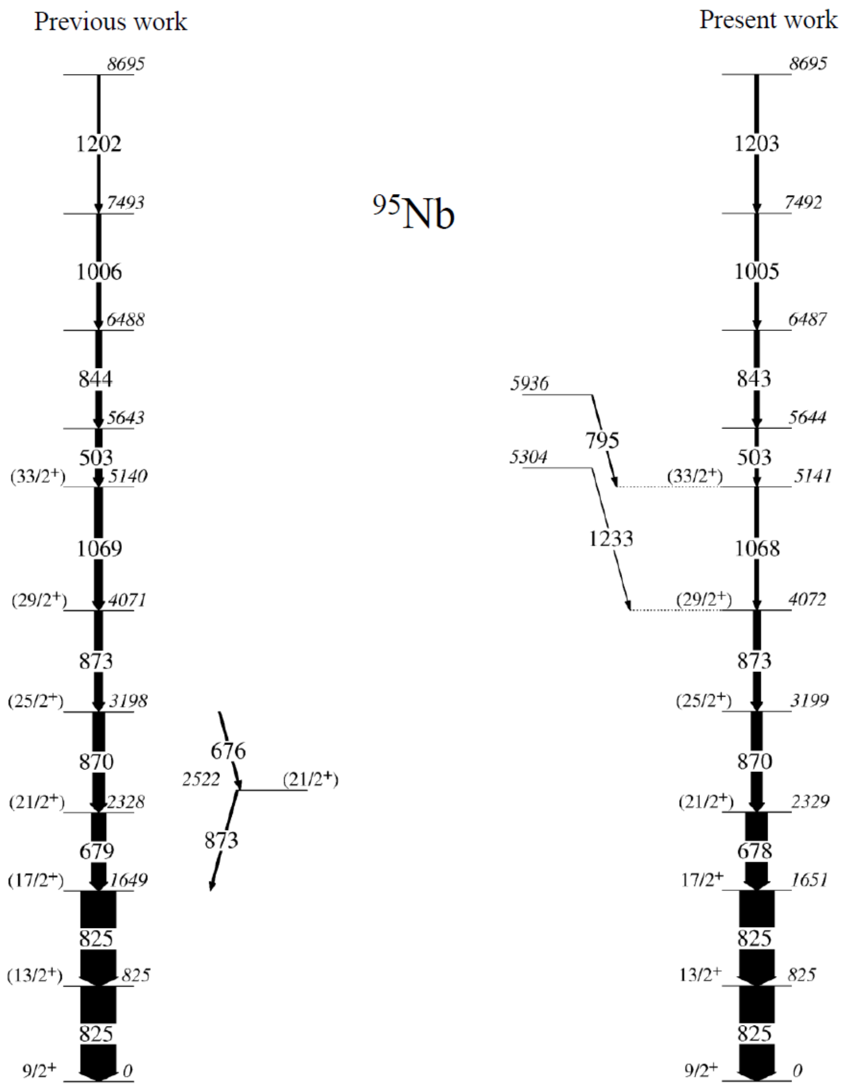

Figure 3: Right: Level scheme as proposed in the present work. Left: Level scheme proposed in Ref. [3].

From the data of the GASP experiment spins and parities can be proposed making angular correlations from the detected γ-rays following the procedure described in [7]. For a cascade of three successive γ-rays $I_0 \xrightarrow{\gamma_0} I_1 \xrightarrow{\gamma_1} I_2 \xrightarrow{\gamma_2} I_3$, three matrices can be generated with a common gate on the γ_0 energy. This generates an alignment of the lower sub-states and it is also useful to resolve the interference between closely spaced transitions. Three two-dimensional symmetric coincidence matrices were generated. The coincidence events were added to each matrix when the γ-rays γ_1 and γ_2 were detected in any pair of detectors with relative separation angle θ, to each other. For the first matrix the separation angle correspond to $\theta = (90 \pm 10)^\circ$. The second matrix contains the sum of the events detetected at separation angles of $\theta = (120 \pm 10)^\circ$ and $\theta = (60 \pm 10)^\circ$. For the third matrix the events with $\theta = (120 \pm 10)^\circ$ and $\theta = (60 \pm 10)^\circ$, were registered. Then making a gate on energy of γ_2 the number of counts of γ_1 were calculated. This way the numbers $N(90)$, $N(120)$ and $N(150)$ were obtained. The angular distribution of γ_1 is described by the function

$$W(t_1, t_2, \theta) = \sum_{\lambda}^{\lambda_{max}} q_\lambda A_\lambda(t_1, t_2) P_\lambda(\cos(\theta)), \tag{3.1}$$

where t_1, t_2 denotes the properties of the transitions γ_1 and γ_2 and the spins of the levels that they connect. The coefficients A_λ were calculated in Ref. [7] for different types of transitions. The attenuation coefficients q_λ were calculated in Ref. [8] following the procedure described in Ref. [7]. These coefficients have the values $q_0 = 1.0$, $q_3 = 0.909$, $q_0 = 0.602$ for the GASP array and they take into account the finite size of the detectors and the effects of choosing $\pm$ 10° as the range for the separation angle between a pair of detectors. A cascade of three well known E2 γ-rays emitted by the ^{96}Zr nucleus (the beam of the experiment) at energies of 617, 915 and 1107 keV were used to obtain normalization factors for the values $N(\theta)$. The coefficients A_2/A_0 were calculated for different γ-rays in the lowest states of the level scheme of ^{95}Nb. Highest γ-rays of this level scheme cannot be analyzed because of the low statistics. From Fig. 3 can been a doublet in the level scheme of ^{95}Nb at 825 keV. Figure 4 shows the angular distribution of the radiation for the two γ-rays at 825 keV in the lowest part of the Fig. 3, as well as the theoretical prediction for a two successive γ-rays from the E2 type.

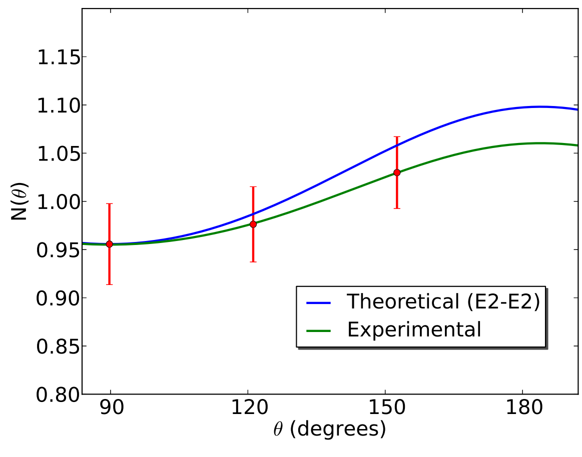

Figure 4: Angular correlations for 825 keV γ—rays.

From Fig. 4 it can be seen that the shape of the angular distribution of the 825 keV γ-rays is the same, within uncertainties, to the function which describes an E2-E2 cascade. Table 2 are shown the energy levels, γ-ray energies and A_2/A_0 ratios obtained for the lowest excited states of ^{95}Nb.

E_f	E_i	$E_{\gamma 1}$	$E_{\gamma 2}$	$A_2/A_0{}^a$	γ-ray multipolarity		J_f^π	J_i^π
					γ_1	γ_2		
0.0	825.3	825(1)	825(1)	0.076(25)	E2	E2	$9/2^+$	$13/2^+$
825.3(12)	1650.6(12)	678(1)	825(1)	–	(E2)	E2	$13/2^+$	$17/2^+$
1650.6(13)	2328.6(13)	870(1)	678(1)	0.049(30)	E2	(E2)	$17/2^+$	$(21/2^+)$
2328.6(13)	3199.0(13)	873(1)	870(1)	0.092(50)	E2	E2	$(21/2^+)$	$(25/2^+)$
3199.0(13)	4072.3(13)	1068(1)	873(1)	0.152(70)	E2	E2	$(25/2^+)$	$(29/2^+)$

Table 2: Energies of excited states of ^{95}Nb together with transition energies ($E_{\gamma 1}$ and $E_{\gamma 2}$), A_2/A_0 ratios, γ-ray multipolarity, spins and parities of the transition levels of the lowest γ-rays placed in the level scheme in Fig. 3.

[a] Theoretical value of A_2/A_0 for transitions of the type E2-E2 conecting levels with spins $2 \longrightarrow 0$ is 0.102

A discussion of the intensities of the γ-rays reported in Table 2 was carried out in a previous work [6]. A special discussion of the ratios A_2/A_0 in Table 2 is carried out below, for each γ-ray, to explain the spins and parities proposed in Table 2.

825 keV: The behavior of the angular correlations for the γ-ray doublet can be seen in Fig 4. This figure together with the value of A_2/A_0 reported at the top in Table 2 allow us to asign spins and parities of the first two excited states as $13/2^+$, $17/2^+$. These values are also in agreement with the shell model calculations shown in Table 3.

678 keV: The presence of a γ-ray doublet of 825 keV in the lower states of the level scheme does not allow us to determine angular correlation for this specific γ-ray. For this reason the predictions of the spins and parities for excited states above excitation energy of 2328.6 keV, must be confirmed. However the consistency with the values of the two neighbor γ-rays could indicate an E2 transition.

870 keV: For this γ-ray the angular correlation with the 678 keV γ-ray transition gives a value of 0.049(30), a bit far to the theoretical value for two successive E2-E2 transitions (0.102). However angular correlations between the γ-rays at energies of 870 and 873 keV gives a value of 0.092(50), which leads us to propose an E2-E2 cascade for γ-rays at energies of 870 and 873 keV. In the same way spins and parities of $(21/2^+)$, $(25/2^+)$ for the levels at energies of $2328.6, 3199.0$ are proposed.

873 and *1069 keV*: The values for these two γ-rays are in agreement with transitions from an E2-E2 cascade. Spins and parities proposed are shown in Table 2.

4. Shell model calculations

The $^{95}_{41}$Nb nucleus is located 4 neutrons to the right of the neutron magic number 50 and one proton up of the proton semi-magic number 40. For these reasons a single particle behaviour is expected. In these contribution we assumed $^{88}_{38}\mathrm{Sr}_{50}$ as an inert core to make shell model calculations. Thus the $^{95}_{41}\mathrm{Nb}_{54}$ nucleus is considered to have 3 valence protons and 4 valence neutrons. The valence orbitals used for protons were $2p_{1/2}$ and $1g_{9/2}$ and the valence orbitals used for neutrons were $2d_{5/2}$, $1g_{7/2}$, $3s_{1/2}$, $2d_{3/2}$, and $1h_{11/2}$. The single particle energies relative to $^{88}_{38}\mathrm{Sr}_{50}$ inert core were taken from Refs. [9, 10]. The values in MeV for neutron orbitals were $\varepsilon_\nu(2d_{5/2}) = -6.359$,

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$\varepsilon_\nu(1g_{7/2}) = -3.684$, $\varepsilon_\nu(3s_{1/2}) = -5.327$, $\varepsilon_\nu(2d_{3/2}) = -4.351$ and $\varepsilon_\nu(1h_{11/2}) = -4.280$. For proton orbitals the single particle energies in MeV were $\varepsilon_\pi(2p_{1/2}) = -6.160$ and $\varepsilon_\pi(1g_{9/2}) = -7.069$. The Oslo code was utilized to make the shell-model calculations [11]. The effective interaction was constructed based in the CD-Bonn nucleon-nucleon interaction described in Ref. [11]. Some of the predicted levels and the $B(\mathrm{E2})$ values found are shown in Table 3.

Initial energy level	Final energy level	J_i^π	J_f^π	E_γ	B(E2) (W.u.)
0.0	850.6	$9/2^+$	$13/2^+$	850.6	23.5
850.6	1733.2	$13/2^+$	$17/2^+$	883.2	26.6
2694.0	1733.8	$21/2^+$	$17/2^+$	960.2	2.3

Table 3: Level energies together with transition energies (E_γ) for the γ-rays with the highest $B(\mathrm{E2})$, predicted by shell model calculations.

The energies of the first two excited states, reported in Table 3, predicted by the shell model calculations are in very good agreement with the experimental values in Table 2. These values are even in better agreement than the previous ones calculated in Ref. [3]. However higher excited states are not well predicted by the calculations performed in this work. A more detailed analysis will be presented in a forthcoming communication.

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