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Spectroscopy of neutron-rich scandium isotopes

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Abstract. Within the SEASTAR III campaign at the Radioactive Isotope Beam Factory, at the RIKEN Nishina Center, neutron-rich isotopes in the vicinity of ^{53}K were produced from the fragmentation of the primary ^{70}Zn beam on a ^{9}Be target. After nucleon knockout reactions on the secondary liquid hydrogen MINOS target the known γ rays of the neutron-rich ^{55}Sc isotope were observed (shown in this proceedings) and γ rays from ^{57,59}Sc isotopes have been identified for the first time. The evolution of the occupied nucleon orbitals of these nuclei in the ground and excited state is investigated under the prism of the tensor force.

1. Theory

In the past decades the rise of new *magic numbers* [1, 2, 3, 4] and the lack of the *"traditional" magic numbers* [5, 6, 7, 8] in nuclei far from stability, with large imbalance of neutron (N) and proton (Z) numbers, have been studied. Two new *magic numbers*, at $N = 32$ and $N = 34$, were found in nuclei in the vicinity of $Z = 20$. In Figure 1 the energies of the first excited states of isotopes of this nuclear chart area are shown. The Figure features the sub-shell closure at $N = 32$, the $N = 34$ sub-shell closure for isotopes with $Z \leq 20$ (^{54}Ca [4] and ^{52}Ar [9]) and the rapid weakening of the sub-shell closure at $N = 34$ for isotopes with $Z > 20$ (^{57}V [10], ^{56}Ti [11, 12] and ^{55}Sc [13]).

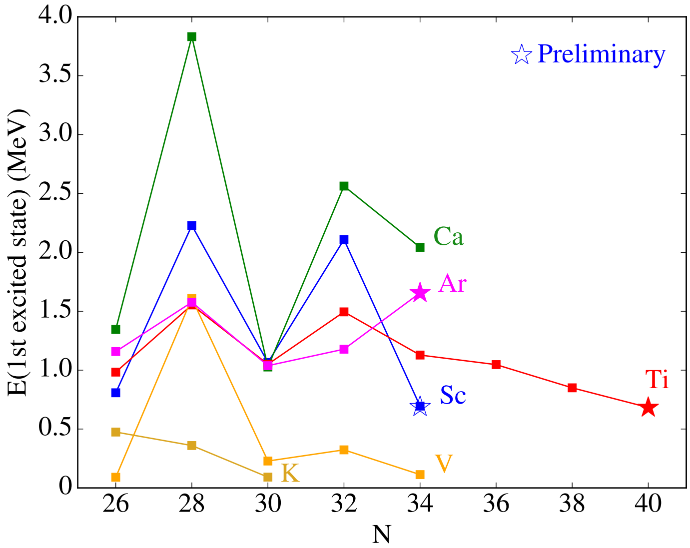

Figure 1. Energy of the first excited states for the Ar, K, Ca, Sc, Ti and V isotopic chains with $26 \geq N \geq 38$. The data for ^{52}Ar [9], ^{55}Sc (this work, preliminary) and ^{62}Ti [14] have been measured in the SEASTAR III campaign (plotted with "star"). For ^{55}Sc the "blue box" corresponds to the literature value [13] and the "blue open star" to the energy measured in this work.

The origin of the $N = 34$ sub-shell closure in ^{54}Ca was explained by D. Steppenbeck et al. in Ref. [4] based on the theoretical work of T. Otsuka et al. and the concept of the tensor force [15, 16]. Due to the tensor force, the single-particle energies are shifted as protons or neutrons occupy certain orbitals, causing the *magic numbers* to change for nuclei far from β-stability. A simple example of the evolution of the interaction between the nucleons in two orbitals, $j_> = l + 1/2$ and $j'_< = l' - 1/2$, is shown in Figure 2 as more nucleons are added to the orbitals. The thicker arrow on the right side of the Figure represents the stronger attractive force between the nucleons.

In Figure 3 the occupied orbitals are shown for the $N = 34$ even-even isotones from ^{60}Fe to ^{54}Ca, for decreasing Z. As protons are removed from the $\pi f_{7/2}$ orbital the interaction between the $\pi f_{7/2}$ and the $\nu f_{5/2}$ orbitals is getting weaker (shown in the figure with a thinner arrow connecting the two orbitals). Hence, the energy of the $\nu f_{5/2}$ moves higher in energy. In ^{56}Ti and ^{54}Ca the two valence neutrons occupy the $\nu p_{1/2}$ orbital causing an inversion of the *ordinary* order of the filling of the orbitals in comparison to stable isotopes. The fully filled $\nu p_{1/2}$ orbital in combination with the $Z = 20$ closed shell serves to explain the $N = 34$ sub-shell closure of ^{54}Ca.

Following the same pattern as before, considering the interaction between the $\pi f_{7/2}$ and the $\nu f_{5/2}$ orbitals, we expect the interaction to be weaker in ^{55}Sc compared to ^{56}Ti, since one

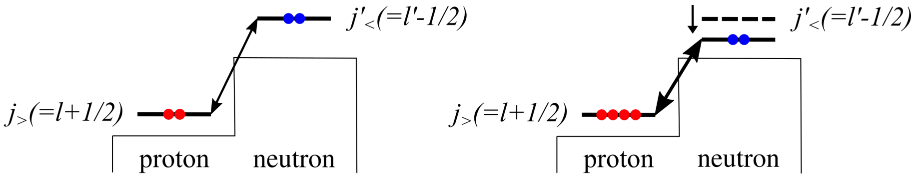

Figure 2. Evolution of the attractive force between nucleons occupying the $j_> = l + 1/2$ and $j'_< = l' - 1/2$ orbitals according to the tensor force [16]. The attractive force is increasing as more nucleons are added to the orbitals (shown in the Figure with a thicker arrow), causing the orbitals to move closer in energy.

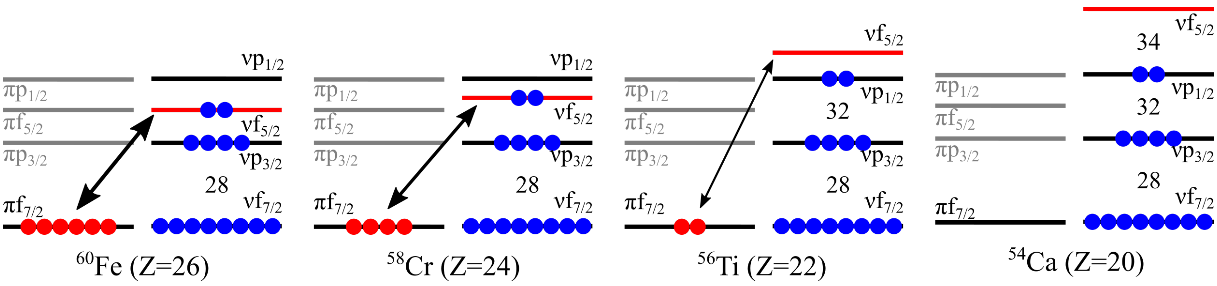

Figure 3. Origins of the $N = 34$ sub-shell closure of ^{54}Ca. The weakening of the $\pi - \nu$ interaction between the $\pi f_{7/2}$ and the $\nu f_{5/2}$ orbitals is indicated by the width of the arrow (see also text). Adapted from Ref. [4].

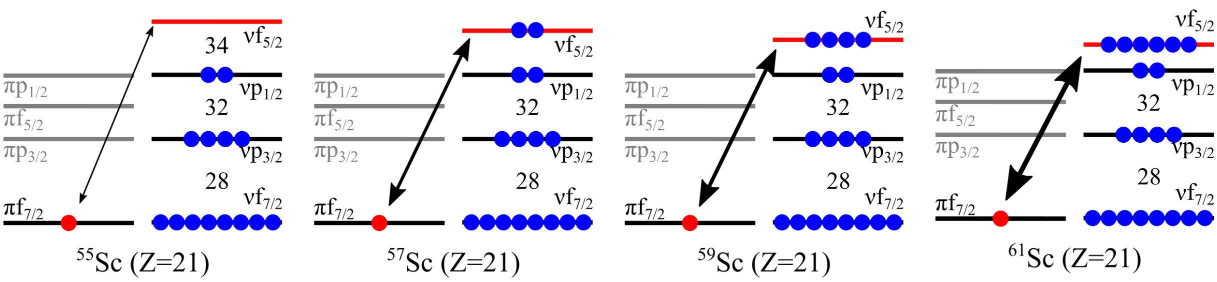

Figure 4. Occupied orbitals for odd scandium isotopes with $34 \geq N \geq 40$. *Inverted* filling order of the $\nu f_{5/2}$ and the $\nu p_{1/2}$ orbitals for ^{55,57,59,61}Sc (see text).

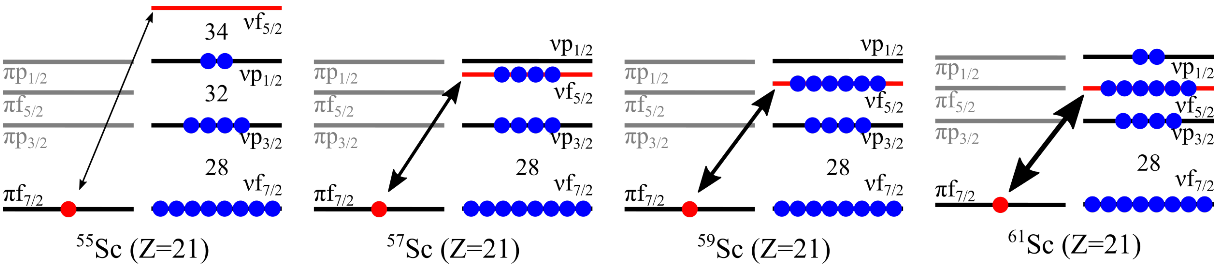

Figure 5. Occupied orbitals for odd scandium isotopes with $34 \geq N \geq 40$. *Ordinary* filling order of the $\nu f_{5/2}$ and the $\nu p_{1/2}$ orbitals for ^{57,59,61}Sc (see text).

proton has been removed from the $\pi f_{7/2}$ orbital. From ^{55}Sc to ^{61}Sc, as neutrons are added to the nucleus, it is expected that the $\pi f_{7/2}$-$\nu f_{5/2}$ interaction gets stronger (thicker arrow in Figure

4 by increasing N). This would result in a decrease in the energy of the $\nu f_{5/2}$ as N is increasing. The questions that arise are: is the interaction strong enough so it will cause the $\nu f_{5/2}$ orbital energy to be lower than the $\nu p_{1/2}$ energy? And in which isotope the order of filling the $\nu f_{5/2}$ and $\nu p_{1/2}$ orbitals is again the *ordinary* order, like in the stable isotopes? Compare Figures 4 and 5.

Information on the nature of the excitations in the ^{55,57,59,61}Sc isotopes can be provided by the observation of the level schemes and the spin and parity assignment of the levels. Experimental data for these neutron-rich isotopes were collected within the SEASTAR III campaign. In the following sections the experimental set-up will be described and the preliminary results of the analysis on ^{55}Sc isotope will be presented. Additionally, the next steps of the analysis will be discussed.

2. SEASTAR III campaign

The SEASTAR III campaign was performed at the Radioactive Isotope Beam Factory (RIBF) operated by the RIKEN Nishina Center in Wako-shi in Japan. A primary ^{70}Zn beam was accelerated by the RIBF accelerator complex up to 345 MeV/u and impinged on a 10-mm-thick ^{9}Be target. The fragments of the reaction, magnetically centered around ^{53}K, were identified using the $ToF - B\rho - \Delta E$ method [17] in the BigRIPS fragment separator [18]. The secondary beam impinged on the MINOS target [19] consisted of a 150-mm-thick liquid hydrogen (LH_2) target, at a temperature of 18 K. The LH_2 target was surrounded by a 300-mm-long time projection chamber, tracking the trajectories of the outgoing protons. The reconstruction of the reaction vertices has been used for the Doppler correction of the γ rays, detected by the DALI2+ array, emitted in flight, by the product of the secondary beam - LH_2 reaction. The DALI2+ [20] array consisted of 226 NaI(Tl) crystals and covered polar angles from 15° to 118° with respect to the center of the MINOS LH_2 target.

The products of the secondary beam - LH_2 reaction passed the SAMURAI magnet with a central magnetic field of 2.7 T and have been identified event-by-event in the SAMURAI spectrometer [21] using two drift chambers and the hodoscope plastic-scintillator array, with the $ToF - B\rho - \Delta E$ method. The set-up is shown in Figure 6, adapted from Ref. [22].

The two-stage particle identification, before and after the secondary beam - LH_2 reaction (from BigRIPS and SAMURAI respectively), allowed the selection of specific reactions by setting gate conditions to the data.

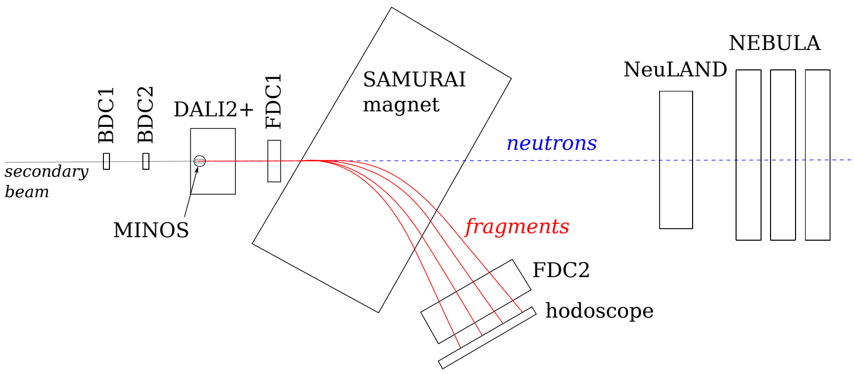

Figure 6. Experimental set-up of the SEASTAR III campaign. The secondary beam (after BigRIPS) impinged on the MINOS target. The fragments passed the SAMURAI magnet and have been identified event-by-event in the SAMURAI spectrometer. The γ rays were detected by the DALI2+ array. Additionally, NeuLAND [23] and NEBULA [24] were used for neutron detection. Adapted from Ref. [22].

3. Analysis - Preliminary results

In Figure 7 (a) the spectrum from DALI2+ after performing gates on BigRIPS and SAMURAI is shown for ^{55}Sc. The neutron knock-out reaction from ^{56}Sc was selected, p(^{56}Sc,pn)^{55}Sc. The ^{56}Sc was gated on BigRIPS and the ^{55}Sc on SAMURAI. The ^{55}Sc isotope was well populated in the experiment, with good statistic. In Figure 7 (b) the γ rays of ^{55}Sc observed from this work can be compared with the ones reported in Ref. [13]. The γ rays observed in Ref. [13] were verified in this work. Both ^{57,59}Sc isotopes were well populated and γ rays with good statistics were observed. Additionally, the ^{61}Sc was weakly populated. The analysis of these data is on-going.

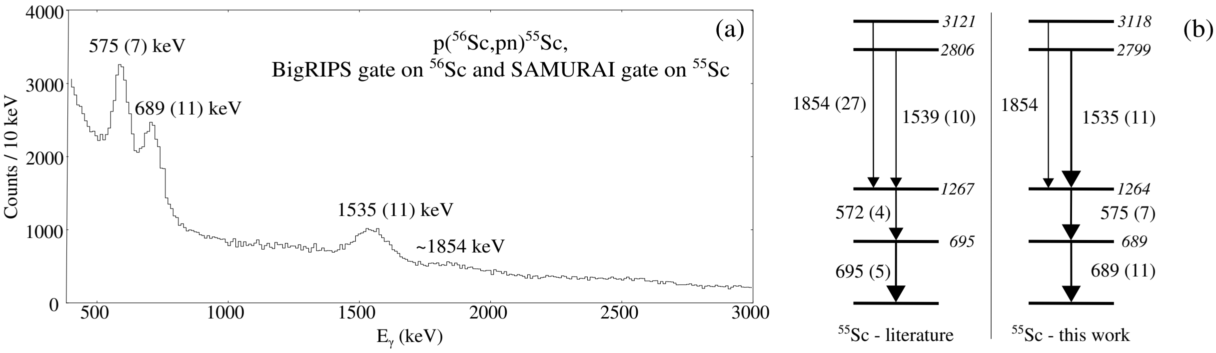

Figure 7. DALI2+ spectra after setting gates on BigRIPS and SAMURAI for ^{55}Sc. The neutron knock-out reaction from ^{56}Sc was selected. (b) The level scheme adapted from Ref. [13] with the γ rays observed for ^{55}Sc and the level scheme with the γ rays observed in this work.

4. Outlook

For the construction of the level schemes the γ-γ coincidence analysis will be used. The parallel momentum distribution analysis (performed already in SEASTAR III data for the ^{51,53}K [25] and ^{54}Ca [26] isotopes), which can be performed due to the use of MINOS, will allow the spin and parity assignment of the states. Additionally, shell model calculations for the identification of the nature of the excitations will be performed.

Acknowledgments

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