Development of new shell structure in pf-shell nuclei

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Abstract. β-delayed γ-ray measurements have been part of an experimental program at the NSCL to understand the role of the πf7/2 − νf5/2 proton-neutron monopole interaction in neutron-rich pf-shell nuclei above 48Ca. Central to this study has been an attempt to observe the development of new shell structure at N = 32, 34 through the systematic observation of E(2+1) as a function of neutron number. Additionally, the ground state spin and parity of odd-odd and odd-A nuclei were interpreted in an extreme single-particle model to follow the monopole migration of the νf5/2 as protons are removed from the πf7/2 state.

1. Introduction

The proton-neutron monopole interaction has a substantial impact on the ordering of single-particle states in neutron-rich nuclei. In the pf shell, the proton-neutron monopole interaction between the spin-orbit partners πf7/2 and νf5/2 was expected to result in the emergence of new shell structure at N = 32 and 34 [1]. A number of β-delayed γ-ray spectroscopy experiments have been performed [2, 3, 4, 5, 6, 7, 8] at the National Superconducting Cyclotron Laboratory (NSCL) to understand the extent of the νf5/2 monopole shift and the development of new shell structure in the πf7/2 − νpf region of the chart of the nuclides (see Fig. 1 for isotopes studied). The monopole shift of the νf5/2 state was followed by systematic measurements of E(2+1) in even-even isotopes and ground state spin and parity assignments in odd-odd and odd-A nuclei.
2. Experiment

$\beta$ decay provides a sensitive and selective means for probing the low-energy quantum states in daughter nuclei. Our interests at the NSCL were focused on the decay of odd-odd parent states with $J > 1$, where the energies of the first excited $2^+$ states could be obtained for the first time by delayed $\gamma$-ray spectroscopy. The $pf$ nuclides of interest were produced in fragmentation reactions of a $^{86}$Kr beam on a $^9$Be target. The nuclides were separated using the A1900 fragment separator [9] and implanted into a double-sided silicon microstrip detector, part of the $\beta$ counting system [10]. Twelve detectors from the NSCL Segmented Germanium Array [11] surrounded the counting system and were used to monitor emitted $\gamma$ rays. Experimental properties deduced from the studies included $\beta$-decay half-lives, apparent branching ratios and tentative ground state spin and parity assignments for the parent nuclides, as well as the low-energy level schemes in the daughter nuclei.

3. Beta decay of odd-odd nuclei

The $\beta$ decay of the odd-odd nuclei $^{54,56}$Sc and $^{56,58}$V were studied to determine the low-energy level structure of the even-even $^{54,56}$Ti and $^{56,58}$Cr nuclei, most importantly the energy of the first excited $2^+$ state, $E(2^+_1)$. A comparison between the systematic variations of $E(2^+_1)$ and $E(4^+_1)$ along both the $N = 32, 34$ isotonic chains is shown in Fig. 2. There is a clear rise in the $E(2^+_1)$ as a function of proton number in the $N = 32$ isotones from Fe to Ca due to the monopole migration of the $\nu f_{5/2}$ single-particle state. A qualitatively different behavior is observed in the $E(2^+_1)$ values for the $N = 34$ isotones where the trend in $E(2^+_1)$ is flat from Fe to Cr. A slight rise in the $E(2^+_1)$ in $^{56}$Ti may be an indication of a developing single-particle energy gap.

The experimental $E(2^+_1)$ values for the Ti and Cr isotopes at $N = 32, 34$ were compared with the results of shell model calculations using the GXPF1 effective interaction [12, 13] to further understand the monopole migration of the $\nu f_{5/2}$ state as protons are removed from the the $\pi f_{7/2}$ level and the resulting effects on the low energy structure of $^{54,56}$Ti and $^{56,58}$Cr. GXPF1 is based on effective two-body matrix elements with some replacement by the G matrix and was derived by fitting 699 levels from $pf$-shell nuclei with $A \geq 47$ and $Z \leq 32$ [12]. One result of shell-model calculations using the GXPF1 interaction is an increase in the $\nu f_{5/2}$ effective single-particle
energy, relative to the $\nu p_{3/2}$, as protons are removed from the $\pi f_{7/2}$ state and appears to arise from the proton-neutron monopole interaction. Beginning in the Cr isotopes and continuing in Ti and Ca nuclei the energy separation between the neutron $p_{3/2}$ orbital and the $p_{1/2}$ and $f_{5/2}$ orbitals leads to the development of an $N = 32$ shell closure, evidenced by the systematic variation of the energies of the first excited $2^+$ states as a function of neutron number, which peak at $N = 32$ [6, 8]. Further evidence of the existence of an $N = 32$ shell closure come from high-spin data [3], where a significant gap between the $\nu p_{1/2}$ and $\nu f_{5/2}$ single-particle states was inferred based on a large energy separation between the $6^+_1$ and the cluster of $8^+_1, 9^+_1, 10^+_1$ levels in $^{54}\text{Ti}$.

In the Ti and Ca isotopes, the continued increase in energy of the $f_{5/2}$ neutron orbital was expected to culminate in a substantial energy separation between the $\nu p_{1/2}$ and $\nu f_{5/2}$ orbitals and the emergence of an $N = 34$ shell closure [12]. However, in $^{56}\text{Ti}_{34}$, the energy of the $2^+_1$ level was $\sim$0.4 MeV lower than the shell model results obtained with the GXPF1 interaction. The experimental $2^+_1$ energy in $^{56}\text{Ti}$ was better reproduced in the shell model using the modified GXPF1A effective interaction [14]. The difference between the GXPF1 and GXPF1A interactions is the alteration of five matrix elements in the latter, four of which have to do with the $p_{1/2}$ and $f_{5/2}$ orbitals. The expected energy separation between the $\nu p_{1/2}$ and $\nu f_{5/2}$ levels in $^{54}\text{Ca}_{34}$ based on shell model calculations with the GXPF1A interaction was reduced slightly, but is still large enough to suggest a shell closure at $N = 34$ but an experiment investigating the low-energy structure of $^{54}\text{Ca}$ is needed.

In addition to the $E(2^+_1)$ and $E(4^+_1)$ values, the migration of the $\nu f_{5/2}$ state as a function of proton number can also be followed by investigating the ground state spin and parities of the parent odd-odd nuclei $^{54,56}\text{Sc}$ and $^{56,58}\text{V}$. The spin and parities for these ground states of the odd-odd nuclei are shown in Fig. 3 along with schematic neutron single-particle levels. Working from the presumed $N = 32$ shell closure identified through $E(2^+_1)$ values as mentioned above, the spin and parities can be interpreted in an extreme single-particle model as the coupling of the odd proton with the odd neutron.

In the odd-odd nuclei discussed here, $^{54,56}\text{Sc}$ and $^{56,58}\text{V}$, the odd proton is located in the
πf7/2 single-particle state based on ground state spin and parity systematics of lighter odd-A Sc and V isotopes. Beyond N = 32, in an extreme single-particle model, the νp3/2 state is filled and the odd proton in the πf7/2 can be coupled with an odd neutron in either the νf5/2 or νp1/2. Nordheim rules [15, 16] and Paar parabolas [17] can be used to determine whether the tentative experimental ground state spin and parity assignment is consistent with the odd proton coupling to an odd neutron in the νf5/2 or νp1/2 single-particle states. The possible spins obtainable from the coupling of an odd proton in the πf7/2 state to an odd neutron in the νf5/2 is (1-6)+. Both the proton and neutron can be considered particles (as opposed to holes) in their respective single-particle orbits and the relative energies of the (1-6)+ levels in the πf7/2 - νf5/2 multiplet as a function of spin are shown in Fig. 3, using the prescription of Paar [17]. It is observed that the energy of the levels as a function of spin form a parabola that is concave down with the 1+ state located at the minimum energy, in agreement with Nordheim’s strong rule. It should also be noted that the 6+ state is a local minimum and if populated could be an isomeric state. The relative energies of the (3,4)+ levels obtained from the coupling of the πf7/2 - νp1/2 single-particle states is shown in Fig. 3 again obtained using the description of Paar [17]. Here, the 3+ level is located below the 4+ level.

Both 56,58V have been assigned 1+ ground states based on the observation of large β decay branches to the 0+ ground states of 56,58Cr [8], respectively. From the discussion above and the Paar parabolas shown in Fig. 3 the 1+ assignment to the 56,58V ground states can only be obtained with the placement of the odd neutrons into the νf5/2 level and is more likely than a 6+ assignment. This suggests that in both 56,58V nuclei the νf5/2 state is below the νp1/2 level.

The odd neutron in 54Sc can be placed either in the νf5/2 or νp1/2 single-particle orbits. The spin and parity of 54Sc has been tentatively assigned as (3,4)+. As can be seen from Fig. 3 this assignment in inconsistent with the placement of the odd neutron in the νf5/2 single-particle state and is instead most likely due to the πf7/2 - νp1/2 coupling scheme. In 56Sc, with two additional neutrons, the experimentally determined ground state spin and parity is tentatively 1+ [5], consistent with the placement of the odd neutron in the νf5/2 state. Additionally, the presence of an isomeric state, tentatively assigned as 6+, has been inferred in 56Sc [6] based on the population of high-spin levels in the daughter 56Ti. A 6+ isomer is consistent with the Paar parabolas describing the πf7/2 - νf5/2 multiplet. Thus, from the ground state spin and parity assignments made to the odd-odd Sc ground states the νp1/2 appears to be lower in energy than the νf5/2 state. The monopole migration of the νf5/2 leads to an inversion of single particle ordering of the νf5/2 and νp1/2 between the V and Sc nuclei.

4. Beta decay of odd mass nuclei

To complement the data on odd-odd nuclei numerous experimental results have been obtained on the β decays of odd-A nuclei in the pf-shell region, including 55Sc, 55,57Ti, and 57,59V. Tentative ground state spin and parities for these nuclei along with schematic single-particle neutron levels are shown in Fig. 3 and can further our understanding of the monopole migration of the νf5/2 level as protons are removed from the πf7/2 state.

The β decay of 55Ti has been previously studied and compared to GXPF1 shell-model calculations [7]. The complex β decay feeding observed from the 55Ti ground state to states in 55V suggested that the νp1/2 state was not the dominant single-particle configuration, leading to the placement of the the νf5/2 state below the νp1/2 state in 55Ti. This conclusion was strengthened following the experimental investigation of the 55Sc β decay [6]. With an odd proton in the πf7/2 state the spin and parity of 55Sc is predicted to be 7/2−, consistent with the systematic trend of other odd-A πf7/2 nuclei. The half-life of 55Sc compares well with GXPF1 shell model calculations assuming a 7/2− ground state for 55Sc. The experimental indication of a large β decay branch from 55Sc to the ground state of 55Ti tends to support a 5/2− or 7/2−
Figure 3. V, Ti, and Sc isotopes in the neutron-rich pf-shell region with tentatively assigned ground state spin and parities. The ground state spin and parities can be examined using an extreme single-particle model to infer the schematic neutron single-particle states shown. The lower portion of the figure show the energy splitting of the multiplets formed through the coupling of the $\pi f_7/2$ - $\nu f_5/2$ or $\pi f_7/2$ - $\nu p_{1/2}$ single-particle levels.

The ground state spin and parity of $^{57}$Ti was expected to be $5/2^-$ based on shell model calculations using the GXPF1 interaction obtained from the placement of the odd neutron in the $\nu f_5/2$ state. There was an overall remarkable agreement between shell model calculations of the $^{57}$Ti $\beta$ decay assuming a $5/2^-$ ground state and the experimental decay scheme presented in Ref. [4]. Many experimental features including a large $\beta$ decay branch to the $^{57}$V ground state, a significant $\beta$ feeding to four states above 1500 keV, and a low-energy triplet of levels in $^{57}$V were reproduced by GXPF1 calculations. The similarities between experiment results and theoretical expectations lead to the placement of the $\nu f_5/2$ below the $\nu p_{1/2}$ state in $^{57}$Ti.

Interpretation of the $^{57}$V $\beta$ decay were initially complicated by a wide range of possibilities for the $^{57}$V ground state spin and parity of $(3/2, 5/2, 7/2)^-$. The first tentative $^{57}$V ground state spin and parity assignment of $3/2^-$ [19] was at odds with more recent measurements favoring higher ground state spins based on a larger observed $\beta$ decay branch to the $^{57}$Cr ground state [8].

The last odd-A nucleus studied in the pf-shell region was the $\beta$ decay of $^{59}$V [4]. The deduced level scheme resulted in the inversion of the level ordering of the two lowest energy states compared to previous experimental results [18]. The low-energy level scheme for $^{59}$Cr calculated using GXPF1 was shown in Ref. [18] and included seven negative parity states below 1.6 MeV. Experimentally, eight levels below 1.6 MeV were identified and are all most likely have spins $\leq 9/2$ with negative parity. The presence of an excited $9/2^+$ state in $^{59}$Cr at 503 keV indicates the increasing importance of the $\nu g_{9/2}$ intruder state. Therefore, disagreement between theory and experiment is not unexpected since the $\nu g_{9/2}$ state is not included in the
GXPFP1 model space.

5. Summary

In summary, a large program investigating the low-energy structure of neutron-rich pf-shell nuclei through $\beta$-delayed $\gamma$-ray spectroscopy has been carried out at the NSCL over the past few years. The central theme of these investigations was an attempt to understand the role of the proton-neutron monopole migration of the $\nu f_{5/2}$ state as protons are removed from the $\pi f_{7/2}$ level.

From the $\beta$ decay of odd-odd nuclei the shell closure at $N = 32$ was identified based on the systematic increase of the $E(2^+)$ state as a function of neutron number. The $N = 34$ shell closure predicted by shell model calculations, using the GXPFP1 effective interaction, in the Ti isotopes was not observed. The $E(2^+)$ in $^{56}$Ti has been observed at an energy $\sim 0.4$ MeV lower than predicted. This discrepancy in the theoretical predictions was remedied with a small alteration to GXPFP1 and resulted in the introduction of the GXPFP1A effective interaction. The new effective interaction successfully reproduces $E(2^+)$ for the Ca, Ti, and Cr isotopes. The shell gap at $N = 34$ is reduced slightly in magnitude but should still be observable in $^{54}$Ca and experiments to verify these predictions are underway.

The ground state spin and parity of odd-odd and odd-A nuclei in the pf shell region were interpreted in an extreme single-particle model to follow the monopole migration of the $\nu f_{5/2}$ single-particle state as protons are removed from the $\pi f_{7/2}$ state. The results indicated that the $\nu f_{5/2}$ state is below the $np_{1/2}$ state in both the V and Ti nuclei. The situation is reversed in the Sc isotopes with the $\nu f_{5/2}$ state above the $np_{1/2}$ state. The migration of the $\nu f_{5/2}$ state follows the same qualitative trend predicted by GXPFP1 calculations but, as already mentioned, the shell gap at $N = 34$ fails to develop in the Ti isotopes but still could be present in $^{54}$Ca.

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