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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 $\pi f_{7/2} - \nu f_{5/2}$ proton-neutron monopole interaction in neutron-rich pf -shell nuclei above ^{48}Ca . 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 $\nu f_{5/2}$ as protons are removed from the $\pi f_{7/2}$ 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 $\pi f_{7/2}$ and $\nu f_{5/2}$ 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 $\nu f_{5/2}$ monopole shift and the development of new shell structure in the $\pi f_{7/2} - \nu pf$ region of the chart of the nuclides (see Fig. 1 for isotopes studied). The monopole shift of the $\nu f_{5/2}$ 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.

Z=28	Ni56	Ni57	Ni58	Ni59	Ni60	Ni61	Ni62	Ni63	Ni64	Ni65	Ni66	Ni67	Ni68
	Co55	Co56	Co57	Co58	Co59	Co60	Co61	Co62	Co63	Co64	Co65	Co66	Co67
	Fe54	Fe55	Fe56	Fe57	Fe58	Fe59	Fe60	Fe61	Fe62	Fe63	Fe64	Fe65	Fe66
	Mn53	Mn54	Mn55	Mn56	Mn57	Mn58	Mn59	Mn60	Mn61	Mn62	Mn63	Mn64	Mn65
	Cr52	Cr53	Cr54	Cr55	Cr56	Cr57	Cr58	Cr59	Cr60	Cr61	Cr62	Cr63	Cr64
	V51	V52	V53	V54	V55	V56	V57	V58	V59	V60	V61	V62	V63
	Ti50	Ti51	Ti52	Ti53	Ti54	Ti55	Ti56	Ti57	Ti58	Ti59	Ti60	Ti61	
	Sc49	Sc50	Sc51	Sc52	Sc53	Sc54	Sc55	Sc56	Sc57	Sc58	Sc59		
	Z=20	Ca48	Ca49	Ca50	Ca51	Ca52	Ca53	Ca54	Ca55	Ca56	Ca57		
	N=28												

Figure 1. Region of the chart of the nuclides centered around the pf shell. Stable isotopes are shown in black. β -decaying parent states studied via delayed γ -ray spectroscopy at the NSCL are shown in gray.

2. Experiment

β 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 γ -ray spectroscopy. The pf nuclides of interest were produced in fragmentation reactions of a ^{86}Kr beam on a ^9Be target. The nuclides were separated using the A1900 fragment separator [9] and implanted into a double-sided silicon microstrip detector, part of the β counting system [10]. Twelve detectors from the NSCL Segmented Germanium Array [11] surrounded the counting system and were used to monitor emitted γ rays. Experimental properties deduced from the studies included β -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 β decay of the odd-odd nuclei $^{54,56}\text{Sc}$ and $^{56,58}\text{V}$ were studied to determine the low-energy level structure of the even-even $^{54,56}\text{Ti}$ and $^{56,58}\text{Cr}$ 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 $f_{5/2}$ 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 $\pi f_{7/2}$ level and the resulting effects on the low energy structure of $^{54,56}\text{Ti}$ and $^{56,58}\text{Cr}$. 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

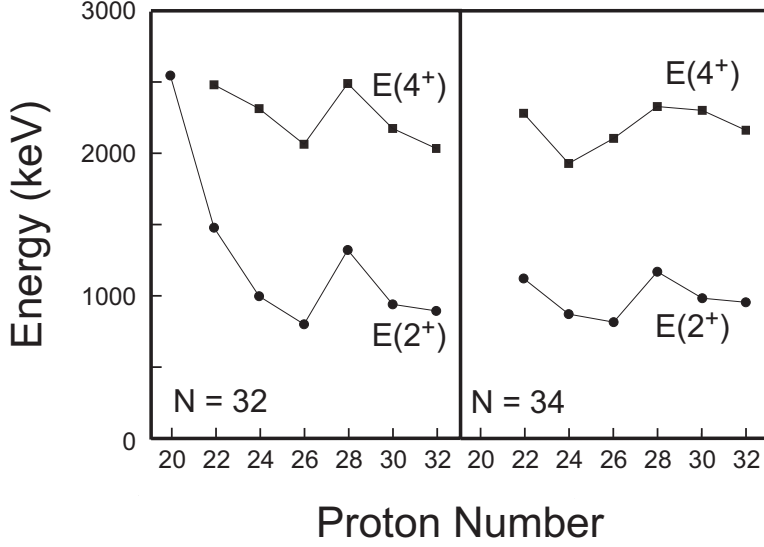


Figure 2. Systematic variation of the $E(2_1^+)$ and $E(4_1^+)$ for the $N = 32$ and $N = 34$ isotones. The dramatic increase in the $E(2_1^+)$ from Fe to Cr observed in the $N = 32$ isotones results from the $N = 32$ shell closure. This dramatic increase is absent in the $N = 34$ isotones.

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}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 ~ 0.4 MeV lower than the shell model results obtained with the GXPF1 interaction. The experimental 2_1^+ energy in ^{56}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}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

$\pi f_{7/2}$ 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 $\nu p_{3/2}$ state is filled and the odd proton in the $\pi f_{7/2}$ can be coupled with an odd neutron in either the $\nu f_{5/2}$ or $\nu p_{1/2}$. 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 $\nu f_{5/2}$ or $\nu p_{1/2}$ single-particle states. The possible spins obtainable from the coupling of an odd proton in the $\pi f_{7/2}$ state to an odd neutron in the $\nu f_{5/2}$ 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 $\pi f_{7/2} - \nu f_{5/2}$ 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 $\pi f_{7/2} - \nu p_{1/2}$ 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 $^{56,58}\text{V}$ have been assigned 1^+ ground states based on the observation of large β decay branches to the 0^+ ground states of $^{56,58}\text{Cr}$ [8], respectively. From the discussion above and the Paar parabolas shown in Fig. 3 the 1^+ assignment to the $^{56,58}\text{V}$ ground states can only be obtained with the placement of the odd neutrons into the $\nu f_{5/2}$ level and is more likely than a 6^+ assignment. This suggests that in both $^{56,58}\text{V}$ nuclei the $\nu f_{5/2}$ state is below the $\nu p_{1/2}$ level.

The odd neutron in ^{54}Sc can be placed either in the $\nu f_{5/2}$ or $\nu p_{1/2}$ single-particle orbits. The spin and parity of ^{54}Sc has been tentatively assigned as $(3,4)^+$. As can be seen from Fig. 3 this assignment is inconsistent with the placement of the odd neutron in the $\nu f_{5/2}$ single-particle state and is instead most likely due to the $\pi f_{7/2} - \nu p_{1/2}$ coupling scheme. In ^{56}Sc , 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 $\nu f_{5/2}$ state. Additionally, the presence of an isomeric state, tentatively assigned as 6^+ , has been inferred in ^{56}Sc [6] based on the population of high-spin levels in the daughter ^{56}Ti . A 6^+ isomer is consistent with the Paar parabolas describing the $\pi f_{7/2} - \nu f_{5/2}$ multiplet. Thus, from the ground state spin and parity assignments made to the odd-odd Sc ground states the $\nu p_{1/2}$ appears to be lower in energy than the $\nu f_{5/2}$ state. The monopole migration of the $\nu f_{5/2}$ leads to an inversion of single particle ordering of the $\nu f_{5/2}$ and $\nu p_{1/2}$ 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 ^{55}Sc , $^{55,57}\text{Ti}$, and $^{57,59}\text{V}$. 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 $\nu f_{5/2}$ level as protons are removed from the $\pi f_{7/2}$ state.

The β decay of ^{55}Ti has been previously studied and compared to GXPF1 shell-model calculations [7]. The complex β decay feeding observed from the ^{55}Ti ground state to states in ^{55}V suggested that the $\nu p_{1/2}$ state was not the dominant single-particle configuration, leading to the placement of the $\nu f_{5/2}$ state below the $\nu p_{1/2}$ state in ^{55}Ti . This conclusion was strengthened following the experimental investigation of the ^{55}Sc β decay [6]. With an odd proton in the $\pi f_{7/2}$ state the spin and parity of ^{55}Sc is predicted to be $7/2^-$, consistent with the systematic trend of other odd-A $\pi f_{7/2}$ nuclei. The half-life of ^{55}Sc compares well with GXPF1 shell model calculations assuming a $7/2^-$ ground state for ^{55}Sc . The experimental indication of a large β decay branch from ^{55}Sc to the ground state of ^{55}Ti tends to support a $5/2^-$ or $7/2^-$

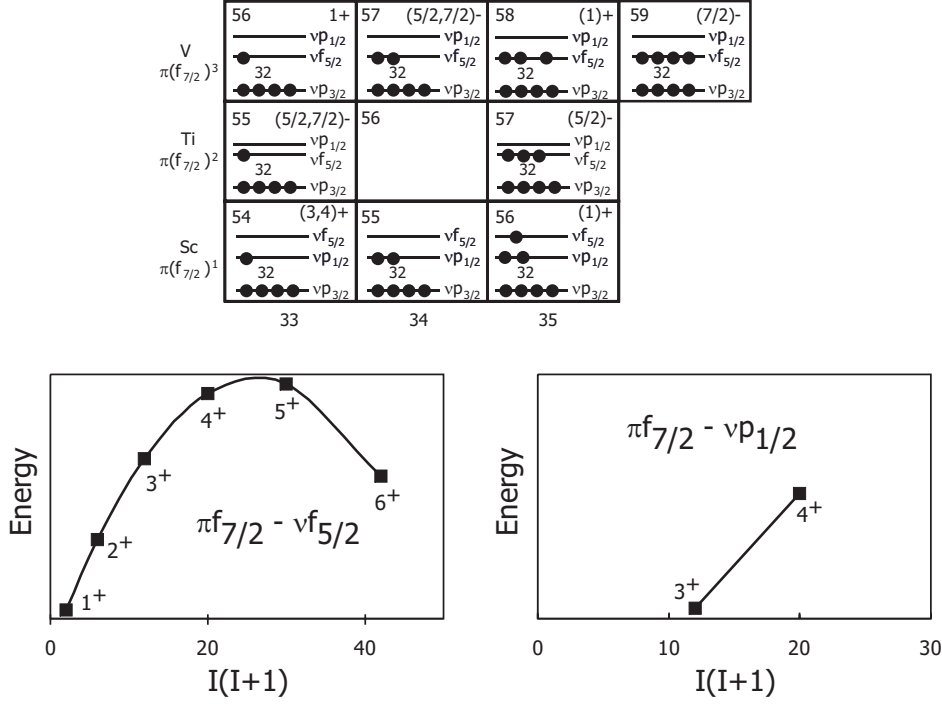


Figure 3. V, Ti, and Sc isotopes in the neutron-rich pf -shell region with tentatively assigned ground state spin and parities. The ground state spin and parities can be examined using an extreme single-particle model to infer the schematic neutron single-particle states shown. The lower portion of the 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

ground state spin and parity in ^{55}Ti .

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 β decay assuming a $5/2^-$ ground state and the experimental decay scheme presented in Ref. [4]. Many experimental features including a large β decay branch to the ^{57}V ground state, a significant β 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 β 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 β decay branch to the ^{57}Cr ground state [8].

The last odd-A nucleus studied in the pf -shell region was the β 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

GXPF1 model space.

5. Summary

In summary, a large program investigating the low-energy structure of neutron-rich pf -shell nuclei through β -delayed γ -ray spectroscopy has been carried out at the NSCL over the past few years. The central theme of these investigation 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 β decay of odd-odd nuclei the shell closure at $N = 32$ was identified based on the systematic increase of the $E(2_1^+)$ state as a function of neutron number. The $N = 34$ shell closure predicted by shell model calculations, using the GXPF1 effective interaction, in the Ti isotopes was not observed. The $E(2_1^+)$ in $^{56}\text{Ti}_{34}$ was observed at an energy ~ 0.4 MeV lower than predicted. This discrepancy in the theoretical predictions was remedied with a small alteration to GXPF1 and resulted in the introduction of the GXPF1A effective interaction. The new effective interaction successfully reproduces $E(2_1^+)$ 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 $\nu p_{1/2}$ 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 $\nu p_{1/2}$ state. The migration of the $\nu f_{5/2}$ state follows the same qualitative trend predicted by GXPF1 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 .

Acknowledgments

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