Probing nuclear structure around *Z, N = 28* using stable and radioactive beams

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This study examines nuclear structure near the magic numbers Z=28 and N=28 through the beta decay of neutron-rich ^{45}Cl and high-spin studies of ^{61}Ni. The decay of ^{45}Cl reveals a weakening of the N=28 shell gap, leading to deformation in neutron-rich argon isotopes. The ^{61}Ni study uncovers the coexistence of single-particle and collective excitations, including magnetic rotational bands. Both experiments highlight the evolution of shell closures and collective behavior near the Z, N=28 magic shell.

1. Introduction

The study of nuclear structure around the magic numbers Z=28 and N=28 is essential for understanding the evolution of nuclear shell closures and the development of deformation and collectivity. As either protons or neutrons move away from these magic numbers, the strong shell gaps can weaken, leading to the onset of phenomena such as nuclear deformation, shape coexistence, and collective excitations. These magic numbers, which reflect strong shell closures, are associated with nuclear stability, but recent studies have shown that they evolve significantly as nuclei become more neutron-rich [1-2]. This paper discusses two distinct experiments exploring nuclear structure near Z, N= 28, one involving the beta decay of neutron-rich ^{45}Cl and the other probing the high-spin states in Z=28, ^{61}Ni, using radioactive and stable beams, respectively.

Experimental Setup:

The production of neutron-rich nuclei, such as ^{45}Cl, and the study of exotic nuclear structures require sophisticated experimental setups. At NSCL, MSU, USA the high-energy ^{48}Ca beam was fragmented by a beryllium target to produce neutron-rich isotopes. The A1900 fragment separator played a crucial role in isolating ^{45}Cl from the other products of the fragmentation process. The selected fragments were then implanted into a double-sided silicon strip detector (DSSD) for identification and beta-decay measurements. A β-counting system, along with HPGe detectors, enabled the detection of both the β-particles and the associated gamma rays in coincidence with the implanted enriched isotopes, allowing for the reconstruction of decay schemes. The selection of neutron-rich isotopes is shown in the particle identification (PID) plot (Fig. 1).

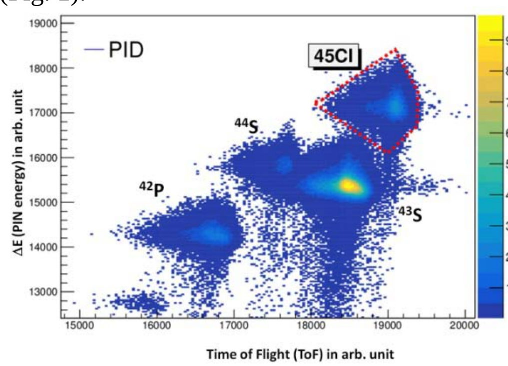

Fig. 1 Particle identification from the implants at Beta counting station at NSCL, MSU, USA

To produce ^{61}Ni, a fusion-evaporation reaction, ^{50}Ti(^{14}C,3n)^{61}Ni, was utilized. A self-supporting ^{50}Ti target was bombarded with a 40-MeV ^{14}C radioactive beam at FSU John D. Fox accelerator facility. The gamma rays emitted as the nucleus de-excited were captured using a Compton suppressed HPGe Clover detectors array.

β^- Decay of Neutron-Rich ^{45}Cl

The beta-minus decay of neutron-rich ^{45}Cl (Z=17, N=28) offers insights into the evolution of the N=28 shell closure in neutron-rich environments. ^{45}Cl primarily decays via beta emission, populating states in ^{45}Ar, with neutron emission leading to excited states in ^{44}Ar. The decay revealed that low-lying negative-parity states in ^{45}Ar are described by single-particle neutron excitations in the fp-shell, while positive-parity states require neutron excitations across the N=28 shell gap, indicating the weakening of the N=28 shell closure [3].

The experiment measured a half-life of 513(36) ms for ^{45}Cl, longer than previously reported. The strong population of the $5/2^+$ state at 3296 keV in ^{45}Ar from β^--decay supports a $3/2^+$ spin-parity assignment for the ^{45}Cl ground state, resolving earlier ambiguity [4]. This suggests normal filling of the proton $d_{3/2}$ orbital, with the $s_{1/2}$ orbital largely unoccupied. The large Q_{β^-} value enabled the identification of new highly excited positive-parity states in ^{44}Ar via β-delayed neutron emission, with tentative spin-parity assignments made for the first time [5].

Shell-model calculations using the FSU interaction successfully reproduce many of the experimental results, especially for positive-parity states. The strong population of these states aligns with expected Gamow-Teller transitions dominating ^{45}Cl decay. These results provide evidence of the weakening N=28 shell gap in neutron-rich systems, supporting the idea that collectivity and deformation emerge as the N=28 magic number becomes less robust. The identification of a 0^+ excited state in ^{44}Ar further supports shape coexistence, with both spherical and deformed structures present in this region.

High-Spin Structure of ^{61}Ni:

In a complementary study, the nuclear structure of ^{61}Ni (Z=28, N=33) was investigated at high-spin states at FSU, USA. In this study, the level scheme of ^{61}Ni was extended upto the excitation energy of 12.8 MeV and a spin-parity of $35/2^+$, with 76 new transitions and 28 new levels identified [6].

At low excitation energies, the observed negative-parity states in ^{61}Ni were interpreted as single-particle excitations involving neutrons in the fp-shell and the $g_{9/2}$ orbital. At higher excitation energies, however, the structure becomes more collective, with the identification of two rotational bands. These bands suggest moderate axial deformation in ^{61}Ni, signaling the coexistence of single-particle and collective excitations at Z=28.

For the first time, two sequences of magnetic dipole (M1) transitions forming magnetic rotational (MR) bands in ^{61}Ni are reported. These MR bands, associated with the "shears mechanism," occur in near-spherical nuclei. MR bands were also observed in the neighboring ^{60}Ni nucleus in a recent study [7]. The energies of the MR band levels were plotted against the shears angle, following the geometrical model, which suggests the involvement of high-j orbitals. Shell-model calculations using the GXPF1Br+VMU interaction effectively reproduced both single-particle and collective excitations in ^{61}Ni, providing a unified view of its nuclear structure.

Conclusion:

These studies investigate nuclear structure near the Z, N = 28 magic numbers, highlighting the interplay between single-particle & collective excitations. The β-decay of ^{45}Cl illustrates the evolution of the N=28 shell closure with increasing neutrons, resulting in deformation in neutron-rich Ar isotopes. Meanwhile, the high-spin study of ^{61}Ni reveals collective behavior, including rotational and magnetic rotational bands, alongside single-particle excitations.

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