In-beam $\gamma$-ray spectroscopy of very neutron-rich nuclei: Excited states in $^{46}$S and $^{48}$Ar

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We report on the first in-beam $\gamma$-ray spectroscopy study of the very neutron-rich nucleus $^{46}$S. The $N = 30$ isotones $^{46}$S and $^{48}$Ar were produced in a novel way in two steps that both necessarily involve nucleon exchange and neutron pickup reactions. $^{9}$Be($^{48}$Ca, $^{48}$K)X followed by $^{9}$Be($^{48}$K, $^{48}$Ar+γ)X at 85.7 MeV/u mid-target energy and $^{9}$Be($^{48}$Ca, $^{46}$Cl)X followed by $^{9}$Be($^{46}$Cl, $^{46}$S+γ)X at 87.0 MeV/u mid-target energy, respectively. The results are compared to large-scale shell-model calculations in the $sd$-$pf$ shell using the SDPF-NR effective interaction and $Z$-dependent modifications.

The experiment was performed to examine the structure of the atomic nucleus in the regime of large neutron excess is driving experimental and theoretical research programs worldwide. Modifications to the familiar ordering of single-particle orbits or new phenomena like the development of neutron halos have been observed in experiments and their microscopic description challenges theories that quantify the nuclear many-body system at large proton-neutron asymmetry.

The experimental challenges are (i) the production of these short-lived, radioactive nuclei and (ii) the study of their properties. Neutron-rich nuclei lighter than calcium are efficiently produced in-flight by the fragmentation of a stable $^{48}$Ca primary beam in the collision with a $^{9}$Be target at energies exceeding 100 MeV/nucleon. The nature of this production mechanism implies that the majority of the produced fragments has fewer neutrons than the projectile. Reactions, however, that involve the removal of several protons with no net loss of neutrons or additional neutrons being picked up from the target nucleus proceed with comparably small cross sections (see for example [1, 2] and references within). The resulting secondary beams of rare isotopes are typically available for experiments at velocities exceeding 30% of the speed of light. A variety of techniques have been developed to enable in-beam spectroscopy studies of fast rare-isotope beams with intensities down to a few atoms per second [3].

Here we report on the in-beam $\gamma$-ray spectroscopy of $^{46}$S and $^{48}$Ar, each produced in a novel way in two steps that both necessarily involve heavy-ion induced nucleon exchange and/or neutron pickup reactions: $^{9}$Be($^{48}$Ca, $^{48}$K)X followed by $^{9}$Be($^{48}$K, $^{48}$Ar+γ)X at 85.7 MeV/u mid-target energy and $^{9}$Be($^{48}$Ca, $^{46}$Cl)X followed by $^{9}$Be($^{46}$Cl, $^{46}$S+γ)X at 87.0 MeV/u mid-target energy, respectively. $^{48}$Ar and $^{46}$S have neutron number $N = 30$, two neutrons more than the $^{48}$Ca primary beam (see Fig. 1). These are the heaviest argon and sulfur isotopes studied with $\gamma$-ray spectroscopy to date. As a result, the first excited $2^+$ state of $^{46}$S was observed for the first time. This is the first time that $^{9}$Be-induced nucleon exchange reactions at intermediate beam energies are used to perform in-beam $\gamma$-ray spectroscopy of nuclei more neutron-rich than the projectile.

![Nuclear Chart](image-url)

**FIG. 1:** (Color online) Part of the nuclear chart showing the most neutron-rich nuclei known to exist out to $Z = 18$. Highlighted are $^{48}$Ca (primary beam), $^{48}$K and $^{48}$Cl (secondary beams) and $^{48}$Ar and $^{46}$S (respective final reaction residues). For comparison, the observation of $^{44}$Si [4], $^{46}$Mg, $^{42}$Al, and possibly $^{43}$Al [5] was only achieved in 2007.

The region around $^{42}$Si with neutron number $N = 28$ has attracted much attention in recent years. While initial one- and two-proton knockout experiments hinted a proton sub-shell gap at $Z = 14$ [7], inelastic proton scattering in the chain of silicon isotopes [8, 9] and ultimately the observation of the first excited $2^+$ state of $^{42}$Si at low energy [10] revealed the breakdown of the $N = 28$ shell gap for silicon. Data on the $N = 30$ isotones in this surprising region are scarce. Excited states...
in $^{48}\text{Ar}$ have been observed following deep-inelastic reactions [11] while the existence of $^{44}\text{Si}$ has only been proven recently [1]. For $^{46}\text{S}$, its $\beta$-decay half-life [3] had been the only observable accessible to experiments.

Our experiments were performed at the Coupled Cyclotron Facility at NSCL on the campus of Michigan State University. The secondary beams of $^{48}\text{K}$ (pure) and $^{46}\text{Cl}$ (purity exceeding 98\%) were produced from a 140 MeV/u stable $^{48}\text{Ca}$ beam impinging on a 705 mg/cm$^2$ $^{9}\text{Be}$ production target and separated using a 390 mg/cm$^2$ Al degrader in the A1900 fragment separator [12]. The momentum acceptance of the separator was restricted to 0.5\% for the $^{48}\text{K}$ beam and to 2\% for the much less intense $^{46}\text{Cl}$ beam, yielding on-target rates of $110 \times 10^3$ particles/s and $6 \times 10^3$ particles/s, respectively.

The $^{9}\text{Be}$ reaction target (376 mg/cm$^2$ thick) was surrounded by the high-resolution $\gamma$-ray detection system SeGA, an array of 32-fold segmented HPGe detectors [13]. The segmentation allows for event-by-event Doppler reconstruction of the $\gamma$ rays emitted by the reaction residues in flight. The emission angle entering the Doppler reconstruction is determined from the location of the segment with the largest energy deposition. Sixteen detectors were arranged in two rings (90° and 37° central angles with respect to the beam axis). The 37° ring was equipped with seven detectors while nine detectors were located at 90°. The photopeak efficiency of the array was calibrated with standard sources and corrected for the Lorentz boost of the $\gamma$-ray distribution emitted by nuclei moving at 39\% of the speed of light.

The particle identification was performed event by event with the focal-plane detection system of the large-acceptance S800 spectrograph [14]. The energy loss measured in the S800 ionization chamber is plotted versus the ion’s time of flight. The energy loss measured in the S800 ionization chamber is plotted versus the ion’s time of flight. The energy loss measured in the S800 ionization chamber is plotted versus the ion’s time of flight. $^{48}\text{Ar}$ can be unambiguously separated from the projectile-like fragmentation residues produced in the reaction $^{48}\text{K}+^{9}\text{Be}$.

\[ \sigma = 0.13(1) \text{ mb} \quad \text{and} \quad \sigma = 0.057(6) \text{ mb} \] for the $^{9}\text{Be}(^{48}\text{K},^{48}\text{Ar})X$ and $^{9}\text{Be}(^{46}\text{Cl},^{46}\text{S})X$ reactions were derived from the yields of $^{48}\text{Ar}$ and $^{46}\text{S}$ divided by the number of incoming $^{48}\text{K}$ and $^{46}\text{Cl}$ projec-
tiles, respectively, relative to the number density of the reaction target. For each measurement, the normalization of the incoming beam rate was evaluated frequently and a systematic uncertainty of 4% was deduced and added in quadrature to the statistical uncertainty.

The γ-ray spectra observed in coincidence with 46S and 48Ar nuclei – event by event Doppler reconstructed – are displayed in Fig. 4. The γ-ray transition at 952(8) keV in 46S is attributed to the decay of the 2⁺ state to the 0⁺ ground state. This constitutes the first observation of an excited state in this nucleus. Gamma-ray transitions at 1037(6) keV and 1706(10) keV were observed in coincidence with 46S and assigned to the 2⁺ → 0⁺ and 4⁺ → 2⁺ transitions, respectively, in agreement with the results of [11]. Populations of 39(8)% and 34(5)% for the 2⁺ and 4⁺ states in 48Ar, respectively, were deduced from the efficiency-corrected peak areas, while the remainder is assumed to populate the ground state. In 46S, 63(12)% of the reactions populate the 2⁺ state. Within our limited statistics, there is no evidence for other γ-ray transitions in the spectrum of 46S.

The energy of the first 2⁺ state of 46S we report here constitutes the first measurement of an excited state in a sulfur isotope more neutron-rich than 44S, whose measured collectivity [16] ultimately proved changes to the nuclear structure at neutron number N = 28. The consistent description of the onset of collectivity at N = 28 in the isotopic chains of sulfur (Z = 16) and silicon (Z = 14) has been a formidable challenge for shell-model calculations and was achieved only recently by Nowacki and Poves in devising two effective interactions, one for Z ≤ 14 and one for Z > 14 [17].

It is now interesting to track the evolution of the 2⁺ energies beyond the eroded N = 28 magic number in the chains of silicon, sulfur and argon isotopes to probe the dependence of the structure at N = 30 on the monopole-shift and pairing modifications that were necessary to describe the silicon isotopes within the shell model.

To study this systematically, shell-model configuration-interaction calculations were carried out in the model space of the sd shell for protons and the pf shell for neutrons starting from the SDFP-NR interaction [15] and introducing a Z-dependent, linear interpolation for pairing and monopole modifications. The experimental energies of the 2⁺ states (Fig. 5(a)) are compared with those obtained with the SDFP-NR Hamiltonian [13] (Fig. 5(b)). Experiment and theory differ in several ways, in particular for silicon isotopes where the calculated energies are about 400 keV too high for 40Si (and for 36,38Si, not shown) and 700 keV too high for 42Si.

Our first modification to SDFP-NR is a reduction of the fp shell J = 0⁺ matrix element by 0.85 for Z = 14. This brings the energy of the 2⁺ state in 40Si (and 36,38Si, not shown) into better agreement with experiment. The likely reason for this reduction, as discussed in [17], is that the reduced proton 2p − 2h core-polarization contributions to the effective interaction for silicon compared to calcium, attributed to the larger shell gap for the orbits involved in the case of silicon (i.e., d5/2 to f7/2) compared to that of calcium (i.e., d3/2 to f5/2). These core-polarization contributions are likely the reason for the need of two different effective interactions in this region [17]. The results for sulfur and argon in Fig. 5(c) were obtained with a linear interpolation in terms of Z between SDFP-NR (for calcium, Z = 20) to SDFP-NR2 (for silicon, Z = 14). A similar argument was used to explain the reduction of the sd shell pairing in the carbon isotopes relative to the oxygen isotopes [18].

Our second modification is to reduce the gap between the neutron f7/2 and p3/2, p1/2 orbitals by 1.0 MeV to obtain the interaction SDFP-NR3 for the silicon isotopes. The results obtained with a linear interpolation in terms of Z between SDFP-NR (for calcium) to SDFP-NR3 (for silicon) are shown in Fig. 5(d). A possible reason for the reduction of the shell gap is the lowering of single-particle energies of low-ℓ orbitals (ℓ = 1) relative to those of high ℓ orbitals (ℓ = 3) when the energies become small as one approaches the neutron drip line – see Fig. 4 in [19].

The SDFP-NR3 results for 2⁺ energies of silicon are in good agreement with experiment while the 2⁺ energies of 42S and 44S obtained with the interpolated interac-

![FIG. 4: Event-by-event Doppler reconstructed γ-ray spectra detected in coincidence with 46S and 48Ar. The 952(8) keV peak is attributed to the de-excitation of the 2⁺ state in 46S. There is no evidence for peaks other than this transition. The two peaks observed at 1037 keV and 1706 keV for 48Ar are attributed to the 2⁺ → 0⁺ and 4⁺ → 2⁺ transitions, respectively, in agreement with a previous measurement [11].](image-url)
In summary, we used the $^9\text{Be}(^{48}\text{K},^{48}\text{Ar}+\gamma)X$ at above 85 MeV/nucleon mid-target energy for the first time to perform in-beam $\gamma$-ray spectroscopy of the $N = 30$ isotopes $^{48}\text{Ar}$ and $^{46}\text{S}$. These heavy-ion induced nucleon-exchange reactions can lead to very exotic nuclei with more neutrons than the projectile beam and thus may be considered a novel approach to reach closer toward the neutron drip line with $\gamma$-ray spectroscopy. $^{48}\text{Ar}$ and $^{46}\text{S}$ are the heaviest nuclei of their respective isotopic chains for which $\gamma$-ray transitions have been measured; the $2^+_1$ state of $^{46}\text{S}$ was established for the first time. The evolution of the $2^+_1$ energies for argon, sulfur and silicon isotopes with neutron numbers $N = 26$, $28$ and $30$ is tracked in comparison to large-scale shell-model calculations using the SDPF-NR effective interaction and $Z$-dependent interpolations between the original effective interaction and modified versions. Our studies revealed that the description of the $N = 30$ isotones improved, but at much reduced sensitivity, when applying the monopole-shift and pairing corrections required to describe the surprising nuclear structure at $N = 28$. In accordance with the work by Nowacki and Poves – the silicon isotopes emerge as key nuclei with a sudden change occurring in the effective interaction.

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**FIG. 5:** (Color online) Measured energies of the first $2^+_1$ states in silicon, sulfur and argon isotopes with neutron numbers $N = 26$, $28$ and $30$ (a) compared to shell-model calculations. The calculation in (b) uses the SDPF-NR effective interaction [13]. The calculations for the silicon isotopes in (c) use the SDPF-NR2 interaction which is derived by reducing the pf shell $J = 0^+$ matrix element by 0.85. The results for sulfur and argon in (c) are obtained from a linear interpolation in terms of $Z$ between SDPF-NR ($Z = 20$) and SDPF-NR2 ($Z = 14$). The calculations for the silicon isotopes in (d) use the interaction SDPF-NR3 derived by additionally lowering the neutron $p_{3/2}$ and $p_{1/2}$ orbitals by 1 MeV. The results for sulfur and argon in (d) are obtained from a linear interpolation in terms of $Z$ between the SDPF-NR ($Z = 20$) and the SDPF-NR3 ($Z = 14$) interactions.

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