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New low-energy 0^+ state and shape coexistence in ^{70}Ni

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In recent models, the neutron-rich Ni isotopes around $N = 40$ are predicted to exhibit multiple low-energy excited 0^+ states attributed to neutron and proton excitations across both the $N = 40$ and $Z = 28$ shell gaps. In ^{68}Ni, the three observed 0^+ states have been interpreted in terms of triple shape coexistence between spherical, oblate, and prolate deformed shapes. In the present work a new (0_2^+) state at an energy of 1567 keV has been discovered in ^{70}Ni using β-delayed, γ-ray spectroscopy following the decay of ^{70}Co. The precipitous drop in the energy of the prolate-deformed 0^+ level between ^{68}Ni and ^{70}Ni with the addition of two neutrons compares favorably with results of Monte Carlo Shell-Model calculations carried out in the large $fpg_{9/2}d_{5/2}$ model space which predict a 0_2^+ state at 1525 keV in ^{70}Ni. The result extends the shape-coexistence picture in the region to ^{70}Ni and confirms the importance of the role of the tensor component of the monopole interaction in describing the structure of neutron-rich nuclei.

Atomic nuclei display regular patterns as either the proton, Z, or neutron, N, number changes. Examples include such properties as the energy necessary to remove a pair of nucleons (protons or neutrons) from a nucleus and the excitation energy of the first 2^+ state in nuclei with even numbers of neutrons and protons. Such regularities eventually led to the establishment of the nuclear shell model wherein nucleons fill separate sets of single-particle states. The latter states cluster together in energy with large gaps between groups at characteristic nucleon numbers [1]: the so-called magic numbers. This nuclear shell structure is analogous to that observed in atomic systems responsible for the regular behavior of the chemical elements; e.g., the chemical inertness of the noble gases [2].

The shape of the nucleus, described by Bohr and Mottelson [3], also exhibits regularity with respect to the location of the shell gaps; near the gaps, nuclei are predominately spherical and more deformed shapes occur as a progression is made toward the middle of a shell. Transitions between spherical and deformed nuclei can occur rapidly as a function of neutron or proton number and have sometimes been used to infer the collapse of predicted shell closures [4] and the development of new ones [5].

Changes in shape can also occur within a single nucleus as a function of excitation energy, based on a redistribution of nucleons across a shell gap that can drive the nucleus toward deformation. Naively, the energy cost to promote a nucleon across the energy gap should be prohibitive, but residual proton-neutron interactions can provide an energy stabilization to offset the cost. When the energy gain obtained from the residual proton-neutron interactions is comparable to the magnitude of the shell gap, the probability of exciting an n-particle n-hole configuration increases and this excitation mode can drive the nucleus towards a deformed shape. Near a shell gap, in nuclei with even numbers of protons and neutrons, such excitations can give rise to multiple, low-energy 0^+ states often taken as a hallmark of shape coexistence. Shape coexistence occurs when two or more states with different underlying configurations of protons and/or neutrons associated with differing intrinsic shapes coexist at similar excitation energies [6]. Prominent examples of this type of shape coexistence can be found in both the Hg [7–9] and Sn [10–13] regions. In particular, ^{186}Pb exhibits triple shape coexistence between spherical, prolate, and oblate configurations, all located within 700 keV [14].

The region around ^{68}Ni has recently been studied extensively, both experimentally and theoretically, and an overall picture of shape coexistence is progressively emerging. Three 0^+ states in $^{68}_{28}$Ni$_{40}$, at 0, 1604 [15, 16], and 2511 keV [17] associated with multiple particle-hole excitations across $Z = 28$ and $N = 40$ [18, 19], have been interpreted in terms of spherical, oblate, and prolate shapes based on comparisons with Monte Carlo Shell-Model (MCSM) calculations [15, 20]. The presence of spherical-prolate shape coexistence in the lighter ^{66}Ni [21], as well as in ^{68}Ni [21, 22], is also expected based on mean-field calculations. However, the mean-field and shell-model calculations have qualitatively different expectations for the presence of shape coexistence beyond $N = 40$ in ^{70}Ni, with the former finding none and the latter suggesting that the prolate excitation occurs at lower excitation energy in ^{70}Ni than in ^{68}Ni. The key difference between the two sets of calculations can be traced to the role of the tensor component of the monopole interaction [23, 24]. As neutrons are added from ^{68}Ni to ^{70}Ni, the occupancy of the $g_{9/2}$ orbital increases and alters the energy gap at $Z = 28$, increasing the probability of proton particle-hole excitations across the gap. These proton excitations drive the nucleus toward a deformed shape, further enhancing the occupancy of the neutron $g_{9/2}$ orbital. As a result, when progressing to more neutron-rich Ni isotopes, only the more recent shell-model calculations have predicted an increase in the depth of the prolate potential well and a decrease in the energy of the associated 0^+ state [20]. Identification of a low-energy excited (0^+) state in ^{70}Ni elevates the experimental evidence of shape coexistence in the Ni isotopes from its isolation to a single nucleus, ^{68}Ni, to a more general characteristic of the region and validates the importance of the tensor interaction.

In the present manuscript, a new (0^+) state in ^{70}Ni at 1567 keV is identified and is in agreement with recent theoretical predictions, expanding the picture of shape coexistence in the region. Excited states in ^{70}Ni were populated through the β decay of ^{70}Co at the National Superconducting Cyclotron Laboratory (NSCL). Ions of ^{70}Co were produced via projectile fragmentation on a ^{9}Be target of a ^{76}Ge primary beam at 130 MeV/A. Fragments of interest were separated from other reaction products using the A1900 fragment separator [25] and transmitted to the experimental end station. This β-decay station consisted of a series of three silicon PIN detectors located approximately 1 m upstream of a central implantation detector. All incident ions were deposited 1 mm deep into a planar Germanium Double-Sided Strip Detector (GeDSSD) [26] and identified event-by-event using standard $\Delta E - TOF$ techniques. The GeDSSD is electrically segmented into 16 5-mm strips on one side and 16 5-mm orthogonal strips on the other for a total of 256 pixels. The position and time of arrival of each ion was recorded and subsequent β-decay electrons were correlated with previously implanted ions using both spatial and temporal information. The GeDSSD was surrounded by 16 detectors of the Segmented Germanium Array (SeGA) [27] arranged into two concentric rings of eight detectors each to record the β-delayed γ rays. All detectors were read out using the NSCL digital data acquisition system [28]. Absolute γ-ray efficiencies were determined using a NIST-calibrated ^{154,155}Eu source and GEANT4 simulations [29] of the detection system.

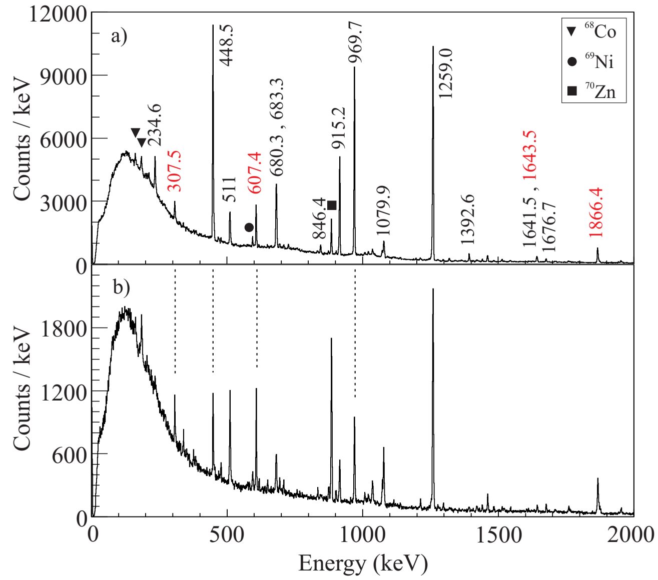

FIG. 1. (color online) Spectrum of β-delayed γ rays observed within (a) 0-500 ms and (b) 500-1000 ms of the arrival of a ^{70}Co ion at the experimental station. Gamma rays with black energy labels, such as the 448.5- and 969.7-keV γ rays, follow the β decay of the high-spin, short-lived ^{70}Co isomeric state, while γ-rays with red energy labels, like those at 307.5, 607.4, and 1866.4 keV, are associated with the decay of the low-spin, long-lived ^{70}Co isomer. For all transitions shown in red, their intensities relative to the 1259.0-keV γ-ray increase from (a) to (b). Additional γ rays associated with ^{69}Co, ^{69}Ni, and ^{70}Zn are also observable and are indicated by black triangles, circles, and squares, respectively.

The β-delayed, γ-ray spectra observed within two correlation windows of 0 - 500 and 500 - 1000 ms of the implantation of a ^{70}Co ion are given in Fig. 1. Many of the transitions labeled as belonging to ^{70}Ni have been seen previously in multinucleon-transfer reactions [30], in-beam γ-ray spectroscopy following secondary fragmentation [30], β decay [31, 32], and isomeric decay studies [33]. Additional transitions were placed in ^{70}Ni based on correlated β-γ-γ coincidence relationships. Some additional γ rays associated with ^{69}Co, ^{69}Ni, and ^{70}Zn are also observable in Fig 1, indicated by black triangles, circles, and squares, respectively, due to the long correlation time taken for the present analysis. However, γ rays from these other implanted nuclei do not impact the present results.

There are two known isomeric states in ^{70}Co; a low-spin, long-lived state [27] and a high-spin, short-lived state [27, 34–36]. The contributions of both isomeric decays are observed in Figs. 1(a) and 1(b) and assignment of γ rays to either the long- or short-lived ^{70}Co isomeric states is based on γ-gated β-decay curves. The 607.4- and 1866.4-keV γ-rays are known from previous studies

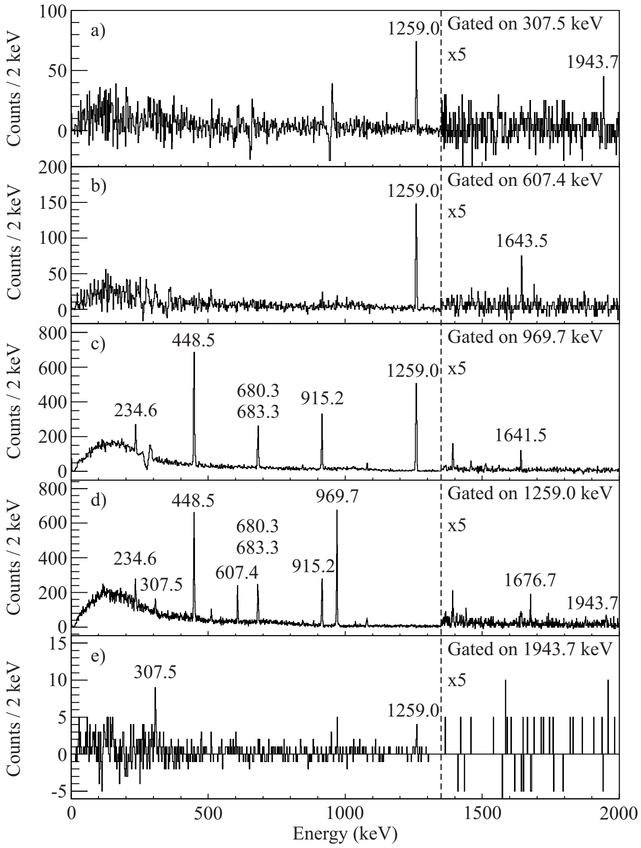

FIG. 2. Background-subtracted γ-γ coincidence spectra following the β decay of ^{70}Co within 2000 ms of the arrival of the ion. Spectra are gated on the (a) 307.5-, (b) 607.4-, (c) 969.7-, (d) 1259.0-, and (e) 1943.7-keV γ rays.

to be exclusive to the β decay of the low-spin, long half-life isomeric state [31]. Many transitions are associated with the deexcitation of the high-spin, short half-life isomeric state and the rapid decrease in peak area at longer correlation times is observed in Fig. 1(b). The 448.5- and 969.7-keV γ rays are marked in Fig. 1 as examples. The 1259.0-keV γ ray is common to both decays.

The 307.5-keV γ ray, associated with the decay of the long-lived ^{70}Co isomer, has not been observed in previous ^{70}Ni studies and is placed in ^{70}Ni based on the γ-γ coincidence relationships. Figure 2 presents a series of γ-γ coincidence spectra gated on the γ-rays at (a) 307.5, (b) 607.4, (c) 969.7, (d) 1259.0, and (e) 1943.7 keV.

The γ rays in coincidence with the $2_1^+ \rightarrow 0_1^+$, 1259.0-keV γ ray are seen in Fig. 2(d). Strong coincidence relationships are observed at 969.7, 448.5, 607.4, 915.2, and 234.6 keV which correspond to the $4_1^+ \rightarrow 2_1^+$, $6_1^+ \rightarrow 4_1^+$, $2_2^+ \rightarrow 2_1^+$, $(6_1^-) \rightarrow 6_1^+$, and $(5_1^-) \rightarrow 6_1^+$ transitions, respectively, where the spins and parities are adopted from the most recent ^{70}Ni level scheme by Chiara *et al.* [30]. A number of other γ rays are observed in Fig. 1 which depopulate higher-energy levels and will be detailed in a subsequent publication. However, the coincident γ rays at 307.5 and 1943.7 keV will be discussed separately below. The 640-keV γ ray observed previously [30] was not detected in coincidence with either the 1259.0- or the 607.4-keV, $2_2^+ \rightarrow 2_1^+$ transition [Fig. 2(b)] in the present work, suggesting that the known (4_2^+) state was not populated in the ^{70}Co β decay and could indicate the long-lived β-decaying ^{70}Co isomer has a spin lower than three. Likewise, the known 8_1^+ isomer at 2861 keV [33] was not observed following ^{70}Co β decay, in agreement with results of earlier investigations [31, 32]. Lastly, the 1259.0-keV γ ray was not observed to be self coincident, as suggested in Ref. [31].

Gating on the 969.7-keV, $4_1^+ \rightarrow 2_1^+$ transition of the ground-state band leads to the coincidence spectrum of Fig. 2(c). Based on the number of counts in the 969.7-keV peak in the singles spectrum, the known ^{70}Ni level scheme, and the detector efficiency at 1259.0 keV, a total of 1158$\pm$12 counts are expected at 1259.0 keV. The measured number of counts is 1130$\pm$50. All other previously known coincident γ rays measured in the present analysis were checked in a similar manner and were found to be consistent with the known level scheme. This exercise confirms both our efficiency determination and the validity of the main portions of the ^{70}Ni, low-energy, level scheme.

The strong 307.5-keV γ ray present in Fig. 1(a), and in the coincidence spectrum gated by the 1259.0-keV γ ray [Fig. 2(d)], is new to the current work. In Fig. 2(a), the gate on this 307.5-keV γ ray indicates a coincidence with a strong 1259.0-keV line and a weaker 1943.7-keV γ ray. The 1943.7-keV coincidence spectrum [Fig. 2(e)] also contains the 307.5- and 1259.0-keV γ rays. The former is not observed in coincidence with any of the other γ rays assigned to the decay of ^{70}Co in Fig. 1(a), suggesting that this 307.5-keV γ ray directly populates the 1259.0-keV, 2_1^+ state from a level at 1567 keV. There is no direct γ-ray emission from the latter level to the ground state, based on the absence of a detectable γ ray in the appropriate region of the β-delayed, γ-ray spectrum in Fig. 1, and on the lack of a 1567-keV γ ray in Fig. 2(e). The low-energy level scheme of ^{70}Ni, highlighting the decay of the long-lived ^{70}Co isomeric state, is shown in Fig. 3 (left). Gamma-ray intensities are relative to the 1259-keV transition.

The relative intensities of the 307.5- and 1943.7-keV transitions strongly suggest the placement of the 1943.7-keV transition feeding the 1567-keV level. If the order of the 307.5- and 1943.7-keV transitions were reversed, a resulting 3203-keV state would have seven times more intensity feeding it than depopulating it. Furthermore, no γ-rays are observed that could correspond to the deexcitation of such a 3203-keV state. The 3203-keV state could not be assigned a 0^+ spin and parity due to the absence of 511-keV γ rays coincident with the 307.5-keV transition. Therefore, the 1943.7-keV transition is placed as feeding the firmly-established 1567-keV state in the re-

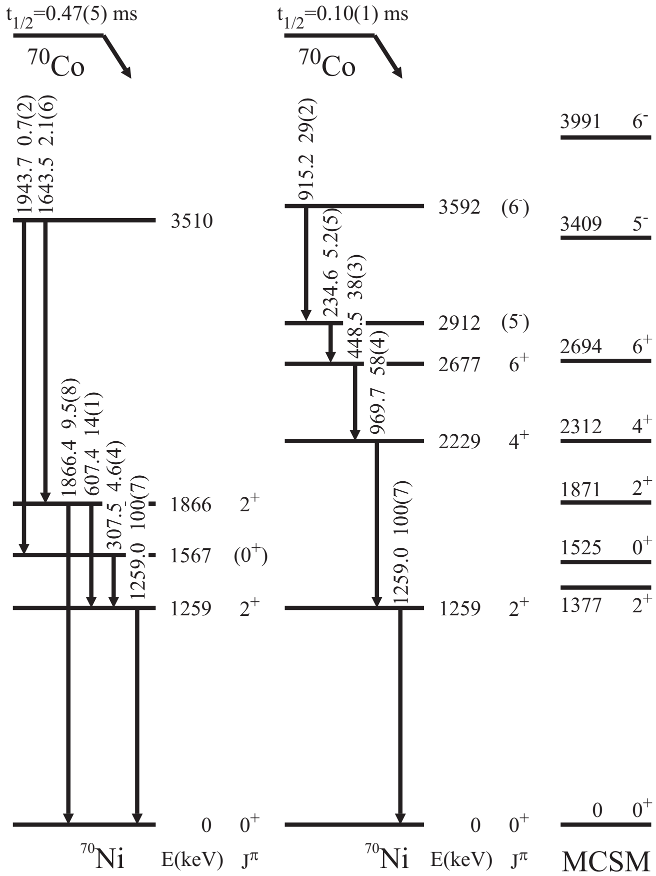

FIG. 3. Simplified low-energy level scheme of ^{70}Ni populated in the decay of ^{70}Co, highlighting the decay of the long-lived ^{70}Co isomeric state (left). Experimentally observed transitions are labeled with their energy and intensity relative to the 1259-keV transition. Experimentally observed levels are labeled with excitation energies along with spins and parities, and are compared to the predictions of the MCSM shown on the extreme right [30].

vised ^{70}Ni level scheme of Fig. 3. The 1567-keV state is tentatively assigned a 0^+ spin and parity based on its association with the decay of the long-lived, low-spin isomeric state, its non observation in multinucleon transfer reactions populating yrast states [30], and the lack of a γ ray at 1567 keV in the β-delayed, γ-ray spectrum. In addition, an upper limit of 100 ns is placed on the lifetime of the 1567-keV state, based on analysis of the time difference spectra between β-decay electrons detected in the planar GeDSSD and the 307.5-keV γ rays detected in SeGA.

Low-energy 0^+ states are now known in both ^{68,70}Ni and the evolution of these states beyond $N = 40$ can be investigated. The two low-energy 0_2^+ and 0_3^+ states in ^{68}Ni are attributed to configurations associated predominately with two-particle, two-hole excitations across the $N = 40$ and $Z = 28$ gaps. The low-energy level structure of ^{68}Ni has been predicted numerous times (see Ref. [15] and references therein). However, only theoretical calculations utilizing the full $fpg_{9/2}d_{5/2}$ model space for both protons and neutrons, thereby allowing excitations across their respective energy gaps, can account for the presence of three 0^+ states in ^{68}Ni [18, 20] at low excitation energy.

Other shell-model calculations with more restrictive model spaces that do not explicitly allow for proton excitations out of the $\pi f_{7/2}$ single-particle state fail to reproduce the energy of the 0_3^+ state [37–39]. A fourth 0^+ level at 2202 keV was briefly proposed experimentally [40], but subsequent investigations employing similar techniques have so far failed to support the claim [17] and such a fourth 0^+ state in ^{68}Ni is not suggested by theoretical calculations either.

The MCSM [15] calculations with the A3DA [41] interaction further predict that the three 0^+ states in ^{68}Ni are characterized by different intrinsic deformations with the lowest-energy state being spherical, the 0_2^+ level having a slight oblate deformation, and the 0_3^+ state being associated with a large prolate deformation. The energy [15, 16] and $E0$ decay [15] of the 0_2^+ state at 1604 keV in ^{68}Ni are consistent with the theoretical predictions of a slight oblate deformation. The 0_3^+ state in ^{68}Ni was confirmed by angular-correlation measurements at 2511 keV [17]. However, the $E0$ branching ratios from the prolate 0_3^+ to either the 0_2^+ or 0_1^+ states have not been directly observed, but the upper limit for the sum intensity has been placed at 4% [42].

The MCSM predictions for ^{70}Ni are included in Fig. 3 (right). Transitioning from ^{68}Ni to ^{70}Ni, the potential well which confines the prolate-deformed two-particle two-hole proton excitation is predicted to increase in depth [20], resulting in a concomitant drop in the energy of the predicted prolate 0^+ state from 2511 keV in ^{68}Ni to 1525 keV in ^{70}Ni. The energies of the 2_2^+ and 4_2^+ states, also associated with the prolate potential well, have been observed to drop for ^{70}Ni compared to ^{68}Ni [30]. This is explained by the increased occupancy of the $\nu g_{9/2}$ orbital in ^{70}Ni compared to ^{68}Ni. The attractive $\nu g_{9/2} - \pi f_{5/2}$ and repulsive $\nu g_{9/2} - \pi f_{7/2}$ monopole interactions of the tensor force alter the effective single-particle energies of the $\pi f_{7/2}$ and $\pi f_{5/2}$ single-particle states, thereby increasing the likelihood of excitations into the $\pi f_{5/2}$, the dominant proton excitation in the prolate-deformed 0^+ states in ^{68,70}Ni [20, 30].

The energy of the tentative 0_2^+ state in ^{70}Ni of 1567 keV agrees with the theoretically predicted value, as observed in Fig. 3, further supporting its 0^+ assignment. The 2_2^+ level at 1866 keV and the 4_2^+ one at 2508 keV (not observed in the present work, but proposed in Ref. [30]) have already been suggested as members of a band built on the 0_2^+ state [30], but the 0_2^+ state itself had not yet been identified. Unfortunately, it was not possible to observe the $2_2^+ \rightarrow 0_2^+$ branch, due to the strong competition from the higher-energy $2_2^+ \rightarrow 0_1^+$ transition. Based on the predicted ratio of $B(E2, 2_2^+ \rightarrow 0_2^+)/B(E2, 2_2^+ \rightarrow 0_1^+)$ of

400 [30], the expected branching ratio of the $2_2^+ \rightarrow 0_2^+$ transition would be unobservable in the present experiment in the singles spectrum or in coincidence with the 1643.5-keV γ ray.

In conclusion, a new (0_2^+) state in ^{70}Ni, located at 1567 keV, has been discovered through β-decay spectroscopy at NSCL. The present experimental results are in good agreement with theoretical predictions by the MCSM with the A3DA interaction which successfully reproduces the low-energy level scheme of ^{68}Ni. The predicted deepening of the prolate potential well from ^{68}Ni to ^{70}Ni is borne out experimentally based on the drop in energy of the excited (0^+) states. The observations support a picture of shape coexistence in the neutron-rich Ni isotopes, based on proton excitations across the $Z = 28$ shell gap.

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