Mapping of fragmented $\nu f_{5/2} \rightarrow \pi f_{7/2}$ transitions in the ^{73}Co → ^{73}Ni decay

S. Go ,[1,2] R. Grzywacz,[1,3] C. Mazzocchi,[4] S. N. Liddick,[5,6] M. Alshudifat,[7] J. C. Batchelder,[8] T. Baumann,[5] A. A. Ciemny,[4] T. N. Ginter,[5] C. J. Gross,[3] K. Kolos,[9] A. Korgul,[4] S. V. Paulauskas,[1] C. J. Prokop,[5,6] M. M. Rajabali,[10,11] K. P. Rykaczewski,[3] S. Taylor,[1] and Y. Xiao[1]

[1]*Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA*
[2]*Department of Physics, Kyushu University, Fukuoka 819-0395, Japan*
[3]*Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
[4]*Faculty of Physics, University of Warsaw, PL 02-093 Warszawa, Poland*
[5]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*
[6]*Department of Chemistry, Michigan State University, East Lansing, Michigan 48824, USA*
[7]*Department of Physics, Al al-Bayt University, Mafraq 25113, Jordan*
[8]*Department of Nuclear Engineering, University of California, Berkeley, California 94702, USA*
[9]*Lawrence Livermore National Laboratory, Livermore, California 94551, USA*
[10]*Department of Physics, Tennessee Technological University, Cookeville, Tennessee 79409, USA*
[11]*TRIUMF, Vancouver, British Columbia, V6T 2A3, Canada*

(Received 5 May 2020; revised 13 September 2020; accepted 13 October 2020; published 29 October 2020; corrected 4 December 2020)

Excited states in ^{73,75}Ni were investigated through the β decay of ^{73,75}Co in an experiment performed at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University (MSU). The experimental results extended the level scheme of ^{73}Ni to 3.2-MeV excitation energy and provided the experimental information on excited states in ^{75}Ni. The β-delayed neutron branching ratio for ^{73}Co was obtained. The experimental results are discussed in comparison with shell-model calculations.

DOI: 10.1103/PhysRevC.102.044331

I. INTRODUCTION

With the increased quality of the experimental data available for neutron-rich unstable nuclei, a more in-depth verification of nuclear models can be achieved. The improved sensitivity of experiments provides either the ability to study an expanded pool of isotopes or to investigate previously unobserved weaker effects, which may sometimes confirm or often revise previous claims. This is particularly important near doubly magic nuclei, which are thought to form the backbone of the nuclear structure models. Recently, the double-magic nature of ^{78}Ni [1,2] was confirmed as predicted by multiple experimental observations on less exotic nuclei [3,4]. Yet, recent experiments also show that there is a lot more complexity in this region with claims of coexisting structures [5,6].

There is a significant body of decay experiments investigating β decays and isomer decays of cobalt isotopes. The experimental data and theoretical predictions have evolved significantly over the past two decades, from a relatively straightforward picture based on the seniority scheme [7–10] to a more sophisticated understanding where the collective excitation has been called for to explain more recent experimental data [11–14]. The early signature of the breaking of the seniority scheme was the lack of observation of the predicted seniority isomers in ^{72,74}Ni [7,8]. The topic was addressed later in a decay measurement with higher statistics [15]. These experimental efforts were accompanied by the development of nuclear structure models [16–18], which are able to interpret a more complex reality emerging from experimental data. The majority of the prior works focused on the interpretation of excited states in nickel isotopes; however, recent TAS work was able to make a more quantitative statement on β-decay properties through the strength distribution for $^{69–71}$Co decays [19].

In the decay of neutron-rich Co isotopes, significant β-decay strength to low-excited levels is attributed to allowed Gamow-Teller (GT) transitions $\nu f_{5/2} \rightarrow \pi f_{7/2}$ (see Fig. 1). The strong selectivity of this transition contains information both on the parent and daughter nuclei. Mapping strong GT transitions is of importance to describe the nuclear decay properties. Here, we continue this analysis and use the shell-model approach to interpret the experimental data. With sufficient precision from future higher statistics experiments, β-decay measurements can complement direct-reaction ones, which sometimes populate different groups of states due to their different selection rules. GT transitions were clearly identified in the decays of even-*A* cobalt isotopes, and the same interpretation was used to also explain the results for odd-*A* isotopes. While the primary GT transitions in the decays of ^{70,72,74}Co isotopes were identified at the relatively high excitation energy of about 3 MeV [15,20,21], it was proposed that this transition can be found at much lower energies, about 1 MeV, for odd-*A* cobalt isotopes [22,23].

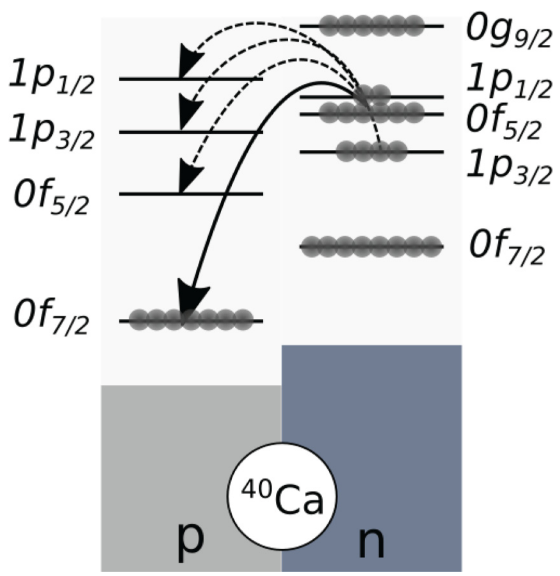

FIG. 1. Schematic drawing for the Gamow-Teller (GT) transitions in Co isotopes. The transitions from the neutron to the proton proceed between their spin-orbit partners.

This work presents new experimental results for the β decay of ^{73,75}Co populating excited states of ^{73,75}Ni. The level scheme of ^{73}Ni is updated with respect to prior work [23] and we report here the first experimental information on an excited state in ^{75}Ni from β-decay spectroscopy. Experimental data reveal dominant GT transitions $\nu f_{5/2} \rightarrow \pi f_{7/2}$ in addition to a small amount of strength in the higher energy region in the decay of ^{73}Co. We also provide a revised theoretical interpretation, which can describe not only the level energies but also transition probabilities. The calculations are extended to more neutron-rich odd-mass nickel isotopes to guide future studies.

This paper begins with a description of the experimental setup in Sec. II, which is followed by the results in Sec. III and a description of shell-model calculations in Sec. IV.

II. EXPERIMENTAL DETAILS

Excited states in ^{73,75}Ni were populated by means of the β decay of ^{73,75}Co. The cobalt ions of interest were produced via projectile fragmentation of an ^{82}Se beam [24] at an energy of 140 MeV/u on a ^{9}Be target. The experiment took place at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University (MSU). The ions of ^{82}Se impinged with an average current of 40 pnA on a ^{9}Be target. The reaction products of interest were separated by the A1900 fragment separator [25] and transmitted to the experimental end station. The fragments were identified on an event-by-event basis by measuring energy loss (ΔE) in a silicon detector placed in the beam line before the detection setup and time of flight (TOF) between the intermediate dispersive image of the A1900 and a Si-PIN detector [26].

The separated fragments of interest were implanted in a germanium double-sided strip detector (GeDSSD) [27], which is a circular disk, 9 cm in diameter and 1 cm thick, segmented into 5-mm-wide strips. The detector was segmented, 16 strips on one side and 16 orthogonal strips on the other side, for space-correlation purposes. The signals were fed to dual-range preamplifiers in order to detect both the high-energy deposition of the heavy ions and the low energy of the β particles. Spatial correlations were allowed between an implanted ion and electrons detected in the pixel itself or in any adjacent pixel. The β-detection efficiency was found to be 85(8)% by the known decay data, in good agreement with simulations [27].

The GeDSSD was surrounded by eight clover germanium detectors in close geometry for detection of γ rays in coincidence with β particles. The γ-ray energy resolution of the clover germanium detectors was estimated to be 2.5 keV at 1.3 MeV. Absolute γ-ray efficiencies were determined by using a calibrated ^{154,155}Eu source and aided by GEANT4 simulations [28] that considered the geometry of clover detectors and GeDSSD. The full-peak efficiency for γ rays was 2.5(1)% at 1.3 MeV. All detector channels were read out by the NSCL Digital Data Acquisition System (DDAS) [29].

The β-decay half-life was determined by fitting the correlated time distribution for β-coincident γ rays. The analytical solution of the Bateman equations [30] with constant background was used,

$$N(t) = N_1(0)\left[e^{-\lambda_1 t} + \frac{\lambda_1}{\lambda_2 - \lambda_1}(e^{-\lambda_1 t} - e^{-\lambda_2 t})\right] + \text{const}, \tag{1}$$

where 1 and 2 identify the parent and daughter nuclei, respectively. $N(t)$ is number of decay events as a function of time, and λ is the decay constant.

III. RESULTS

A. β decay of ^{73}Co

A total of 1.2×10^5 ^{73}Co ions was implanted in the GeDSSD. For each identified and implanted ion, a correlation was made in time and space between the implanted ion and its subsequent β decay. The energy spectra of γ rays in coincidence with β particles correlated with ^{73}Co are shown in Fig. 2. The observed transitions of 239, 284, 524, and 774 keV are consistent with previous work [23]. Peaks at 152, 768, 990, 1059, 1142, 1174, 1593, 1941, and 3000 keV were newly assigned as transitions in ^{73}Ni following β decay of ^{73}Co. The transitions at 454, 843, and 1095 keV correspond to the de-excitation of excited states in ^{72}Ni, which are populated in the β-delayed neutron (βn) decay of ^{73}Co [22]. A βn-emission branching ratio of 6(3)% is found in this work. The value was estimated on the basis of the efficiency-corrected intensity of the de-excitation of the first-excited level at 1095 keV in ^{72}Ni [20] and the observed the β intensity to ^{73}Ni as shown in Fig. 3. The other peaks in the spectra were assigned as transitions in ^{73}Ni by comparing the spectra of ^{72}Ni in this and in the prior data [20]. In our previous study, weak γ rays at 158 and 194 keV were observed [23]; however, these lines were not observed here despite statistics larger by about 8 times. The lack of observation of these two transitions might

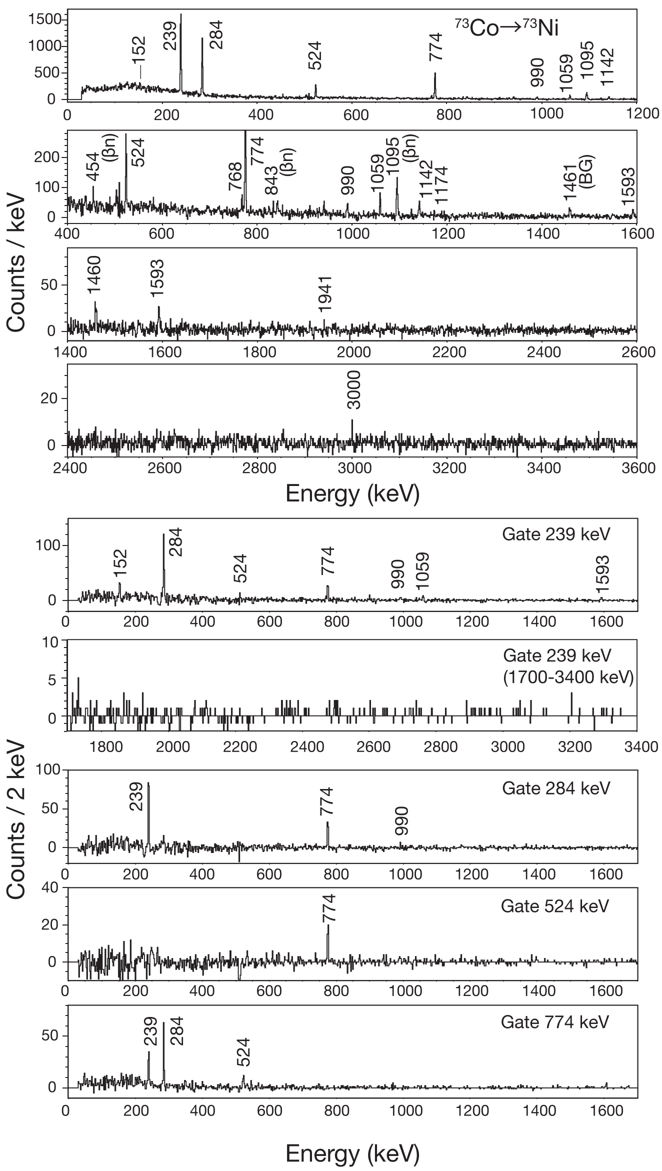

FIG. 2. (Top) β-gated γ-ray energy spectrum for the decay of ^{73}Co up to 3.6 MeV (correlation time 120 ms, background subtracted). The 454-, 843-, and 1095-keV peaks correspond to transitions in ^{72}Ni populated in the βn channel. The 1460-keV line labeled with BG corresponds to the known ^{40}K natural background line. (Bottom) β-γ-γ coincidence spectra for the decay of ^{73}Co $\rightarrow$ ^{73}Ni. From top to bottom, the spectra are gated on the 239-, 284-, 524-, and 774-keV transitions.

be attributed to the relatively high background in low-energy region in this work or unknown contamination [23].

The proposed partial level scheme of ^{73}Ni as obtained in this work is shown in Fig. 3. It was constructed on the basis of transition energies, relative intensities and coincidences, when available. All the observed γ-ray energies and γ-γ coincidences information are listed in Table I. The β-γ-γ coincidence analysis revealed that the 152-, 990-, 1059- and 1593-keV transitions are in cascade with the 239-keV transition in addition to the previously known transitions at 284 and 774 keV.

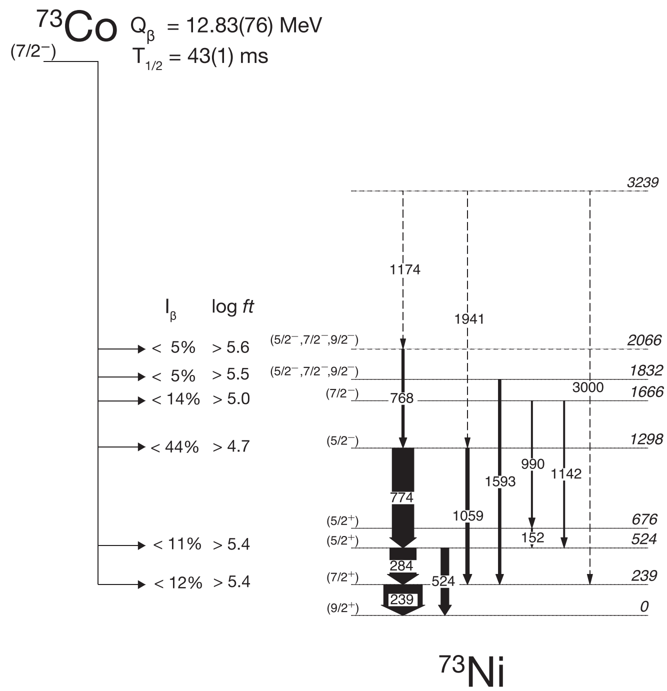

FIG. 3. The partial decay scheme of ^{73}Co as obtained in this work. The decay energy (Q_β) value stems from Ref. [31]. See text for details.

The 1059-keV transition agrees with the energy difference between the known levels at 239 and 1298 keV [23]. The 1593-keV transition was assigned to de-excite the new level at 1832 keV based on its coincidence with the 239-keV transition. An excited state at 1666 keV is assigned on the basis of the energy sum between the 152- and 990-keV transitions. The energy difference between the levels at 1666 and 524 keV agrees well with the observed transition at 1142 keV; however, the coincidence between the 1142- and 239-keV lines was not observed because of the limited statistics. A level positioned at 3239-keV excitation energy is supported by weak transitions of 1174, 1941, and 3000 keV. These transition energies match well the difference of level energies for previously known low-lying levels. The 2066-keV level is also supported by the energy sum of the 768- and 1174-keV lines and agrees with the energy difference between the level of 3239 and 1298 keV. However, the coincidences between γ-ray transitions were too weak to confirm this, and only the information of transition energy and relative intensities was used for this assignment.

A half-life of 43(1) ms was obtained as the weighted mean value; see Table I, and its value is consistent with the previous works [2,22,23]. Energies of the assigned transitions, relative intensities, and half-lives obtained in this study are also summarized in Table I. The half-life values for each γ-ray transition are compatible within 1σ with the previous work with the exception of the 284-keV line, which agrees within 2σ. The logft values were calculated using the β-feeding intensity I_β for each state, which was estimated using the intensity of the γ-ray transition in the proposed partial level

TABLE I. List of ^{73}Ni levels observed in the β decay of ^{73}Co. The energy $E_{\rm level}$, the tentative spin-parity assignments J^π, the β feeding I_β, the calculated $\log ft$ values, the de-exciting γ-ray transition-energy E_γ, their relative intensities I_γ to the 239-keV transition, half-lives obtained by gating on the corresponding $\beta\gamma$ transition, and coincident γ rays for each transition are summarized. Note that the I_β and $\log ft$ values are considered as upper and lower limits, respectively. The error for the transition energy was estimated by quadratic sum of statistical and systematic error.

$E_{\rm level}$ (keV)	J^π	I_β (%)	$\log ft$	E_γ (keV)	I_γ	$T_{1/2}$ (ms)	Coincident γ rays
239.0(2)	$(7/2^+)$	12	5.4	239.0(2)	100	45(1)	152, 284, 774, 990, 1059, 1593
523.6(3)	$(5/2^+)$	11	5.4	284.4(2)	68(1)	43(1)	239, 774, 990
676.0(5)	$(5/2^+)$			152.4(4)	7(4)		239
				523.6(3)	21(1)	42(3)	774
1298.4(4)	$(5/2^-)$	44	4.7	774.3(2)	56(1)	41(2)	239, 284, 524
1665.7(4)	$(7/2^-)$	14	5.0	990.4(3)	10(2)	27(6)	239
				1142.1(2)	9(1)	53(9)	
1831.6(5)	$(5/2^-, 7/2^-, 9/2^-)$	5	5.5	1592.6(5)	7(1)	39(6)	239
2065.5(5)	$(5/2^-, 7/2^-, 9/2^-)$	5	5.6	767.6(3)	7(1)	46(7)	239
3239.3(5)	$(5/2^-, 7/2^-, 9/2^-)$			1173.7(5)			
				1941.1(5)			
				3000.3(5)			

scheme (see Fig. 3). The decay energy value $Q_\beta = 12.83(76)$ MeV [31] was adopted for the calculation. Note that the $\log ft$ values are considered as lower limits due to unobserved β feedings to high-energy levels.

The ground-state spin parity of ^{73}Co is assumed to be $(7/2^-)$, which corresponds to a neutron hole in the $\nu f_{7/2}$ orbital. The ground-state spin parity of the daughter ^{73}Ni is $(9/2^+)$, due to the $\nu g_{9/2}$ orbital coupled to an even-even core. Hence, GT transitions can populate excited states with $(9/2^-, 7/2^-, 5/2^-)$. The strong apparent β feeding of the 1298-keV level supports the $I^\pi = (5/2^-)$ assignment, as already concluded previously [23]. The $\log ft$ value for the transition to the 1298-keV level is consistent with our previous work [23] even though new transitions populating it were identified in this work. This observation supports the fact that this level is fed by an allowed GT transition. On the other hand, the relatively-high β feeding to the level at 239 keV found in the previous work [23] was updated because of the new transitions. The $(5/2^-)$ assignment for the 1298-keV state is consistent with the systematics of ^{69}Ni [10] and ^{71}Ni [23] and our shell-model calculations, as described in Sec. IV.

Multiple β-decaying states have been reported in even-mass Co isotopes [9,13,15,20]. The occurrence of these isomeric states is attributed to the large spin gap between the ground state and lowest excited states. Around $N = 40$, the isomeric β-decaying state in ^{69}Co [10] was attributed to proton cross-shell excitations from $\pi f_{5/2}$ with the development of deformation. Recent experimental and theoretical work investigated excited states of ^{73}Co by means of in-beam γ-ray spectroscopy and shell-model calculations [32]. Their shell-model calculations predicted an excited state with $I^\pi = 1/2^-$ at 670 keV. If this would occur at much lower excitation energy, it could be a β-decaying state in ^{73}Co with the large spin gap with the $I^\pi = 7/2^-$ ground state. Since there was no significant difference in γ-gated half-lives for the transitions in this work (see Table I), multiple β-decaying states were not assigned in the proposed decay scheme.

Among other transitions, tentative spin-parity assignments were achieved by combining the apparent $\log ft$ values and the γ-ray feeding pattern. The spin parities of the levels at 1832, 2066, and 3239 keV were assigned from $(5/2^-)$ to $(9/2^-)$ by assuming allowed GT transitions. The 1666-keV level was tentatively assigned as $(7/2^-)$, among the possible $(5/2^-)$, $(7/2^-)$, and $(9/2^-)$, to reproduce the relative intensities between the 990- and 1142-keV transitions. Another possibility predicted by our shell-model calculations, as described in Sec. IV, is $(1/2^-)$ for the 676-keV level and $(5/2^-)$ for the 1666-keV level. In this configuration, we would need to assume a hindered $E1$ transition for the 1142-keV transition and $E2$ for the one at 990 keV in order to reproduce experimental relative intensities.

B. β decay of ^{75}Co

A total of 1.3×10^3 ^{75}Co ions was implanted in the experimental setup. The β-γ spectrum associated with the β decay of ^{75}Co is shown in Fig. 4. The timing gate for the spectrum was selected up to 100 ms. The background shows the spectrum with the delayed gate from 200 to 300 ms. Peaks at 232 and 893 keV were observed in the present work. These transitions were not considered as the product of βn decay of ^{75}Co by comparing the γ-ray spectra with those of $^{73\text{–}74}$Ni. The half-life gated on 232 keV was deduced to be 27(13) ms, in agreement with the literature value of 26.5(12) ms [2].

The proposed partial level scheme of ^{75}Ni is shown in Fig. 5. The ground state of ^{75}Co is assumed to be $(7/2^-)$, which is attributed to a vacancy in the proton $f_{7/2}$ orbital, while the ground state of the daughter ^{75}Ni is assigned to be $(9/2^+)$ due to the neutron in the $g_{9/2}$ orbital coupled to an even-even core. We assigned the 232-keV transitions as the de-excitation of the first excited state of ^{75}Ni, and the spin parity of the 232-keV level was tentatively assigned as $(7/2^+)$ by systematics of less neutron-rich odd-mass Ni isotopes.

As for the decay of ^{75}Co, a strong GT decay strength from $\nu f_{5/2}$ to $\pi f_{7/2}$ could also be expected as is seen in the decay of

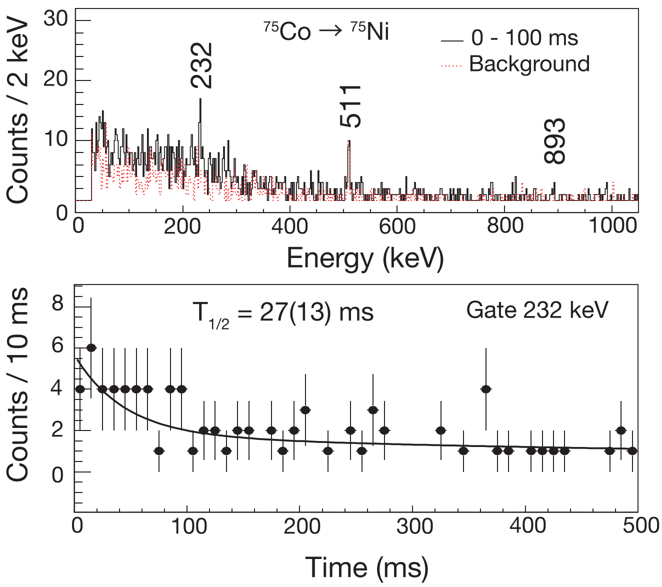

FIG. 4. (Top) β-gated γ-ray energy spectrum for the decay of ^{75}Co. The black and red lines show the spectra up to 100-ms correlation time and background (200–300 ms), respectively. (Bottom) Time distribution of the β-decay events of ^{75}Co correlated with the 232-keV transition.

other cobalt isotopes. The line at 893 keV could be assigned to the transition from a possible $5/2^-$ state in ^{75}Ni; however, we could not conclude whether these two transitions are in parallel or cascade because of the limited statistics.

The upper limit for βn emission (P_n) of ^{75}Co was reported as 16% [33]. Possible transitions in ^{74}Ni as the result of βn decay were not observed in this work (see Fig. 4). This is most likely due to limited statistics and detection efficiency for the de-excitation of the first excited state of ^{74}Ni at 1024 keV [8,15].

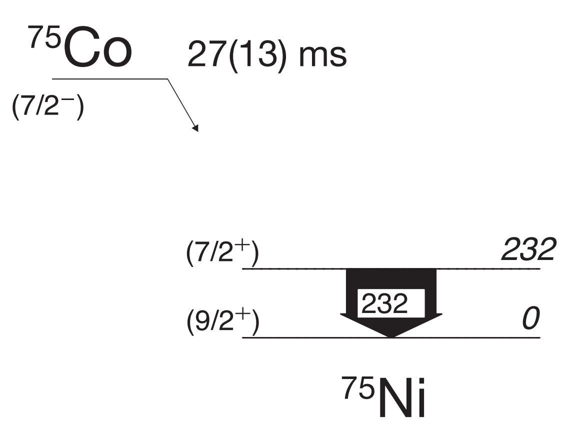

FIG. 5. The partial decay scheme of ^{75}Co obtained in this work. See text for details.

TABLE II. Single-particle energies used for the shell-model calculations for the $fpgpn$ interactions. E_π and E_ν represent proton and neutron single-particle energies. The energy of the $0g_{9/2}$ was increased by 1 MeV with respect to calculations in [11] necessary to reproduce the $9/2^+$ g. s. spin of ^{73}Ni.

	E_π (MeV)	E_ν (MeV)
$0g_{7/2}$	6.00	8.90
$0g_{9/2}$	0.00	3.40
$1p_{1/2}$	−5.54	−1.14
$0f_{5/2}$	−1.68	2.62
$1p_{3/2}$	−6.04	−2.68
$0f_{7/2}$	−4.96	−4.62

IV. SHELL-MODEL CALCULATIONS

A. Excited states in ^{73}Ni

Shell-model calculations were performed in the configuration space with ^{40}Ca core with $fpgpn$ interactions [11] to interpret the obtained levels. The calculations and the same truncation scheme were used originaly to explain the total absorption spectroscopy data on ^{70}Co [11]. This model uses configuration space of $0f_{7/2}, 1p_{3/2}, 0f_{5/2}, 1p_{1/2}, 0g_{9/2}$, and $0g_{7/2}$ for protons and neutrons. The single-particle energies are listed in Table II. The conventional quenching factor of 0.6 was used for these calculations. It is expected to provide the realistic strength distribution because the configuration space includes spin-orbit partners in both protons and neutrons. The results of these calculations were shown in Fig. 6. The level scheme and B(GT) distribution agrees qualitatively with the experimental data.

The ground state of ^{73}Co is determined by the vacancy in the $Z = 28$ closed shell and is expected to be $7/2^-$. The decay of Co isotopes is driven by the transformation of $\nu f_{5/2}$ into $\pi f_{7/2}$ which will fill the vacancy (see Fig. 1). In the decay of odd-even cobalt isotopes, we expect a population of $5/2^-$, $7/2^-$, and $9/2^-$ states by allowed GT transitions. This interaction generates two strong GT transitions to low-energy excited $5/2^-$ states close to experimental values. The selectivity of the GT operator will lead to a population pattern in which the GT transition matrix elements will reflect the composition of the wave function.

A closer inspection shows a nonvanishing strength to states with higher excitation energy around 2 MeV, which were also observed in the experimental data. To understand the origin of the strength, we have performed shell-model calculations for the B(GT) and relative splitting of the lowest $5/2^-$ states as a function of the relative energy difference between single-particle energies (see Fig. 7). This figure shows variations of energy splitting, B(GT), and relative occupancies between the three states as a function of the single-particle energy of the $\nu f_{5/2}$ relative to the other levels, which are fixed. One observes a relatively weak energy sensitivity for the relative splitting of the $5/2^-$ levels but a strong variation of the B(GT). The strong level crossing effect is observed for the second and

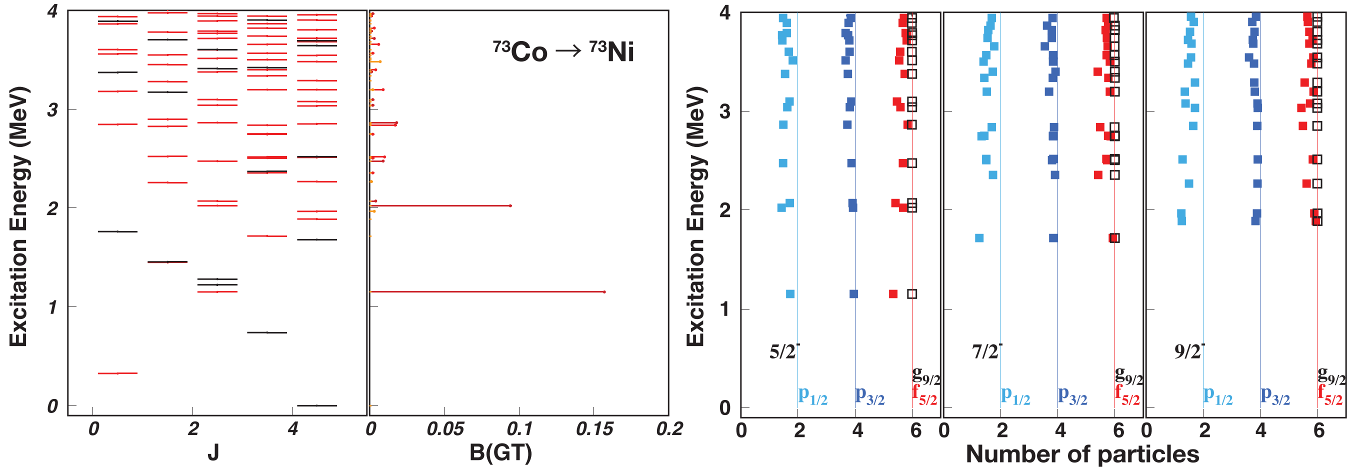

FIG. 6. (Left) ^{73}Ni levels from shell-model calculations using the *f pgpn* interactions with ^{40}Ca core [11] and corresponding B(GT) strength distribution from ^{73}Co. Positive- and negative-parity states are colored in black and red, respectively. The B(GT) values are plotted without any quenching factor. The experimental values correspond to B(GT) <0.13 and B(GT) <0.06 MeV^{-1} for the first and second excited states. (Right) Three panels show occupancies for the neutron single-particle levels for three different spins.

third excited states. There is a clear dependence on the B(GT) and occupancy of the $f_{5/2}$ state in ^{73}Ni. The $5/2^-$ configuration with a weaker B(GT) has stronger contribution of the $(\nu p_{1/2}^{-1} \times 2^+)$. It is interesting to note that these calculations predict a rapid change of configuration without drastic change of the relative energy splitting between the considered $5/2^-$ states. Note that the $\log ft$ values are lower limits in this work, and therefore future experimental work for determining $\log ft$ will be important to make more quantitative statements for the decay strength.

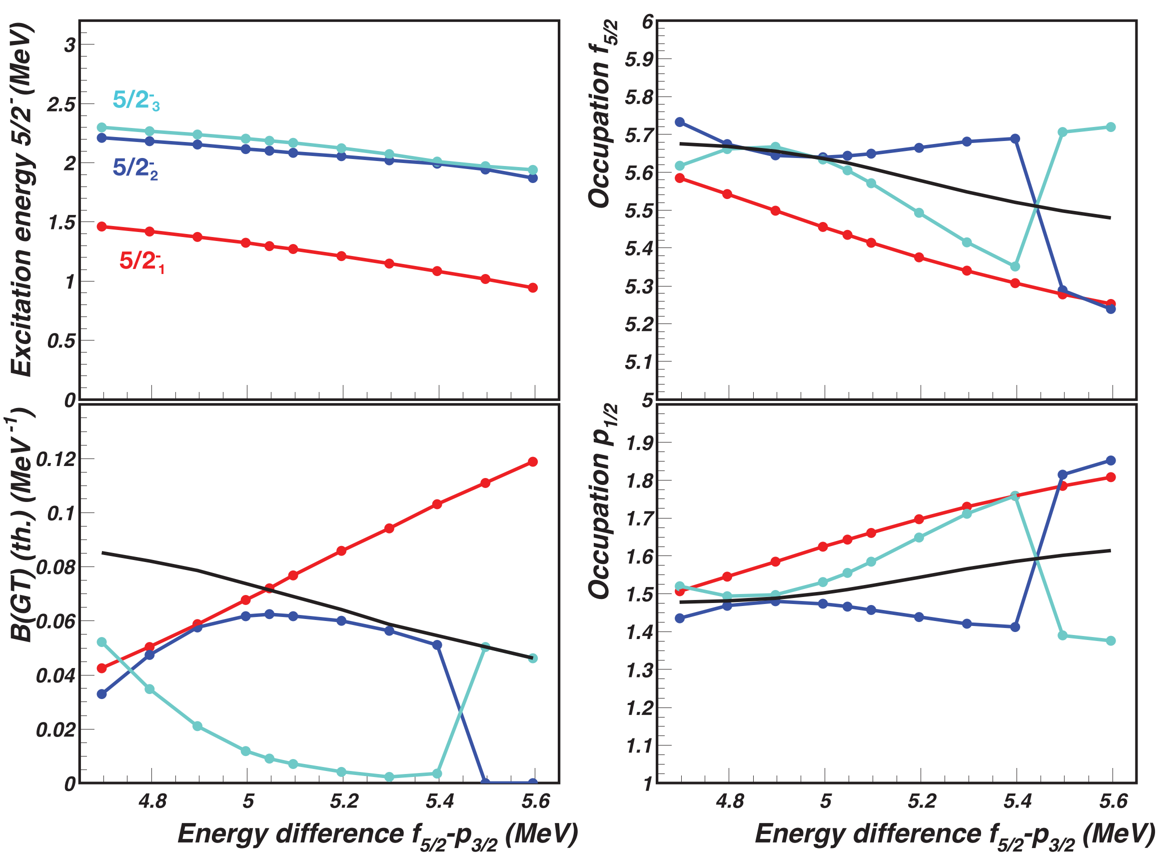

FIG. 7. (Left) Excitation energies and calculated B(GT) strengths for $5/2^-_{1,2,3}$ states as a function of energy between single-particle $f_{5/2}$ and $p_{3/2}$. Each color corresponds to the $5/2^-_{1,2,3}$ states. Black line represents sums of B(GT) for the second and third $5/2^-$ states. (Right) Occupations for $f_{5/2}$ and $p_{1/2}$ orbitals for the $5/2^-_{1,2,3}$ states. Black line represents average occupations for second and third $5/2^-$ states.

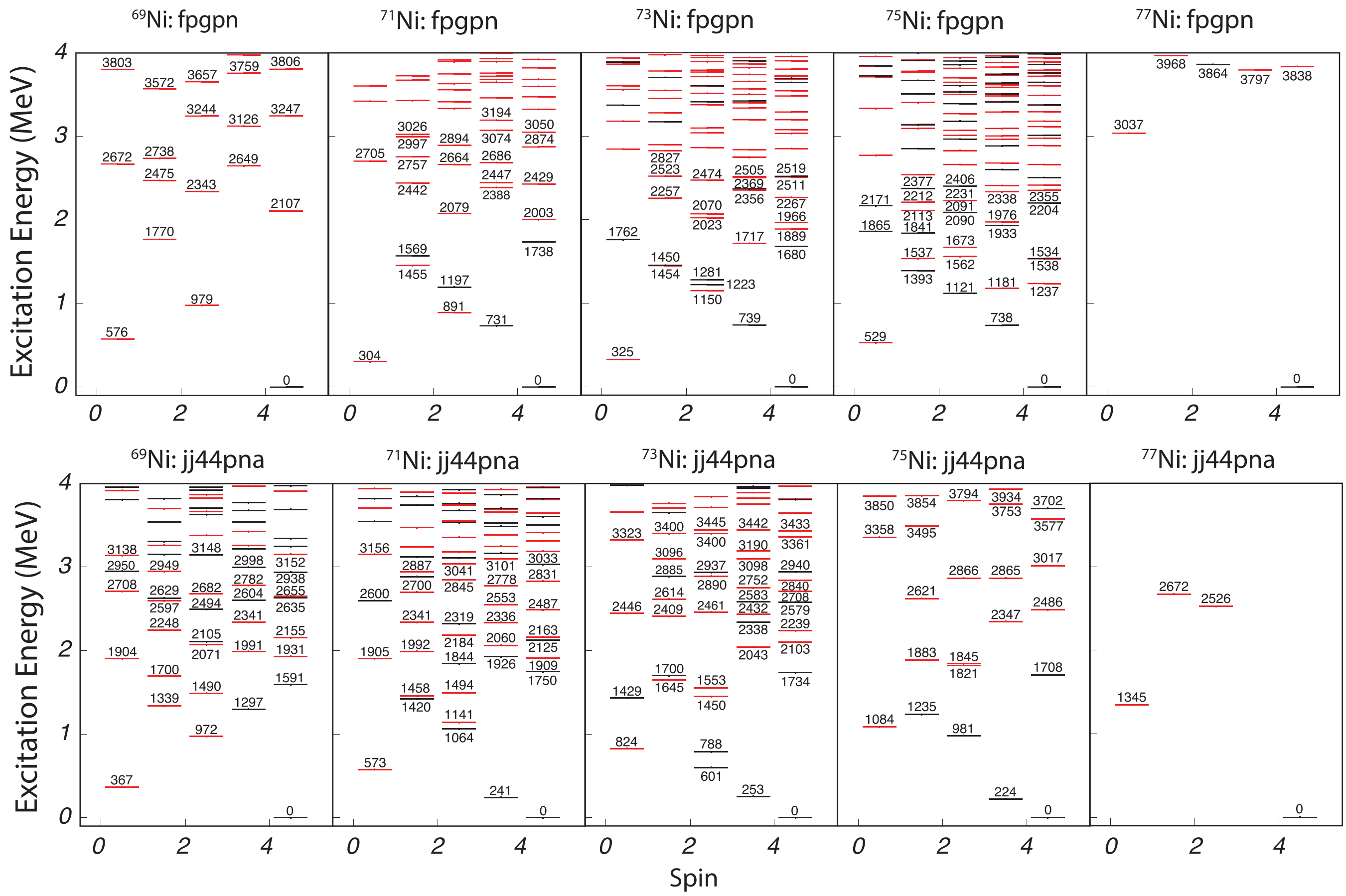

FIG. 8. Calculated levels by the $fpgpn$ interaction [11] with ^{40}Ca core and $jj44pna$ [34] interactions with ^{56}Ni core. The positive- and negative-parity states are in black and red.

While the above example shows apparent sensitivity of the β decay to the properties of the daughter nucleus, it is important to note that the GT operator is in fact probing both the parent and daughter nuclei involved through the occupation numbers. In the above example, the $f_{5/2}$ component is probed because the decay to the $\nu p_{1/2}$, $p_{3/2}$, and $g_{9/2}$ components is not energetically favored. β decay and the theoretical analysis from shell-model calculations probe neutron-occupied states and proton vacancies in the mother and the daughter. The study of exotic nuclei located in the vicinity of closed shell has the added value of providing a unique insight into such properties. Experimental results and shell-model calculations show several weak GT transitions to excited states in ^{73}Ni below 4 MeV. The transformation to the proton single-particle states above $Z = 28$ results in a continuum of states.

B. Level structure of odd-mass nickel isotopes

The systematic comparison of calculated and experimental levels for odd-A nickel isotopes is shown in Figs. 8 and 9. The shell-model calculations were performed by $fpgpn$ interactions [11] with ^{40}Ca core, as described in Sec. IV A, and $jj44pna$ interactions [34] with ^{56}Ni core.

Looking first at the $(5/2_1^-)$ states in each isotope, which are attributed to the dominant single-hole configuration $(\pi f_{5/2})^{-1}$. The excitation energies have a general agreement with calculated results in the both interactions. For example, the $(5/2_1^-)$ level in ^{73}Ni at 1298 keV, as confirmed in this work

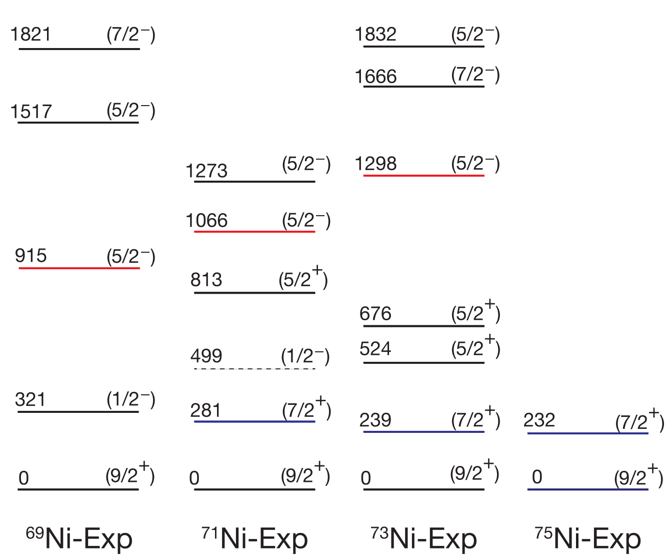

FIG. 9. Comparison of experimental levels for odd-A nickel isotopes. Levels for ^{69}Ni stem from Ref. [10], while part of the levels for ^{71,73}Ni are obtained from Ref. [23]. The levels with $(5/2_1^-)$ and $(7/2^+)$ are in red and blue, respectively.

by the observation of the 1059-keV transition, agrees well with the calculated $5/2_1^-$ level at 1150 keV predicted by the $fpgpn$ interactions. The largest β-decay strength to this level also supports the population via the allowed GT transition from the ground state of ^{73}Co.

In ^{75}Ni, the $5/2_1^-$ state was predicted above 1.5 MeV by both interactions. Assuming the ground state to be $(7/2^-)$ in ^{75}Co, a strong β-decay strength to it would be observed. One possibility is a level at 1125-keV by summing 893- and 232-keV transitions, which could be a candidate for the $5/2_1^+$ state. In this study, γ-ray coincidences did not confirm this scenario due to the limited statistics. Future studies with more statistics will be needed for determining the position of the $5/2_1^-$ state.

A similar trend was also seen in the calculated $1/2^-$ levels, which is attributed to the single-hole configurations $(\nu p_{1/2})^{-1}$. The $1/2^-$ state can be expected below 1 MeV in ^{73}Ni from the both calculations; however, it was not identified in this work. In the calculation with the $fpgpn$ interactions, the first excited state is predicted as $1/2^-$. The transition from $1/2^-$ to the ground state $(9/2^-)$ could have a long half-life due to the large spin gap. In the results with the $jj44pna$ interactions, there might be a possible observable of an $M2$ transition from $1/2^-$ to $5/2_1^+$ with a μs-order isomeric state; however, the transition was not observed in this work.

Turning to low-energy positive-parity states, the first excited state in ^{75}Ni at 232 keV obtained in the present work agrees well with the shell-model calculations by the $jj44pna$ interactions while the states are predicted systematically higher than the experimental levels in the case of the $fpgpn$ interactions.

The calculations show an interesting pattern for $5/2_1^+$ states in the $jj44pna$ interactions. The energy drops with increasing neutron number until midshell at ^{73}Ni and then rise in ^{75}Ni. The state can be regarded as a three-particle and three-hole effect, as explained in Ref. [35]. In general, quasivibrational and quasirotational states coexsitence will occur due to coupling a few-particle cluster to the vibrational field [35]. This results in the lowering of the $j-1$ state when the particles have the same spin. The $7/2^+$ state lowers in this case. A similar trend is also observed in the case of the $fpgpn$ interactions; however, the lowest energy of $5/2_1^+$ states is predicted in ^{75}Ni.

The systematics of βn-branching ratios for Co isotopes is shown in Fig. 10. The figure includes experimental branching ratios from previous works [23,33] and predicted values from finite-range droplet model (FRDM) calculations [36]. The P_n value of 6(3)% for ^{73}Co in this work agrees well with $P_n < 7.9\%$ by Hosmer et al. [33]. More on the neutron-rich side, the upper limit of the βn emission for ^{75}Co was estimated to be 16% [33], and $P_n = 55\%$ for ^{77}Co is predicted by the FRDM calculations [36]. The trend of increasing neutron-emission probability is attributed to the large energy window above the neutron separation energy (S_n). The relatively small branching ratios for neutron emission in the cobalt decays could be due to the strong allowed GT transitions for their neutron-bound daughters.

On the basis of the results of shell-model calculations in ^{77}Ni, the $5/2^-$ state is not predicted below 4 MeV in the $fpgpn$ interactions. In this case, a strong β-delayed neutron emission channel could occur in the decay of ^{77}Co due to the neutron separation energy of ^{77}Ni ($S_n = 3240(640)$ keV [37]). Assuming the results by the $jj44pna$ interactions, the $5/2_1^-$ state is predicted at 2.5 MeV, and the strong β-decay strength without the neutron emission could be expected. In this case, a high-energy $M2$ transition from the $5/2^-$ state to the ground state or a $E2$ transition to the $1/2^-$ state might be observed. Future measurements on the β decay of ^{77}Co will be a key to solve the different predictions.

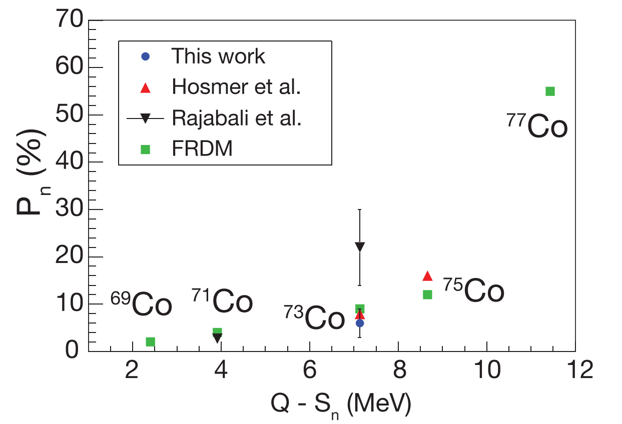

FIG. 10. Neutron emission probabilities (P_n) for the indicated nuclei as a function of the difference between the β-decay Q value and neutron separation energy S_n. The Q_β and S_n are taken from Ref. [36]. The experimental upper limits were taken from Ref. [23] and Ref. [33]. The green squares correspond to predicted P_n values from FRDM calculations [36].

V. SUMMARY

Excited states in ^{73,75}Ni were investigated through the β decay of ^{73,75}Co at the National Superconducting Cyclotron laboratory (NSCL). The level scheme of ^{73}Ni was updated up to excitation energies of 3.2 MeV, and the first excited state in ^{75}Ni was observed for the first time. We observed strong GT feeding to low-lying excited states in addition to a small β-decay strength to highly excited levels in the decay of ^{73}Co. We performed shell-model calculations with the $fpgpn$ interaction assuming ^{40}Ca core and the $jj44pna$ interactions assuming ^{56}Ni core and discussed them in comparison with the experimental results.

ACKNOWLEDGMENTS

This material is based upon work supported by the Department of Energy National Nuclear Security Administration through the Nuclear Science and Security Consortium under Awards No. DE-NA-0002132, No. DE-NA-0003180, and No. DE-NA-0000979. M.M.R. was supported through DOE Office of Science under Grant No. DE-SC0016988, the Natural Sciences and Engineering Research Council of Canada (NSERC), and the Tennessee Technological University Faculty Development Fund. A.A.C. acknowledges support by the Polish Ministry of Science and Higher Education through Grant No. 0079/DIA/2014/43 ("Grant Diamentowy"). The operation of the National Superconducting

Cyclotron Laboratory at Michigan State University is supported by the NSF under Grant No. PHY-1565546. We would like to thank Prof. Alex Brown for providing us the *fpgpn* interactions.

[1] R. Taniuchi, C. Santamaria, P. Doornenbal, A. Obertelli, K. Yoneda, G. Authelet, H. Baba, D. Calvet, F. Château, A. Corsi, A. Delbart, J.-M. Gheller, A. Gillibert, J. D. Holt, T. Isobe, V. Lapoux, M. Matsushita, J. Menéndez, S. Momiyama, T. Motobayashi, M. Niikura, F. Nowacki, K. Ogata, H. Otsu, T. Otsuka, C. Péron, S. Péru, A. Peyaud, E. C. Pollacco, A. Poves, J.-Y. Roussé, H. Sakurai, A. Schwenk, Y. Shiga, J. Simonis, S. R. Stroberg, S. Takeuchi, Y. Tsunoda, T. Uesaka, H. Wang, F. Browne, L. X. Chung, Z. Dombradi, S. Franchoo, F. Giacoppo, A. Gottardo, K. Hadyńska-Klęk, Z. Korkulu, S. Koyama, Y. Kubota, J. Lee, M. Lettmann, C. Louchart, R. Lozeva, K. Matsui, T. Miyazaki, S. Nishimura, L. Olivier, S. Ota, Z. Patel, E. Şahin, C. Shand, P.-A. S oderstr om, I. Stefan, D. Steppenbeck, T. Sumikama, D. Suzuki, Z. Vajta, V. Werner, J. Wu, and Z. Y. Xu, Nature (London) **569**, 53 (2019).

[2] Z. Y. Xu, S. Nishimura, G. Lorusso, F. Browne, P. Doornenbal, G. Gey, H.-S. Jung, Z. Li, M. Niikura, P.-A. Söderström, T. Sumikama, J. Taprogge, Z. Vajta, H. Watanabe, J. Wu, A. Yagi, K. Yoshinaga, H. Baba, S. Franchoo, T. Isobe, P. R. John, I. Kojouharov, S. Kubono, N. Kurz, I. Matea, K. Matsui, D. Mengoni, P. Morfouace, D. R. Napoli, F. Naqvi, H. Nishibata, A. Odahara, E. Şahin, H. Sakurai, H. Schaffner, I. G. Stefan, D. Suzuki, R. Taniuchi, and V. Werner, Phys. Rev. Lett. **113**, 032505 (2014).

[3] E. Sahin, F. L. Bello Garrote, Y. Tsunoda, T. Otsuka, G. de Angelis, A. Görgen, M. Niikura, S. Nishimura, Z. Y. Xu, H. Baba, F. Browne, M.-C. Delattre, P. Doornenbal, S. Franchoo, G. Gey, K. Hadyńska-Klek, T. Isobe, P. R. John, H. S. Jung, I. Kojouharov, T. Kubo, N. Kurz, Z. Li, G. Lorusso, I. Matea, K. Matsui, D. Mengoni, P. Morfouace, D. R. Napoli, F. Naqvi, H. Nishibata, A. Odahara, H. Sakurai, H. Schaffner, P.-A. Söderström, D. Sohler, I. G. Stefan, T. Sumikama, D. Suzuki, R. Taniuchi, J. Taprogge, Z. Vajta, H. Watanabe, V. Werner, J. Wu, A. Yagi, M. Yalcinkaya, and K. Yoshinaga, Phys. Rev. Lett. **118**, 242502 (2017).

[4] M. Madurga, S. V. Paulauskas, R. Grzywacz, D. Miller, D. W. Bardayan, J. C. Batchelder, N. T. Brewer, J. A. Cizewski, A. Fijałkowska, C. J. Gross, M. E. Howard, S. V. Ilyushkin, B. Manning, M. Matoš, A. J. Mendez, K. Miernik, S. W. Padgett, W. A. Peters, B. C. Rasco, A. Ratkiewicz, K. P. Rykaczewski, D. W. Stracener, E. H. Wang, M. Wolińska-Cichocka, and E. F. Zganjar, Phys. Rev. Lett. **117**, 092502 (2016).

[5] A. Gottardo, D. Verney, C. Delafosse, F. Ibrahim, B. Roussière, C. Sotty, S. Roccia, C. Andreoiu, C. Costache, M.-C. Delattre, I. Deloncle, A. Etilé, S. Franchoo, C. Gaulard, J. Guillot, M. Lebois, M. MacCormick, N. Marginean, R. Marginean, I. Matea, C. Mihai, I. Mitu, L. Olivier, C. Portail, L. Qi, L. Stan, D. Testov, J. Wilson, and D. T. Yordanov, Phys. Rev. Lett. **116**, 182501 (2016).

[6] X. F. Yang, C. Wraith, L. Xie, C. Babcock, J. Billowes, M. L. Bissell, K. Blaum, B. Cheal, K. T. Flanagan, R. F. Garcia Ruiz, W. Gins, C. Gorges, L. K. Grob, H. Heylen, S. Kaufmann, M. Kowalska, J. Kraemer, S. Malbrunot-Ettenauer, R. Neugart, G. Neyens, W. Nörtershäuser, J. Papuga, R. Sánchez, and D. T. Yordanov, Phys. Rev. Lett. **116**, 182502 (2016).

[7] R. Grzywacz, R. Béraud, C. Borcea, A. Emsallem, M. Glogowski, H. Grawe, D. Guillemaud-Mueller, M. Hjorth-Jensen, M. Houry, M. Lewitowicz, A. C. Mueller, A. Nowak, A. Płochocki, M. Pfützner, K. Rykaczewski, M. G. Saint-Laurent, J. E. Sauvestre, M. Schaefer, O. Sorlin, J. Szerypo, W. Trinder, S. Viteritti, and J. Winfield, Phys. Rev. Lett. **81**, 766 (1998).

[8] C. Mazzocchi, R. Grzywacz, J. C. Batchelder, C. R. Bingham, D. Fong, J. H. Hamilton, J. K. Hwang, M. Karny, W. Krolas, S. N. Liddick, A. F. Lisetskiy, A. C. Morton, P. F. Mantica, W. F. Mueller, K. P. Rykaczewski, M. Steiner, A. Stolz, and J. A. Winger, Phys. Lett. B **622**, 45 (2005).

[9] M. Sawicka, R. Grzywacz, I. Matea, H. Grawe, M. Pfützner, J. M. Daugas, M. Lewitowicz, D. L. Balabanski, F. Becker, G. Bélier, C. Bingham, C. Borcea, E. Bouchez, A. Buta, M. La Commara, E. Dragulescu, G. de France, G. Georgiev, J. Giovinazzo, M. Górska, F. Hammache, M. Hass, M. Hellström, F. Ibrahim, Z. Janas, H. Mach, P. Mayet, V. Méot, F. Negoita, G. Neyens, F. de Oliveira Santos, R. D. Page, O. Perru, Z. Podolyák, O. Roig, and K. P. Rykaczewski, M. G. Saint-Laurent, J. E. Sauvestre, O. Sorlin, M. Stanoiu, I. Stefan, C. Stodel, Ch. Theisen, D. Verney, and J. Żylicz, Phys. Rev. C **68**, 044304 (2003).

[10] W. F. Mueller, B. Bruyneel, S. Franchoo, H. Grawe, M. Huyse, U. Köster, K.-L. Kratz, K. Kruglov, Y. Kudryavtsev, B. Pfeiffer, R. Raabe, I. Reusen, P. Thirolf, P. Van Duppen, J. Van Roosbroeck, L. Vermeeren, W. B. Walters, and L. Weissman, Phys. Rev. Lett. **83**, 3613 (1999).

[11] A. Spyrou, S. N. Liddick, F. Naqvi, B. P. Crider, A. C. Dombos, D. L. Bleuel, B. A. Brown, A. Couture, L. Crespo Campo, M. Guttormsen, A. C. Larsen, R. Lewis, P. Möller, S. Mosby, M. R. Mumpower, G. Perdikakis, C. J. Prokop, T. Renstrøm, S. Siem, S. J. Quinn, and S. Valenta, Phys. Rev. Lett. **117**, 142701 (2016).

[12] B. P. Crider, C. J. Prokop, S. N. Liddick, M. Al-Shudifat, A. D. Ayangeakaa, M. P. Carpenter, J. J. Carroll, J. Chen, C. J. Chiara, H. M. David, A. C. Dombos, S. Go, R. Grzywacz, J. Harker, R. V. F. Janssens, N. Larson, T. Lauritsen, R. Lewis, S. J. Quinn, F. Recchia, A. Spyrou, S. Suchyta, W. B. Walters, and S. Zhu, Phys. Lett. B **763**, 108 (2016).

[13] P.-A. Söderström, S. Nishimura, Z. Y. Xu, K. Sieja, V. Werner, P. Doornenbal, G. Lorusso, F. Browne, G. Gey, H. S. Jung, T. Sumikama, J. Taprogge, Z. Vajta, H. Watanabe, J. Wu, H. Baba, Z. Dombradi, S. Franchoo, T. Isobe, P. R. John, Y.-K. Kim, I. Kojouharov, N. Kurz, Y. K. Kwon, Z. Li, I. Matea, K. Matsui, G. Martínez-Pinedo, D. Mengoni, P. Morfouace, D. R. Napoli, M. Niikura, H. Nishibata, A. Odahara, K. Ogawa, N. Pietralla, E. Şahin, H. Sakurai, H. Schaffner, D. Sohler, I. G. Stefan, D. Suzuki, R. Taniuchi, A. Yagi, and K. Yoshinaga, Phys. Rev. C **92**, 051305(R) (2015).

[14] A. Gottardo, G. de Angelis, P. Doornenbal, L. Coraggio, A. Gargano, N. Itaco, K. Kaneko, P. Van Isacker, T. Furumoto, G. Benzoni, J. Lee, H. Liu, M. Matsushita, D. Mengoni, V. Modamio-Hoybjor, S. Momiyama, T. Motobayashi, D. R. Napoli, M. Niikura, E. Sahin, Y. Shiga, H. Sakurai, R. Taniuchi, S. Takeuchi, H. Wang, J. J. Valiente-Dobòn, R. Avigo, H. Baba, N. Blasi, F. L. Bello Garrote, F. Browne, F. C. L. Crespi,

S. Ceruti, R. Daido, M.-C. Delattre, D. Fang, Z. Dombradi, T. Isobe, I. Kuti, G. Lorusso, K. Matsui, B. Melon, T. Miyazaki, S. Nishimura, R. Orlandi, Z. Patel, S. Rice, L. Sinclair, P. A. Söderström, D. Sohler, T. Sumikama, J. Taprogge, Z. Vajta, H. Watanabe, O. Wieland, J. Wu, Z. Y. Xu, M. Yalcinkaya, and R. Yokoyama, Phys. Rev. C **102**, 014323 (2020).

[15] A. I. Morales, G. Benzoni, H. Watanabe, G. de Angelis, S. Nishimura, L. Coraggio, A. Gargano, N. Itaco, T. Otsuka, Y. Tsunoda, P. Van Isacker, F. Browne, R. Daido, P. Doornenbal, Y. Fang, G. Lorusso, Z. Patel, S. Rice L. Sinclair, P.-A. Söderström T. Sumikama, J. J. Valiente-Dobón, J. Wu, Z. Y. Xu, A. Yagi, R. Yokoyama, H. Baba, R. Avigo, F. L. Bello Garrote, N. Blasi, A. Bracco, A. M. B. F. Camera, S. Ceruti, F. C. L. Crespi, M.-C. Delattre, Z. Dombradi, A. Gottardo, T. Isobe, I. K. N. Kurz, I. Kuti, S. Lalkovski, K. Matsui, B. Melon, D. Mengoni, T. Miyazaki, V. Modamio-Hoybjor, S. Momiyama, D. R. Napoli, M. Niikura, R. Orlandi, Z. Podolyák P. H. Regan, H. Sakurai, E. Sahin, D. Sohler, H. Schaffner, R. Taniuchi, J. Taprogge, Z. Vajta O. Wieland, and M. Yalcinkaya, Phys. Lett. B **781**, 706 (2018).

[16] F. Nowacki, A. Poves, E. Caurier, and B. Bounthong, Phys. Rev. Lett. **117**, 272501 (2016).

[17] G. Hagen, G. R. Jansen, and T. Papenbrock, Phys. Rev. Lett. **117**, 172501 (2016).

[18] Y. Tsunoda, T. Otsuka, N. Shimizu, M. Honma, and Y. Utsuno, Phys. Rev. C **89**, 031301(R) (2014).

[19] S. Lyons, A. Spyrou, S. N. Liddick, F. Naqvi, B. P. Crider, A. C. Dombos, D. L. Bleuel, B. A. Brown, A. Couture, L. Crespo Campo, J. Engel, M. Guttormsen, A. C. Larsen, R. Lewis, P. Möller, S. Mosby, M. R. Mumpower, E. M. Ney, A. Palmisano, G. Perdikakis, C. J. Prokop, T. Renstrøm, S. Siem, M. K. Smith, and S. J. Quinn, Phys. Rev. C **100**, 025806 (2019).

[20] A. I. Morales, G. Benzoni, H. Watanabe, S. Nishimura, F. Browne, R. Daido, P. Doornenbal, Y. Fang, G. Lorusso, Z. Patel, S. Rice, L. Sinclair, P.-A. Söderström, T. Sumikama, J. Wu, Z. Y. Xu, A. Yagi, R. Yokoyama, H. Baba, R. Avigo, F. L. Bello Garrote, N. Blasi, A. Bracco, F. Camera, S. Ceruti, F. C. L. Crespi, G. de Angelis, M.-C. Delattre, Z. Dombradi, A. Gottardo, T. Isobe, I. Kojouharov, N. Kurz, I. Kuti, K. Matsui, B. Melon, D. Mengoni, T. Miyazaki, V. Modamio-Hoyborg, S. Momiyama, D. R. Napoli, M. Niikura, R. Orlandi, H. Sakurai, E. Sahin, D. Sohler, H. Shaffner, R. Taniuchi, J. Taprogge, Z. Vajta, J. J. Valiente-Dobón, O. Wieland, and M. Yalcinkaya, Phys. Rev. C **93**, 034328 (2016).

[21] A. I. Morales, G. Benzoni, H. Watanabe, Y. Tsunoda, T. Otsuka, S. Nishimura, F. B. R. Daido, P. Doornenbal, Y. F. G. Lorusso, Z. Patel, S. Rice, L. Sinclair, P.-A. Söderström, T. Sumikama. J. Wu, Z. Y. Xu, A. Yagi, R. Yokoyama, H. Baba, R. Avigo, F. L. Bello Garrote, N. Blasi, A. Bracco, F. Camera, S. Ceruti, F. C. L. Crespi, G. de Angelis, M.-C. Delattre, Z. Dombradi, A. Gottardo, T. Isobe, I. Kojouharov, N. Kurz, I. Kuti, K. Matsui, B. Melon, D. Mengoni, T. Miyazaki, V. Modamio-Hoybjor, S. Momiyama, D. R. Napoli, M. Niikura, R. Orlandi, H. Sakurai, E. Sahin, D. Sohler, H. Schaffner, R. Taniuchi, J. Taprogge, Z. Vajta, J. J. Valiente-Dobòn, O. Wieland, and M. Yalcinkaya, Phys. Lett. B **765**, 328 (2017).

[22] M. Sawicka, I. Matea, H. Grawe, R. Grzywacz, M. Pfützner, M. Lewitowicz, J. M. Daugas, B. A. Brown, A. Lisetskiy, F. Becker, G. Bélier, C. Bingham, R. Borcea, E. Bouchez, A. Buta, E. Dragulescu, G. de France, G. Georgiev, J. Giovinazzo, F. Hammache, F. Ibrahim, P. Mayet, V. Méot, F. Negoita, F. De Oliveira-Santos, O. Perru, O. Roig, K. Rykaczewski, M. G. Saint-Laurent, J. E. Sauvestre, O. Sorlin, M. Stanoiu, I. Stefan, C. Stodel, C. Theisen, D. Verney, and J. Żylicz, Eur. Phys. A **22**, 455 (2004).

[23] M. M. Rajabali, R. Grzywacz, S. N. Liddick, C. Mazzocchi, J. C. Batchelder, T. Baumann, C. R. Bingham, I. G. Darby, T. N. Ginter, S. V. Ilyushkin, M. Karny, W. Królas, P. F. Mantica, K. Miernik, M. Pfützner, K. P. Rykaczewski, D. Weisshaar, and J. A. Winger, Phys. Rev. C **85**, 034326 (2012).

[24] O. B. Tarasov, M. Portillo, D. J. Morrissey, A. M. Amthor, L. Bandura, T. Baumann, D. Bazin, J. S. Berryman, B. A. Brown, G. Chubarian, N. Fukuda, A. Gade, T. N. Ginter, M. Hausmann, N. Inabe, T. Kubo, J. Pereira, B. M. Sherrill, A. Stolz, C. Sumithrarachichi, M. Thoennessen, and D. Weisshaar, Phys. Rev. C **87**, 054612 (2013).

[25] D. J. Morrissey, B. M. Sherrill, M. Steiner, A. Stolz, and I. Wiedenhoever, Nucl. Instrum. Methods B **204**, 90 (2003).

[26] W. F. W. Schneider, B. Kohlmeyer, and R. Bock, Nucl. Instrum. Methods **87**, 253 (1970).

[27] N. Larson, S. N. Liddick, M. Bennett, A. Bowe, A. Chemey, C. Prokop, A. Simon, A. Spyrou, S. Suchyta, S. J. Quinn S. L. Tabor, P. L. Tai, Vandana Tripathi, and J. M. VonMoss, Nucl. Instrum. Methods A **727**, 59 (2013).

[28] S. Agostinelli *et al.*, Nucl. Instrum. Methods A **506**, 250 (2003).

[29] C. J. Prokop, S. N. Liddick, B. L. Abromeit, A. T. Chemey, N. R. Larson, and S. Suchyta, and J. R. Tompkins, Nucl. Instrum. Methods A **741**, 163 (2014).

[30] H. Bateman, Proc. Cambridge Phil. Soc. **15**, 423 (1910).

[31] G. Audi, A. H. Wapstra, and C. Thibault, Nucl. Phys. A **729**, 337 (2003)

[32] T. Lokotko, S. Leblond, J. Lee, P. Doornenbal, A. Obertelli, A. Poves, F. Nowacki, K. Ogata, K. Yoshida, G. Authelet, H. Baba, D. Calvet, F. Château, S. Chen, A. Corsi, A. Delbart, J.-M. Gheller, T. Isobe, V. Lapoux, M. Matsushita, S. Momiyama, T. Motobayashi, M. Niikura, H. Otsu, C. Péron, A. Peyaud, E. C. Pollacco, J.-Y. Roussé, H. Sakurai, C. Santamaria, Z. Y. Xu, M. Sasano, Y. Shiga, S. Takeuchi, R. Taniuchi, T. Uesaka, H. Wang, V. Werner, F. Browne, L. X. Chung, Z. Dombradi, S. Franchoo, F. Giacoppo, A. Gottardo, K. Hadynska-Klek, Z. Korkulu, S. Koyama, Y. Kubota, M. Lettmann, C. Louchart, R. Lozeva, K. Matsui, T. Miyazaki, S. Nishimura, L. Olivier, S. Ota, Z. Patel, E. Sahin, C. Shand, P.-A. Söderström, I. Stefan, D. Steppenbeck, T. Sumikama, D. Suzuki, Z. Vajta, and J. Wu, Phys. Rev. C **101**, 034314 (2020).

[33] P. Hosmer, H. Schatz, A. Aprahamian, O. Arndt, R. R. C. Clement, A. Estrade, K. Farouqi, K.-L. Kratz, S. N. Liddick, A. F. Lisetskiy, P. F. Mantica, P. Möller, W. F. Mueller, F. Montes, A. C. Morton, M. Ouellette, E. Pellegrini, J. Pereira, B. Pfeiffer, P. Reeder, P. Santi, M. Steiner, A. Stolz, B. E. Tomlin, W. B. Walters, and A. Wöhr, Phys. Rev. C **82**, 025806 (2010).

[34] A. F. Lisetskiy, B. A. Brown, M. Horoi, and H. Grawe, Phys. Rev. C **70**, 044314 (2004).

[35] Y. Paar, Nucl. Phys. A **211**, 29 (1973).

[36] P. Möller, M. R. Mumpower, T. Kawano, and W. D. Myers, At. Data Nucl. Data Tables **125**, 1 (2019).

[37] M. Wang, G. Audi, F. G. Kondev, W. J. Huang, S. Naimi, and X. Xu, Chin. Phys. C **41**, 030003 (2017).

Correction: Two minor typographical errors in the second column of Table I have been fixed.