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Two-hole structure outside ^{78}Ni: Existence of a μs isomer of ^{76}Co and β decay into ^{76}Ni

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In the EURICA campaign aimed at exploration of the ^{78}Ni region, an isomeric state of ^{76}Co has been observed via γ-ray spectroscopy. The nuclei were produced by in-flight fission of a ^{238}U beam at the Radioactive Isotope-Beam Factory. Two coincident γ rays of 192.02(30) and 446.4(7) keV from the decay of a $t_{1/2} = 2.96(^{29}_{25})$ μs isomeric state of ^{76}Co have been observed. The decay of the isomer was assigned to an $E1$ transition with a reduced transition probability of $B(E1; 3^+ \to 2^-) = 1.79(16) \times 10^{-8}$ W.u. A β-decaying state with spin-parity 1^- and a half-life of 16(4) ms was also observed in the data, and the known state with a half-life of $22(^7_5)$ ms was assigned to have a spin-parity of 8^-. Furthermore, the isomer of ^{76}Ni has been remeasured to 547.8(33) ns giving a $B(E2; 8^+ \to 6^+)$ value of 0.786(5) W.u. A new excited state at 2994.6(5) keV, decaying via a γ ray of 2004.5(4) keV, has also been observed. This is in agreement with either of the predicted 0^+_2 or 2^+_2 states. These results are discussed in terms of the shell model and the interaction of the $\nu p_{1/2}$ and $\pi f_{7/2}$ orbitals.

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One of the currently most active topics in the study of the structure of exotic nuclei is the change in shell structure far

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away from stability [1]. The classical shell model, where nuclei with neutron and proton numbers $N,Z = 2$, 8, 20, 28, 50, 82, or 126 are considered to be more strongly bound, i.e., magic nuclei, is known to work well for nuclei close to stability, but a large amount of experimental results show that this is no longer the case for nuclei with very exotic N/Z ratios. These changes are associated with the monopole component of the proton-neutron interaction [1–6], and a large ongoing experimental effort is currently aiming to investigate how these shell and subshell closures evolve for very exotic nuclei at and below ^{78}Ni [7–10]. One way to gain this kind of information is from the study of single neutron and proton particle and hole states outside ^{78}Ni.

In this paper we present new experimental results on ^{76}Co, one neutron-hole and one proton-hole in ^{78}Ni. This is a region with very sparse experimental information on the internal structure, currently limited to the decay of the yrast cascade of the two neutron-hole nucleus ^{76}Ni [11,12], and the 2^+ energy and $B(E2; 2^+ \rightarrow 0^+)$ value [13] of the two proton-particle nucleus ^{80}Zn. Both those measurements as well as the β-decay half-life systematics around ^{78}Ni give evidence that points to double magicity in this nucleus [7,14]. No spectroscopic information exists for ^{76}Co, even its bound nature was just recently confirmed at RIKEN with five counts [15], before the experiment reported on in this paper.

The ^{76}Co nuclei were produced by in-flight fission of a 345 MeV/u ^{238}U beam on a 3 mm beryllium target and then separated using the BigRIPS fragment separator [16] and the ZeroDegree spectrometer [17]. The primary beam intensity was ~7 pnA. Two aluminum wedge-shaped energy degraders with thicknesses of 6 and 4.5 mm were placed at the focal planes F1 and F5, respectively, for purification of the beam. The particle identification (PID) of the secondary beam was done on an event-by-event basis, using the ΔE-TOF-$B\rho$ method, where ΔE is the energy loss in the ionization chambers, TOF is the time-of-flight between F3 and F7, and $B\rho$ the magnetic rigidity measured from the ion positions and angles at F3, F5, and F7. See figure in Ref. [7] for the resulting PID. At the final focal point, F11, the WAS3ABi silicon detector stack was used for implantation and β-decay correlation measurements [18,19], and the EURICA spectrometer [19,20] was used for measuring the energy and time of the γ rays. The EURICA array consisted of 12 HPGe cluster detectors arranged in three rings at 51°(five clusters), 90°(two clusters), and 129° (five clusters) relative to the beam axis. The clusters were placed at a nominal distance of 22 cm from the center of WAS3ABi but adjusted to be as close as possible to the WAS3ABi chamber to increase the efficiency. In total, approximately 1000 ^{76}Co ions were implanted in WAS3ABi during 10 days of measurement.

To verify the decay scheme of ^{76}Co, the strongly populated seniority isomer of ^{76}Ni was used as a reference. This isomer has previously been measured to have a lifetime of 0.59 μs [11,12]. In Fig. 1, the isomeric decay spectrum of ^{76}Ni is shown. Four γ rays with energies 142.56(25), 355.37(25), 929.97(25), and 990.10(25), respectively, can be observed. From the weighted average of four transitions we improve the precision in the half-life of the isomer from $0.59(^{18}_{11})$ μs [12] to 547.8(33) ns giving a $B(E2; 8^+ \rightarrow 6^+)$ value of 0.786(5) W.u. The relative intensities of these transitions, corrected for electron conversion, are 100.6(28), 98.2(21), 100.1(25), and 101.7(26)% for 143, 355, 930, and 990 keV, respectively. This is consistent with decays in a single cascade, further verified from $\gamma\gamma$ coincidence spectra that show all of these transitions in strong coincidence with no previously unknown transitions observed. We thus resolve the discrepancy from previous measurements where the 355 keV transition was either not observed [11] or, although with low statistics and within error bars, observed but only having a 50% intensity relative to the other transitions [12].

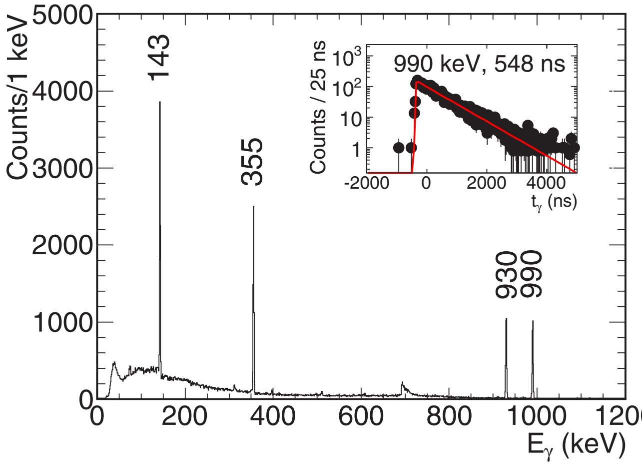

FIG. 1. (Color online) Isomer-decay spectrum and the decay time histogram of the 990 keV γ-ray (inset) of ^{76}Ni. Measured energies of the observed transitions are shown over each γ-ray peak. The red line shows the fit of an exponential decay convoluted with a Gaussian time resolution.

In Fig. 2 the γ-ray spectrum associated with implantation of ^{76}Co is shown. Two γ-ray transitions with energies of 192.02(30) and 446.4(7) keV, following the decay of a $t_{1/2} = 2.96(^{29}_{25})$ μs isomeric state, can clearly be seen in the singles spectrum. Furthermore, using $\gamma\gamma$ coincidences we find that they are coincident with each other. From the relative time difference between the two γ rays no evidence for a second isomer could be observed, suggesting that only one of the γ rays originate from an isomeric state, while the other is from a prompt transition below the isomer.

Considering ^{76}Co to be a one proton hole and one neutron hole in a ^{78}Ni core, its low-energy states can be obtained by coupling the states of ^{77}Ni and ^{77}Co. In this case, both these nuclei are next to what is believed to be a doubly closed shell nucleus [7], and are therefore expected to have a sparse level scheme at low energies. Due to this, the low lying states of ^{76}Co should be arising from the coupling of their respective ground states. The coupling of an $f_{7/2}$ proton hole and a $g_{9/2}$ neutron hole results in states with spins 1^- to 8^-. Due to the residual interaction the multiplet is expected to split into a parabolic shape for the even-spin states, with 2^- and 8^- being its lowest lying members, while the odd-parity states are increasing in energy from the 1^- to 7^- states. From such a picture, the lowest lying states are expected to be the 1^-, 2^-, and 8^- states, which are the ones that the isomer is expected to decay into.

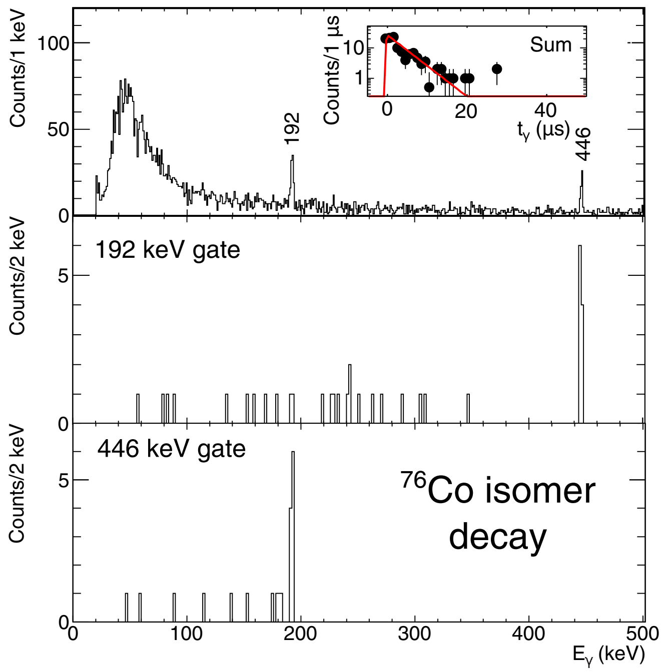

FIG. 2. (Color online) Singles (top) and $\gamma\gamma$-gated (middle, bottom) isomer γ-ray spectra of ^{76}Co. The time distribution summed over the 192 keV and the 446 keV transitions in ^{76}Co is shown in the inset. The red lines shows the fit of an exponential decay convoluted with a Gaussian time resolution. Measured energies of the observed transitions are shown over each γ-ray peak.

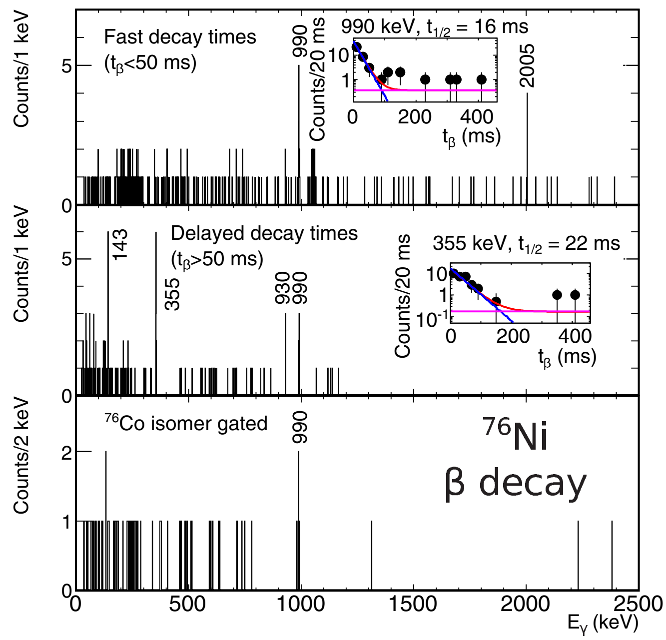

FIG. 3. (Color online) Spectra of γ-ray transitions in ^{76}Ni following β decay of ^{76}Co. The top panel shows the prompt component of the γ-ray spectrum and the middle panel shows the delayed component. The insets show the β-decay time-distribution gated on the prompt 990 keV (top) and delayed 355 keV (middle) γ rays, respectively. Blue curves represent the exponential decay and magenta lines the constant background component of the total decay function, shown in red. Bottom panel shows the total γ-ray spectrum correlated with at least one of the two isomeric γ-ray transitions in ^{76}Co.

To determine the final state of the isomer decay, the β-delayed γ-ray spectra of ^{76}Ni were examined. These spectra are shown in Fig. 3. The time distribution of the β decays correlated with ^{76}Co implantations, gated on the $2^+ \rightarrow 0^+$ and $6^+ \rightarrow 4^+$ transitions, are distinctly different. Two distinct components in the γ-ray decay spectra of ^{76}Ni can clearly be observed in coincidence with different parts of the β-decay time distribution. One component corresponds to the β-delayed γ rays correlated with fast decay times and consists of a single transition between the $2^+ \rightarrow 0^+$ states of ^{76}Ni, below the isomer. In addition, another single γ-ray with energy 2004.5(4) keV is clearly seen. The second component corresponds to the delayed decay times and these γ-rays show a spectrum originating from the $J^P = 8^+$ isomer of ^{76}Ni. We expect that for allowed β-decay transitions $\Delta J \leqslant 1$.

Thus, assuming that both decays originate from the low-energy states of the $\pi f_{7/2}^{-1} \otimes \nu g_{9/2}^{-1}$ multiplet, we assign the two components to be ^{76}Co(8^-) $\rightarrow$ ^{76}Ni(8^+) and ^{76}Co(1^-) $\rightarrow$ ^{76}Ni(2^+,0^+). The half-life of ^{76}Co has previously been reported to be $22(^{7}_{5})$ ms [7]. While the two components have been previously identified in Ref. [21], we are here able to assign the $22(^{7}_{5})$ ms component to the 8^- state and the 16(4) ms component to the 1^- state. Unfortunately it is not possible from the data to determine which of these two is the ground state. To see which of these two states is the final state of the ^{76}Co isomer decay, the β-delayed γ-ray spectrum of ^{76}Ni correlated with isomeric γ rays from ^{76}Co was produced. In this spectrum, three counts can be seen in the 990 keV region while the 930 and 355 keV regions each have zero counts and the 143 keV region has one count, all of them within the prompt part of the γ-ray time spectrum. Thus, the strongest candidate for the final transition in ^{76}Co would be into the 1^- state.

For the spin and parity of the isomeric state itself, and the ordering of the transitions, we calculate the Weisskopf estimates of the reduced transition probabilities for the decay of the possible states. If the decay would go via the ground-state multiplet it is expected that the transition probability is reasonably close to 1 W.u., similar to what is observed for ^{76}Ni. However, as shown in Table I, no such transition can reproduce the observed half-life of the isomer. Another possibility is that the isomeric state decays via a parity-changing transition, meaning that there is a low lying positive-parity state in this nucleus. To create such a state we need to include the first negative-parity orbital below $\nu g_{9/2}$, which is $\nu p_{1/2}$. This would mean that the transition would have $\Delta l = 3$ and thus we would expect the transition to have a transition probability $B(^{E}_{M}\lambda) \ll$ 1 W.u. which is more in agreement with our experimental data. In the case of the coupling of an $f_{7/2}$ proton hole and a $p_{1/2}$ neutron hole we get states with spin 3^+ and 4^+. Due to the dipole interaction the state with the lower spin 3^+ is expected to lie at lower excitation energy [22].

To verify this, shell-model calculations were carried out with an up-to-date Lenzi-Nowacki-Poves-Sieja (LNPS) interaction [6,23] including monopole changes to ensure the correct propagation of proton single-particle energies [24]. Since the negative and positive parity states are obtained with relatively

TABLE I. Expected half-lives ($t_{1/2}$) for different possibilities of the ^{76}Co decay. Decays within the $\pi f_{7/2}^{-1} \otimes \nu g_{9/2}^{-1}$ ground state multiplet (intraband) have been estimated to have a probability of 1 W.u. while transition probabilities from the $\pi f_{7/2}^{-1} \otimes \nu p_{1/2}^{-1}$ multiplet (interband) have been calculated using the LNPS interaction. The value that best agrees with the experimental data of $t_{1/2} = 2.96(^{29}_{25})$ μs has been highlighted in bold font.

Multipolarity	$t_{1/2}$ (192 keV) (μs)	$t_{1/2}$ (446 keV) (μs)
Intraband (1 W.u.)		
$M1$	3×10^{-6}	2×10^{-7}
$E2$	1×10^{-1}	2×10^{-3}
$M3$	2×10^{7}	6×10^{4}
Interband (LNPS)		
$E1; 3^+ \rightarrow 2^-$	**6**	5×10^{-1}
$M2; 3^+ \rightarrow 2^-$	2×10^{4}	3×10^{2}
$E3; 3^+ \rightarrow 2^-$	2×10^{10}	5×10^{7}

pure structures, about 70%, of $\pi f_{7/2}^{-1} \otimes \nu g_{9/2}^{-1}$ or $\pi f_{7/2}^{-1} \otimes \nu p_{1/2}^{-1}$ hole configurations, respectively, the relative $\nu g_{9/2}^{-1}$ and $\nu p_{1/2}^{-1}$ positions can be fine tuned by changing the strength of the $\pi f_{7/2}^{-1} \otimes \nu p_{1/2}^{-1}$ monopole. The results of these calculations are shown in Fig. 4.

Using this tuned interaction, the $E1$, $M2$, and $E3$ transition probabilities for the $3^+,4^+ \rightarrow 2^-$ transitions were calculated. For the $E1$ transitions the calculations yield a transition probability of $B(E1; 3^+ \rightarrow 2^-) = 10^{-8}$ e^2 fm^2, which is in agreement with the experimental data that would give $B(E1; 192\text{ keV}) = 1.79(16) \times 10^{-8}$ W.u. For this case, 1 W.u. is approximately equal to 1 e^2 fm^2, so these values should be directly comparable. For the $E3$ multipolarity, $e_n = 0.48$ e and $e_p = 1.36$ e were chosen as effective charges, based on systematics within the sd shell [26]. This yields values of $B(E3; 3^+ \rightarrow 2^-) = 0.0069$ e^2 fm^6 and $B(E3; 4^+ \rightarrow 2^-) = 0.0582$ e^2 fm^6 for the two possible parity changing transitions. For the $M2$ transitions two sets of transition probabilities have been calculated, using bare effective charges and with a 0.75 quenching on the spin part of the $M2$ factors. The values obtained are $B(M2; 3^+ \rightarrow 2^-) = 0.0095$ μ_n^2 fm^2 and $B(M2; 4^+ \rightarrow 2^-) = 0.0013$ μ_n^2 fm^2, and $B(M2; 3^+ \rightarrow 2^-) = 0.0054$ μ_n^2 fm^2 and $B(M2; 4^+ \rightarrow 2^-) = 0.0013 = 0.0007$ μ_n^2 fm^2, respectively. From these calculations, summarized in Table I, we can see that what best reproduces the experimental results is the 192 keV $E1$ transition, while the other possibilities are orders of magnitude higher or lower than the shell-model predictions.

Based on the above discussion on ^{76}Co we can tentatively assign the 2005 keV γ-ray transition in ^{76}Ni to a decay into the first 2^+ state. As this level is populated by the 1^- state of ^{76}Co it must be a low-spin state and, thus, either decay into the 0^+ ground state or the first excited 2^+ state. If this new state is the 2_2^+ state, the dominant transition would be the $2_2^+ \rightarrow 2_1^+$ $M1/E2$ transition, and if it is the 0_2^+ state, only the $0_2^+ \rightarrow 2_1^+$ $E2$ transition would have nonzero γ-ray emission probability. Both of these states are consistent with recent Monte Carlo shell-model calculations [25], shown in Fig. 4.

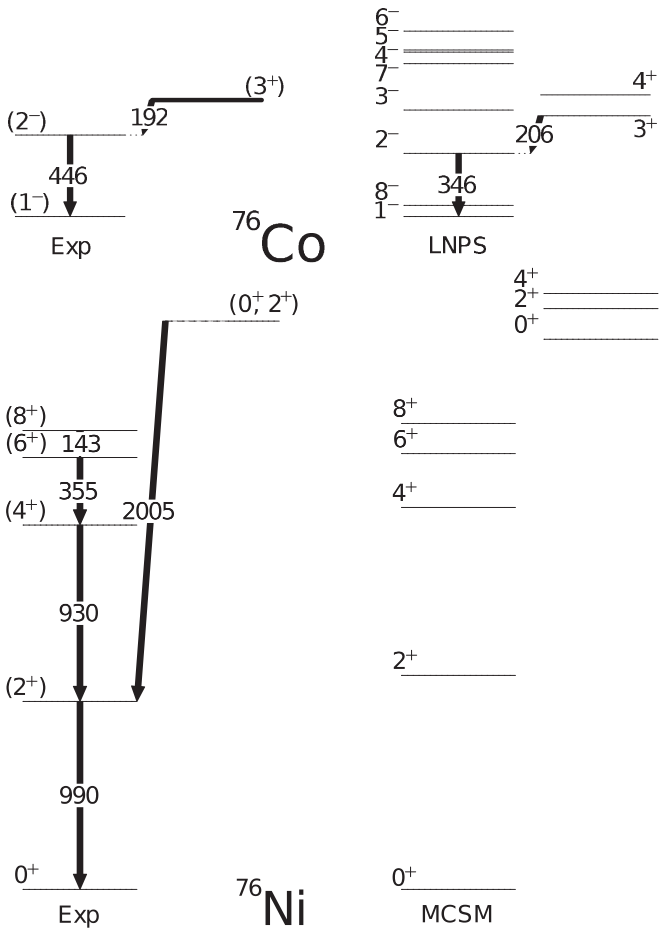

FIG. 4. Proposed experimental level scheme of ^{76}Ni (bottom left) and ^{76}Co (top left) with two levels at 446.4(7) and 638.4(8) keV, relative to the lowest 1^- state, compared to Monte Carlo shell-model calculations [25] (bottom right) and shell-model calculations using a modified LNPS interaction (top right).

As a final point we note that both for ^{68}Ni and ^{76}Co, $\pi f_{7/2}$ is nearly filled and with the adjustment of the $\pi f_{7/2} \nu p_{1/2}$ monopole we can recalculate the $N = 40$ shell gap in ^{68}Ni, experimentally determined to be 2.9 MeV from mass measurements. Our tuned interaction gives us a slightly better value of 3.1 MeV compared to 3.4 MeV before the adjustment.

To summarize, we have identified two isomers of ^{76}Co. One of them has been assigned to be a β-decaying 8^- state and the other to originate from a low-lying 3^+ γ-decaying state, in agreement with LNPS shell-model calculations taking the known effects in the shell evolution in the ^{78}Ni region into account. We have also identified a candidate for the 0_2^+ or 2_2^+ states of ^{76}Ni. These results will help constrain further developments of theoretical models in the $\pi f_{7/2} \otimes \nu g_{9/2}$ region between ^{60}Ca and ^{78}Ni, where scarce experimental data are available.

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