



Evolution of the nuclear structure in neutron-rich Cu isotopes: first spectroscopy of odd-odd ^{74}Cu and ^{76}Cu

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Abstract Excited states in the odd-odd isotopes ^{74}Cu and ^{76}Cu were observed for the first time in a spectroscopic study following the β decay of ^{74}Ni and ^{76}Ni . The experiment

was performed at the Radioactive Isotope Beam Factory at RIKEN Nishina Center using the EURICA setup and the BigRIPS separator. Level schemes were constructed based on the analysis of γ - γ coincidences. The time correlations between β and γ decay showed no evidence for population

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of isomeric states in either nucleus. The experimental results are compared to large-scale Monte Carlo shell-model calculations with the A3DA-m interaction. The low-lying states in ^{74}Cu and ^{76}Cu are interpreted as spin multiplets arising from the coupling of an odd proton in the $2p_{3/2}$ or $1f_{5/2}$ orbital with an odd neutron in the $1g_{9/2}$ or $2p_{1/2}$ orbital. The results provide information on the evolution of single-particle orbitals along the chain of neutron-rich Cu isotopes and on the proton-neutron interaction in the vicinity of ^{78}Ni , which serve as important benchmarks for shell-model calculations. The non-observation of the low-energy isomeric state at 65 keV in ^{76}Cu , combined with the observed decay pattern from higher-lying states, strongly supports a spin-parity assignment of $3^{(-)}$ for the ground state and (6^{-}) for the isomeric state, resolving a long-standing ambiguity discussed in previous studies.

1 Introduction

One of the fundamental questions in nuclear physics is to understand how nuclear structure changes when moving away from well-known stable nuclei towards exotic nuclei with large proton-neutron asymmetry. The chain of copper isotopes, with one valence proton outside the $Z = 28$ shell, is particularly well suited to study the evolution of proton single-particle orbitals. Level schemes have been established for all isotopes along the chain from stable Cu isotopes up to ^{79}Cu with $N = 50$, with the exception of odd-odd ^{74}Cu and ^{76}Cu . Earlier studies of the Cu isotopic chain have found the excited $\pi 1f_{5/2}$ single-particle state to rapidly decrease in energy relative to the $\pi 2p_{3/2}$ ground state as neutrons fill the $\nu 1g_{9/2}$ orbital in ^{71}Cu and ^{73}Cu [1, 2]. The ordering of the two states becomes inverted in ^{75}Cu , where the ground state was found to have $I^\pi = 5/2^-$ [3], and an isomeric $3/2^-$ state was found at very low excitation energy [4]. The excitation energy of the $3/2^-$ state continues to increase relative to the $5/2^-$ ground state in ^{77}Cu [5] and ^{79}Cu [6], consistent with the crossing of the $\pi 1f_{5/2}$ and $\pi 2p_{3/2}$ orbitals. The change in single-particle energies was explained by the tensor component of the monopole interaction, which is attractive between the $\nu 1g_{9/2}$ and $\pi 1f_{5/2}$ orbitals, but repulsive between the $\nu 1g_{9/2}$ and $\pi 2p_{3/2}$ orbitals [7]. It was demonstrated that the monopole-based universal interaction V_{MU} , which contains the tensor interaction, reproduces the crossing of the $1f_{5/2}$ and $2p_{3/2}$ orbitals [8]. Large-scale shell-model calculations based on a ^{48}Ca core and an effective interaction derived from the CD-Bonn potential, which also reproduced the inversion of the $1f_{5/2}$ and $2p_{3/2}$ orbitals, predicted a quenching of the $Z = 28$ shell gap between the effective single-particle energies (ESPE) from 5.8 MeV at $N = 40$ to 4.6 MeV at $N = 50$ [9]. Monte Carlo shell-model (MCSM) calculations [10] based on a larger valence space outside a ^{40}Ca core

with the A3DA-m interaction [11] were able to reproduce detailed spectroscopic data for both ^{77}Cu [5] and ^{79}Cu [6]. The MCSM calculations found that the $5/2^-$ state is lowered not only due to the tensor monopole effects, but also due to multipole correlation effects, causing the physical $5/2^-$ and $3/2^-$ states to cross at $N = 46$. According to these calculations, the $\pi 1f_{5/2}$ and $\pi 2p_{3/2}$ single-particle orbitals do not cross before $N = 48$, resulting in a larger gap of ~ 5 MeV at $N = 50$ [5, 12].

Significant progress has been made in understanding the structure of the odd-mass Cu isotopes between neutron numbers $N = 40$ and 50, with known partial level schemes for all odd-mass Cu isotopes along the chain. Several studies have been performed, including studies following β decay [1, 2, 5, 13], Coulomb excitation [14], transfer [15, 16] and knock-out reactions [6, 17, 18], from lifetime measurements [4, 19], and measurements of nuclear moments [3, 12, 20, 21]. The low-lying states can be understood either as proton single-particle states, particle-core coupled states, collective states, or states based on a $2p - 1h$ configuration. The available spectroscopic information on the neutron-rich odd-mass Cu isotopes, in particular on the intruder states, supports the notion of shape coexistence in the region near ^{78}Ni [13, 18].

By comparison, much less is known for the neutron-rich odd-odd Cu isotopes. Their ground states and excited states at low energy are expected to be dominated by negative-parity multiplets arising from the coupling of an odd proton in the $\pi 2p_{3/2}$ or $\pi 1f_{5/2}$ orbital with a neutron in the $\nu 1g_{9/2}$ orbital. In the case of ^{70}Cu , the multiplet structure gives rise to β -decaying isomeric states at low excitation energy [22]. Level schemes have been established for ^{70}Cu [23] and ^{72}Cu [24] following the β decay of ^{70}Ni and ^{72}Ni , respectively. These studies provided information on the proton-neutron interaction outside the ^{68}Ni core and on the robustness of the $N = 40$ sub-shell closure. Coulomb excitation experiments using isomeric beams provided transition matrix elements between the members of the multiplets, which were compared to shell-model calculations to obtain information about core polarization [25, 26]. Magnetic dipole and electric quadrupole moments were measured for the ground states up to $A = 74$ [20] and later up to $A = 78$ [27], with firm spin assignments of 2^- for ^{72}Cu and ^{74}Cu [28], 3^- for ^{76}Cu , and a tentative assignment of (6^-) for ^{78}Cu [27].

A previously disputed isomeric state in ^{76}Cu was unambiguously established in a recent mass measurement at 64.8(25) keV excitation energy [29]. The measured half-life of the isomeric state, $t_{1/2} = 672(110)$ ms [29], is consistent with the literature value of 637.7(55) ms [30]. It was therefore concluded in Ref. [29] that the isomeric state corresponds to the previously identified 3^- state, whereas the longer-lived ground state (with presumably lower spin) has remained unidentified in all previous experiments except an early β -decay study of ^{76}Cu which found two distinct half-

lives in the feeding of excited states in ^{76}Zn [31]. However, a new β -decay study excluded the existence of a longer half-life in ^{76}Cu and proposed that the ground state and isomeric state have similar half-lives [32]. Spin assignments for the ground state and isomeric state remain unclear in the light of the new β -decay study [32].

In the case of ^{78}Cu , a recent spectroscopic study identified several excited states following the β decay of ^{78}Ni , provided experimental two-body matrix elements for the $\pi 1f_{5/2}\nu 1g_{9/2}^{-1}$ interaction, and found an isomeric (0^-) state based on the $\pi 1f_{5/2}\nu 2d_{5/2}$ configuration [33].

The present work provides the first spectroscopic information on the odd-odd isotopes ^{74}Cu and ^{76}Cu , completing the Cu isotopic chain from stable to ^{79}Cu . Low-lying states in these odd-odd nuclei can provide further information on the evolution of single-particle energies and the transition from particle-particle to particle-hole coupling outside ^{68}Ni and ^{78}Ni , respectively, as neutrons fill the $\nu 1g_{9/2}$ orbital. The level schemes for the neutron-rich odd-odd Cu isotopes serve as benchmarks for large-scale shell-model calculations, and can be used to improve calculations for exotic nuclei beyond ^{78}Ni . In addition, the results can be used for future astrophysical calculations, as properties of nuclei in the vicinity of ^{78}Ni are important for modelling the nucleosynthesis in the region of the first r -process abundance peak [34,35].

Experimental details and the data analysis are described in Sect. 2. Results including spectra, level schemes, and spin-parity assignments, are presented in Sect. 3. The results are discussed and compared to MCSM calculations in Sect. 4, followed by a summary and conclusions in Sect. 5.

2 Experimental setup and data analysis

The experiment was carried out during the EURICA campaign [36] at the Radioactive Isotope Beam Factory (RIBF) [37] at the RIKEN Nishina Center. In-flight fission of a ^{238}U beam at 345 MeV per nucleon and 10 pnA intensity was used to produce neutron rich nuclides on a ^9Be target of 555 mg/cm² areal density. The fission fragments were separated using the BigRIPS separator, which was optimized for the transmission of ^{78}Ni and ^{81}Zn during two separate beam times. Both experiments contributed with approximately equal amount to the decay data for ^{74}Ni and ^{76}Ni . Ions were identified by their time-of-flight, magnetic rigidity, and characteristic energy loss. Ions of interest were further transmitted through the ZeroDegree spectrometer [38] and implanted into the Wide-range Active Silicon-Strip Stopper Array for Beta and ion detection (WAS3ABi) [37]. To detect γ rays following the β decay of the nuclides of interest, the WAS3ABi detector was surrounded by the HPGe EURICA array [36].

Table 1 Nuclear properties half-life ($t_{1/2}$) [39], Q_β -values [42], and neutron-emission (P_n) of ^{74}Ni and ^{76}Ni , and observed properties in the current experiment for ^{74}Cu and ^{76}Cu . N_{ion} is number of ions observed, and N_β is number of observed β decays from the implanted ions. I_β (obs.) is the intensity of β -feeding relative to the total number of observed β decays. I_β (tot.) is the intensity of beta feeding relative to the total number of Ni decays, when neutron emission is taken into account

	^{74}Ni	^{76}Ni
$t_{1/2}$ [ms]	507.7(46)	234.6(27)
Q_β [keV]	7310(200)	8790(300)
P_n	3.5 ± 0.6^a	14.0 ± 3.6^b
N_{ion}	1.7×10^5	6.3×10^5
N_β	$7.5(2) \times 10^4$	$2.67(9) \times 10^5$
I_β (obs.)	46(3)%	55(4)%
I_β (tot.)	49(3)%	69(5)%

^aAverage of two calculated values [43,44], with an uncertainty overlapping both

^bMeasured value [45]

The resulting PID plot of the ion identification can be found in Ref. [39]. Ion implantations in WAS3ABi were correlated in time and position with subsequent β decays and with γ emission detected by the EURICA detectors. Data from the two BigRIPS settings were analyzed separately. The resulting γ -ray spectra and γ - γ coincidence matrices were combined afterwards. Sorting γ -ray singles spectra for different correlation time windows between ion implantation and β decay allowed discriminating γ rays following the decay of Ni isotopes from those following subsequent daughter decays. Reducing the time window for β -decay events reduces the contribution from subsequent daughter decays in cases where the β decay from Ni to Cu went undetected. Known γ rays following the decay of ^{74}Cu and ^{76}Cu into ^{74}Zn and ^{76}Zn [40], respectively, were used to validate the procedure. After assigning the strongest transitions to the Cu isotopes of interest, the time gates were relaxed to increase statistics for the γ - γ coincidence analysis and construction of level schemes. A more detailed explanation of the data analysis can be found in Ref. [33].

Table 1 summarizes the number of implanted ions and β -decay events, together with the β -decay half-lives and Q_β -values, as well as number of observed β decays and β -feeding intensities. The known β -decay half-lives were reproduced using the present data and the technique described in Ref. [41] to validate the correlation between ions and β -decays.

Figure 1 shows γ -ray singles spectra for the two odd-odd Cu isotopes under investigation. The level of statistics allowed using strict time conditions (1 s for ^{74}Cu and 300 ms for ^{76}Cu), resulting in relatively clean spectra with little contamination from daughter decays. All peaks that are labeled by their energy were assigned to the respective Cu

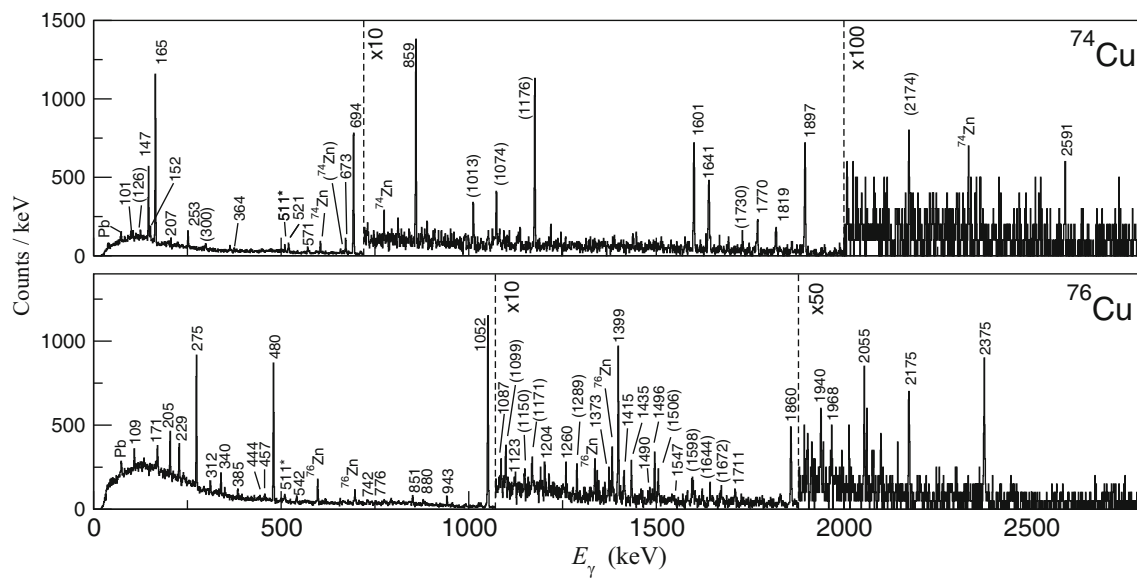


Fig. 1 Singles γ -ray spectra for ^{74}Cu (top) and ^{76}Cu (bottom). Note that the higher-energy regions of the spectra were scaled by the indicated factors. Ion- β correlation windows of 1 s ($A = 74$) and 300 ms ($A = 76$) were used. Peaks marked by their energy (in keV) are transitions assigned to the respective ^ACu isotope. Energies are given in

parentheses for transitions that were assigned to ^ACu , but could not be placed in the level scheme. Transitions following the subsequent decay of ^ACu are labelled by the ^AZn isotope of their origin. The peaks at 511 keV and 75 keV are due to pair creation and annihilation, and Pb X-rays from surrounding shielding material, respectively

isotopes. Some transitions, however, could not be placed in the level scheme because of lacking γ - γ coincidence relationships. These transitions, which are labeled by their energies in parentheses, were assigned to the respective Cu isotopes based only on their time correlation with the β -decay detection. A narrow time gate selecting prompt γ -ray transitions suppressed the known isomeric low-energy transitions in ^{75}Cu [13,46] in the spectra following the decay of ^{76}Ni . No other known transitions from states in odd-mass Cu isotopes, populated by β -delayed neutron emission, were observed.

Coincidence relationships between γ rays were used to validate their assignment to the respective Cu isotopes. The construction of the level schemes for the two Cu isotopes was based on coincidence relationships, energy sums and differences, and γ -ray intensities. Only γ rays that could be placed unambiguously were included in the level schemes. In some cases, where different orderings of γ rays within a cascade were possible, intensity relations were used to decide on the ordering. A more detailed description of the process to construct the level schemes can be found in Ref. [47].

The intensity of β -decay feeding was determined from the intensity balance of γ rays feeding and depopulating a given state, which was corrected for detection efficiency and internal conversion. This information was used, together with the β -decay half life and Q_β values (c.f. Table 1), to calculate the $\log ft$ value for a given state [48]. The $\log ft$ values provide information on the forbiddenness of the β decay [49] and can help to constrain spin and parity values for the excited states.

It should be noted, however, that the $\log ft$ values have to be considered lower limits because of possible unobserved γ feeding and the so-called *Pandemonium* effect [50]. Because of these uncertainties, only tentative spin assignments could be made.

3 Results

3.1 ^{74}Cu

Before the present experiment, no excited states in ^{74}Cu were known, but the ground-state spin was measured in a laser spectroscopy experiment and firmly assigned as 2^- [27].

Of the two odd-odd Cu isotopes under study, ^{74}Cu is the least exotic with the highest production cross section. Nevertheless, there is less statistics in the γ -ray spectra for ^{74}Cu than for ^{76}Cu because the magnetic rigidity in BigRIPS was optimized for the heavier, more exotic isotopes near ^{78}Ni and ^{81}Zn . Selected γ - γ coincidence spectra for ^{74}Cu are shown in Fig. 2, and the resulting level scheme with 11 excited states is presented in Fig. 3. The information from the level scheme is furthermore summarized in Table 2, together with the experimental uncertainties. Table 2 contains all γ -ray transitions assigned to ^{74}Cu , irrespective of whether they could be placed in the level scheme. The analysis of time correlations yielded no indication for an isomeric state in ^{74}Cu .

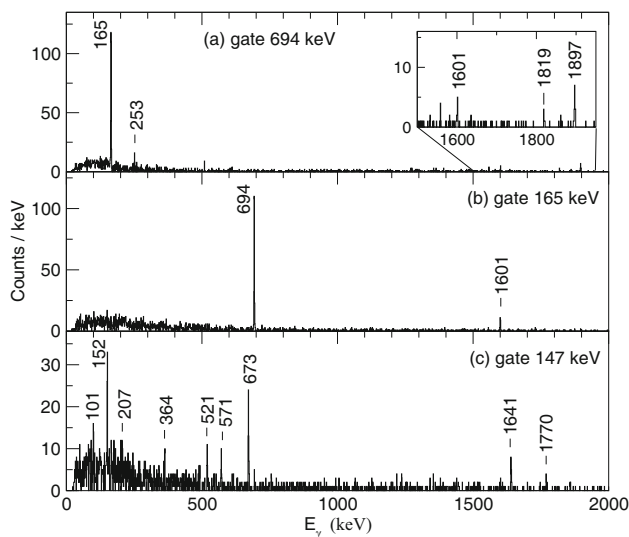


Fig. 2 γ - γ coincidence spectra for ^{74}Cu gated on the 694 keV (a), 165 keV (b), and 147 keV transitions (c)

The 165 keV and 694 keV lines are the strongest transitions in the γ -ray singles spectrum for ^{74}Cu . The two transitions are in coincidence with each other, and there is also a line at 859 keV, corresponding to their energy sum. Gating on the 694 keV transition (c.f. Fig. 2a) reveals coincidences with several other transitions, whereas gating on the 165 keV transition (c.f. Fig. 2b) reveals no other coincidences except with a weak transition at 1601 keV. It is therefore concluded that the 694 keV transition directly feeds into the ground state. The state at 859 keV is the most strongly fed state through β decay, receiving 21(1)% of the observed feeding, which is an order of magnitude more than feeding to any other state at similar energy. The strong β feeding can only be explained by an allowed Gamow–Teller transition, and $I^\pi = (1^+)$ is therefore tentatively assigned to the state at 859 keV. The strongest decay path from the 859 keV state proceeds via the 165–694 keV cascade and the state at 694 keV, with a weak parallel decay by an $E1$ transition directly to the ground state.

Gating on the 147 keV transition (c.f. Fig. 2c), another strong line in the singles spectrum, reveals a group of several low-energy transitions, which are partly in coincidence with each other and partly in parallel. These transitions connect a group of five low-lying excited states, with the 147 keV transition feeding the ground state. None of these low-lying states are fed by the previously discussed 694 keV state or the (1^+) state at 859 keV, and none of these low-lying states receives significant β feeding.

The two states at 2460 and 2590 keV are strongly fed through β decay, with observed feeding of 7.7(8)% and 6.9(6)%, respectively. Such strong feeding to states above 2 MeV results in low $\log ft$ values. We therefore tentatively assign $I^\pi = (1^+)$ to both states. Three transitions from the 2590 keV state are observed, one directly to the 2^- ground

state, and the others to the excited states at 694 and 819 keV, respectively. The observation of a direct transition to the 2^- ground state is consistent with a (1^+) assignment for the state at 2590 keV. The state at 694 keV is limited to $I \leq 3$ because of its feeding from the (1^+) states at 2590 and 859 keV and its decay to the 2^- ground state, which otherwise would involve transitions of high multipolarity. The (1^+) state at 2460 keV decays to the (1^+) state at 859 keV and to the state at 819 keV. The latter is also fed by the (1^+) state at 2590 keV. The feeding from (1^+) states limits also the state at 819 keV to $I \leq 3$. This state does, however, decay to the 147, 298, and 718 keV states, serving as one of the few connections between the lower (below 694 keV) and the upper part of the level scheme. It can also be noted that none of the tentatively assigned (1^+) states decays directly into any of the lower-lying states below 694 keV, suggesting that these states are higher-spin states. Further spin assignments would be speculative, and cannot be done based on the present experiment due to missing feeding.

3.2 ^{76}Cu

Despite a careful search, no direct evidence for a γ -decaying isomeric state in ^{76}Cu was found in the time correlation between β and γ decays. In particular, no γ decay was observed for the isomeric state at 64.8(25) keV excitation energy that was recently identified in a mass measurement [29].

If the isomeric state was indeed corresponding to the 3^- state, and the ground state had either spin 1 or 2, as was argued in Ref. [29], the γ decay from the isomeric state should have been observed in the present experiment. As will be discussed in more detail in Sect. 4, the data from the present experiment is only consistent with the 3^- assignment for the ground state and a higher spin value for the isomeric state.

Besides the isomeric state at 64.8 keV, no excited states were known in ^{76}Cu before the present experiment. A selection of γ - γ coincidence spectra for ^{76}Cu is shown in Fig. 4. The resulting level scheme with 24 excited states is shown in Fig. 5. Information on the identified γ -ray transitions and energy levels, together with their observed β feeding and limits on $\log ft$ values, is summarized in Table 3.

The strongest transition in the γ -ray singles spectrum for ^{76}Cu was found at 1052 keV. Earlier β -decay studies of ^{76}Zn assigned a weak 1053 keV transition to the decay scheme of ^{76}Zn [31, 40]. The time correlation between the implantation of ^{76}Ni ions and β -decay events in the present experiment, and the lack of γ - γ coincidences with other known transitions in ^{76}Zn leaves no doubt that the strong 1052 keV transition originates from an excited state in ^{76}Cu . This transition is in coincidence with several other transitions (c.f. Fig. 4a), whereas the strong 480 keV transition is only in coincidence with the 1052 keV transition (c.f. Fig. 4b). It is therefore

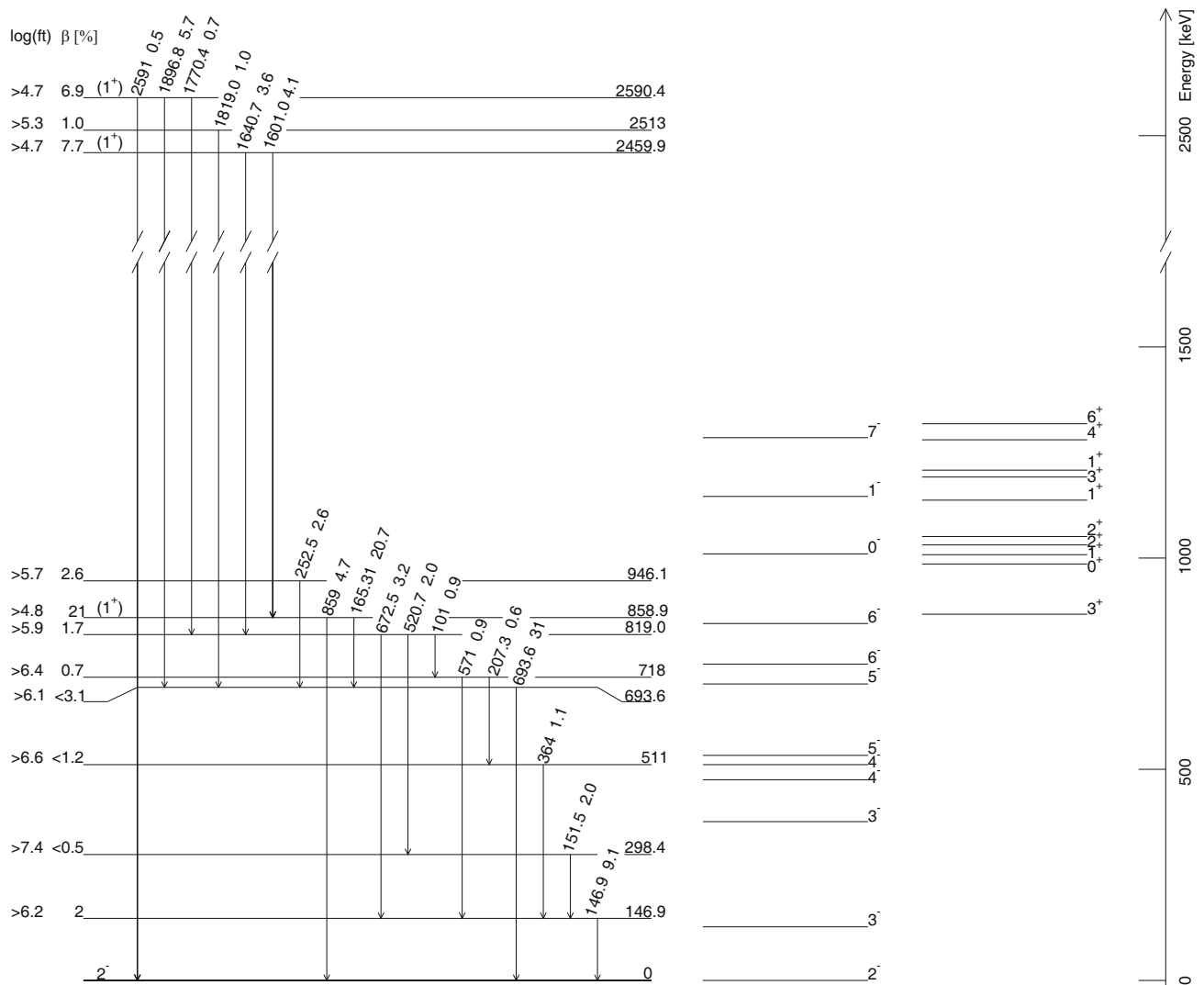


Fig. 3 Experimental level scheme for ^{74}Cu (left) and calculated energy levels with negative and positive parity from shell-model calculations with the A3DA-m interaction (right). Experimental intensities of the γ rays and β feeding are listed in Table 2

concluded that the 1052 keV transition directly feeds the 3⁻ ground state. A small β -feeding intensity of 5(3)% to the state at 1052 keV was observed in the present experiment. However, this β -feeding intensity represents only an upper limit because of possible unobserved γ feeding. Because of this uncertainty it is difficult to assign a spin value to the 1052 keV state.

The state at 1532 keV on top of the 480–1052 keV cascade has the strongest observed β feeding with 22.0(8)%, and consequently the lowest $\log ft$ value of all observed states, consistent with an allowed Gamow–Teller transition. We therefore tentatively assign $I^\pi = (1^+)$ to the state at 1532 keV. This (1⁺) state decays to the state at 1052 keV via a 480 keV transition. Assuming dipole or quadrupole multipolarity for this transition, the state at 1052 keV is limited to low spin of $I \leq 3$. The 480 keV transition is parallel to a cascade of

two transitions of 205 and 275 keV. Gating on the 275 keV transition (c.f. Fig. 4c) reveals several transitions feeding the state at 1327 keV excitation energy, which are included in the level scheme. With strong feeding from the (1⁺) state, also the 1327 keV state is limited to low spins of $I \leq 3$. No other state in ^{76}Cu was observed to have particularly strong feeding, and attempts to assign spin values to any other states would therefore be highly speculative.

In addition to the 1052 keV state, three other states at 171, 943, and 1496 keV were found to decay directly to the ground state. The state at 1496 keV is fed from the state at 2911 keV via a 1415 keV transition, and in addition to its decay to the ground state, it also decays via a 444 keV transition to the state at 1052 keV. The 943 keV transition is in coincidence with four other transitions, including a 1968 keV transition from the state at 2911 keV (c.f. Fig. 4e). This state

Table 2 Energy of the observed states in ^{74}Cu , their spin and parity where a tentative assignment was possible, observed β -feeding, $\log ft$ values, together with energies and intensities of the observed γ rays. Note that the $\log ft$ values are only limits because of possible unobserved β feeding. The lower part shows γ -ray transitions assigned to ^{74}Cu that could not be placed in the level scheme

E_{state} [keV]	I^π	β -feeding [%]	$\log ft$	E_γ [keV]	I_γ [%]
146.9(1)		2(1)	> 6.2	146.9(1)	9.1(5)
298.4(4)		< 0.5	> 7.4	151.5(3)	2.0(2)
511(1)		< 1.2	> 6.6	364(1)	1.1(7)
693.6(6)		< 3.1	> 6.1	693.6(6)	31(1)
718(1)		0.7(4)	> 6.4	207.3(6)	0.6(2)
				571(1)	0.9(2)
819.0(6)		1.7(7)	> 5.9	101(2)	0.9(3)
				520.7(4)	2.0(3)
				672.5(6)	3.2(4)
858.9(6)	(1^+)	21(1)	> 4.8	859(2)	4.7(4)
				165.31(8)	20.7(9)
946.1(7)		2.6(3)	> 5.7	252.5(3)	2.6(3)
2459.9(7)	(1^+)	7.7(8)	> 4.7	1601.0(4)	4.1(7)
				1640.7(4)	3.6(4)
2513(1)		1.0(3)	> 5.6	1819.0(9)	1.0(3)
2590.4(7)	(1^+)	6.9(6)	> 4.7	1770.4(2)	0.7(1)
				1896.8(3)	5.7(5)
				2591(6)	0.5(2)
				125.7(1)	0.7(1)
				299.7(9)	2.0(3)
				1013(1)	1.2(2)
				1074(2)	1.8(2)
				1176(1)	5.7(5)
				1730.2(5)	0.5(1)
				2174(2)	0.6(2)

Table 3 Energies of the observed states in ^{76}Cu , their spin and parity where a tentative assignment was possible, observed β -feeding, $\log ft$ values, together with energies and intensities of the observed γ rays. Note that the $\log ft$ values are only limits because of possible unobserved β feeding. The lower part shows γ -ray transitions assigned to ^{76}Cu that could not be placed in the level scheme

E_{state} [keV]	I^π	β -feeding [%]	$\log ft$	E_γ	I_γ [%]
170.7(2)		< 0.1		170.7(2)	2.6(3)
482.7(3)		0.3(2)	> 6.9	312.0(2)	1.2(1)
943.0(4)		< 0.1		943.0(4)	1.8(2)
1022(1)		0.3(2)	> 6.8	851.2(4)	1.7(1)
1051.67(3)		5(3)	> 5.5	1051.67(3)	49(2)
1326.5(1)		4.8(7)	> 5.5	274.8(2)	14.2(6)
1362.6(6)		2.0(2)	> 5.9	340.3(1)	1.4(2)
				879.8(5)	0.9(1)
1435.7(3)		0.6(4)	> 6.4	109.2(2)	1.6(1)
				384.8(3)	1.0(1)
1496(1)		< 2.2	> 6.4	444(1)	< 2.3
				1496(1)	1.4(2)
1531.8(1)	(1^+)	22.0(8)	> 4.8	204.7(2)	3.3(2)
				480.15(9)	18.7(8)
1555.2(2)		< 0.8		228.7(2)	3.0(2)
1719.0(8)		0.6(1)	> 6.3	776.0(7)	0.6(1)
1893(1)		< 0.3		457(1)	0.7(3)

Table 3 continued

E_{state} [keV]	I^π	β -feeding [%]	$\log ft$	E_γ	I_γ [%]
2097.4(4)		0.4(3)	> 6.1	542.2(3)	1.02(4)
2146.8(7)		0.2(2)	> 6.6	1203.8(5)	1.0(1)
2450(1)		5.0(4)	> 5.2	1123(1)	0.5(1)
				1399.2(3)	4.5(3)
2815(2)		1.2(6)	> 5.8	1260(2)	0.6(6)
				1490(2)	0.58(2)
2889(1)		0.8(1)	> 5.8	742.3(7)	0.8(1)
2911(2)		4.8(4)	> 5.0	1414.6(5)	1.4(1)
				1547.4(5)	0.3(1)
				1860(2)	2.7(3)
				1968(2)	0.4(1)
2990(1)		0.7(1)	> 5.8	1435(1)	0.7(1)
3184(1)		0.6(2)	> 5.8	1087(1)	0.6(2)
3267(3)		2.4(2)	> 5.2	1373.3(5)	0.7(1)
				1710.5(8)	0.7(1)
				1831(3)	0.5(1)
				1940(3)	0.5(1)
3426(2)		1.4(2)	> 5.4	2375(2)	1.4(2)
3611(3)		1.3(1)	> 5.4	2055(3)	0.5(1)
				2175(2)	0.8(1)
				1099.4(4)	0.9(1)
				1150.3(8)	0.6(1)
				1170.6(6)	0.8(1)
				1288.9(4)	0.6(1)
				1505.8(8)	1.1(1)
				1598.3(7)	1.2(1)
				1644(2)	0.3(3)
				1672.2(9)	0.8(1)

also decays to the state at 1052 keV, lending further confidence in the placement of the 943 keV transition. Gating on the 171 keV transition reveals two parallel cascades of transitions with 312, 340, 851, and 880 keV, respectively, establishing evidence for states at 483, 1022, and 1363 keV, as illustrated in Fig. 4d. The state at 1363 keV is fed by a 1547 keV transition from the state at 2911 keV. It can be noted that a 340.9 keV transition was placed in the decay scheme of ^{76}Zn following the β decay of ^{76}Cu [31,40]. Time correlations and coincidence relations show that the 340 keV peak is predominantly originating from ^{76}Cu . The contribution from ^{76}Zn to the 340 keV peak was estimated from the time correlation analysis. When removing the contribution from ^{76}Zn , the 340 keV transition is weaker than the 851 keV transition, and is therefore placed as feeding a state at 1022 keV. The four low-lying states at 171, 483, 943, and 1022 keV receive little to no feeding, consistent with higher spin values.

Higher-lying states that decay by more than one transition and the observation of parallel cascades help to resolve ambiguities in the level scheme. Examples include the states at 2450, 2815, 3267, and 3611 keV, in addition to the 2911 keV state already discussed. The 3267 keV state decays to four states at 1327, 1436, 1555, and 1893 keV, which are firmly placed in the level scheme. The 2450 keV state also decays to the 1327 keV state, in addition to the 1052 keV state. Thanks to the relatively high level of statistics of the γ - γ coincidence spectra for ^{76}Cu , it was possible to construct a more comprehensive level scheme as compared to ^{74}Cu . However, due to the large spread in β -feeding intensity and the systematic uncertainty related to unobserved feeding, spin assignments are very difficult.

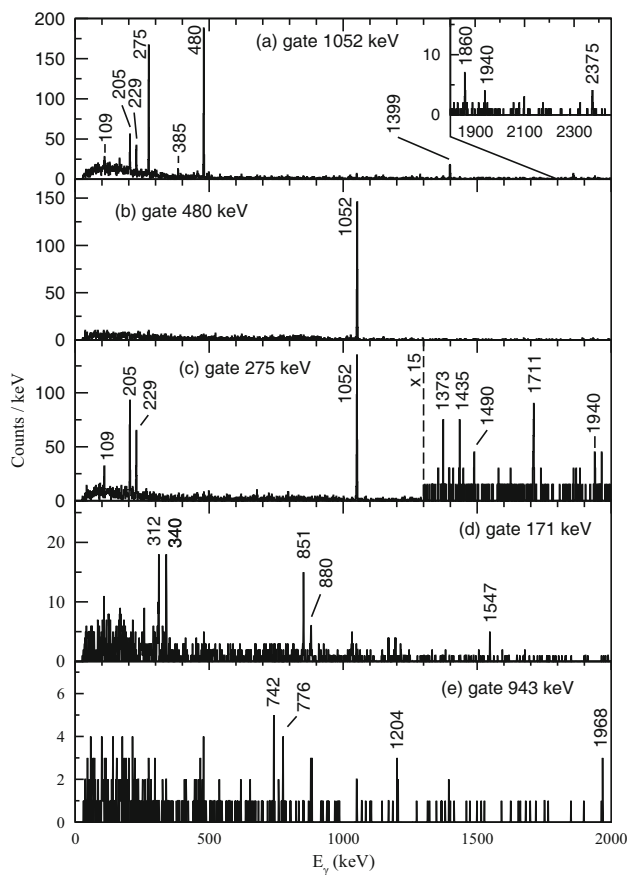


Fig. 4 γ - γ coincidence spectra for ^{76}Cu gated on the 1052 keV (a), 480 keV (b), 275 keV (c), 171 keV (d), and 943 keV transition (e)

4 Discussion

The $\pi 1f_{5/2}$ and the $\pi 2p_{3/2}$ orbitals are the lowest available orbitals outside the $Z = 28$ shell closure, whereas the neutrons are filling the $\nu 1g_{9/2}$ orbital just below the $N = 50$ shell. The ground states of the neutron-rich, odd-odd Cu isotopes can therefore be explained by the coupling of an unpaired proton in either the $\pi 1f_{5/2}$ or the $\pi 2p_{3/2}$ orbital with an unpaired neutron in the $\nu 1g_{9/2}$ orbital. This coupling gives rise to multiplets of negative-parity states with spins in the range $2^- \leq I^\pi \leq 7^-$ for the proton in the $\pi 1f_{5/2}$, and $3^- \leq I^\pi \leq 6^-$ for the proton in the $\pi 2p_{3/2}$ orbital. One can therefore expect to find several negative-parity states at low excitation energy, although the members of the multiplets with high spin might not be populated in β decay. The easiest way to couple the valence particles to positive-parity states is by neutron excitation from $\nu 2p_{1/2}$ into $\nu 1g_{9/2}$, leaving an unpaired neutron in the $\nu 2p_{1/2}$ orbital. Positive-parity states are expected to be found at somewhat higher excitation energy, and those with low spin are expected to be strongly fed in β decay by allowed transitions.

4.1 Non-observation of the ^{76}Cu isomer and spin assignment for the ground state

The recent mass measurement of Canete et al. unambiguously identified an isomer in ^{76}Cu at 65 keV excitation energy [29]. Because the half-life of the isomer is consistent with the half-life of the state that was assigned $I = 3$ by laser spectroscopy [27], Canete et al. argued that the $I = 3$ state is the isomer and not the ground state, and that the ground state has been missed in previous experiments [29]. They suggest that the ground state has lower spin of $I = 1$ or 2. However, this argumentation is based on the assumption that the half-lives of the ground state and the isomer are sufficiently different to be distinguishable. It was not possible to determine the half-life of the ground state in the experiment of Canete et al. New decay studies of ^{76}Cu by Olaizola et al. [32] exclude the existence of a longer half-life of $t_{1/2} = 1.27(30)$ s that was earlier claimed by Winger et al. [31]. The data of Olaizola et al. suggests that the isomer and the ground state have similar half-lives in the range 600–700 ms [32]. Without any information about the electromagnetic decay of the isomer, it was not possible to decide whether the isomer or the ground state corresponds to the $I = 3$ state [32].

The data from the present experiment show no evidence for a γ decay of the isomeric state. Canete et al. refer to the observation of two γ rays of 62 and 66 keV in the present experiment as described in an earlier Master's thesis [47] in support of their interpretation of $I^\pi = 3^-$ for the isomer. However, these two low-energy γ rays originate from ^{75}Cu [13], populated by β -delayed neutron emission, as is clearly stated in the Master's thesis [47].

The non-observation of the γ decay of the isomer in the present experiment can have two possible explanations: (i) The isomeric state in ^{76}Cu is not populated, neither by direct β feeding from ^{76}Ni , nor by γ feeding from above. (ii) The isomeric state does not decay by γ emission, either because electromagnetic decay cannot compete with β decay, or because the transition is too strongly converted. If the assignment of $I^\pi = 3^-$ for the isomeric state was correct, its population by direct β feeding would be negligible, but it would be populated by γ feeding from above. The 3^- state in ^{78}Cu , for example, receives significant feeding from higher-lying states [33]. Furthermore, if the ground state had lower spin of $I = 1$ or 2, a 3^- state at 65 keV excitation energy should not be isomeric, as electromagnetic decay should dominate over β decay. Only in the case of $I^\pi = 1^+$ for the ground state, as favored by Canete et al., one would expect a lifetime of the order of 1 ms for the 3^- state, still inconsistent with the observed half-life of the isomer. An M2 transition would be strongly converted ($\alpha \simeq 2.69$), but still have sufficient γ intensity to be observed. In addition, a 1^+ ground state would receive significant direct β feeding, which is inconsistent with the large fraction of observed β feeding to excited

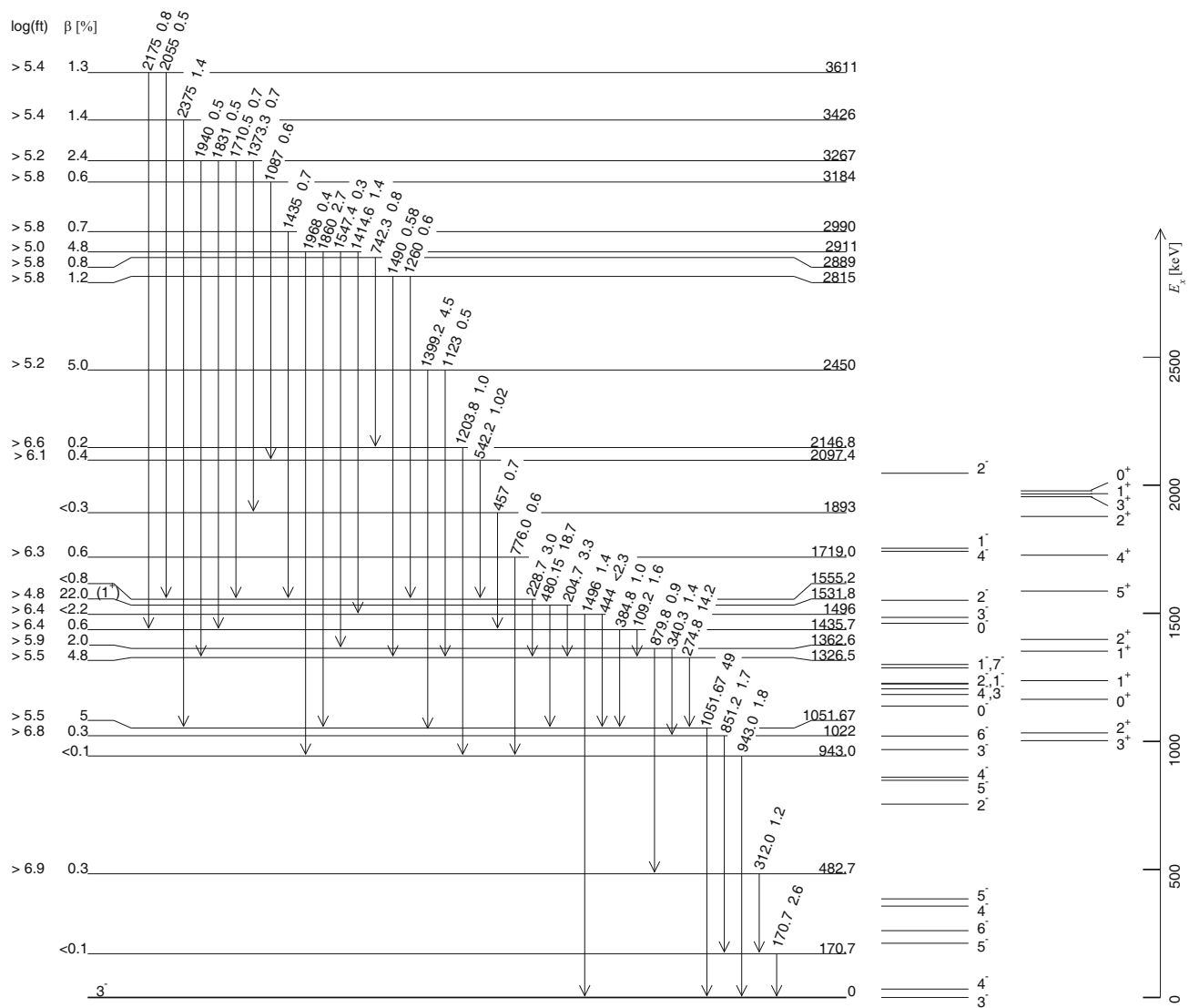


Fig. 5 Experimental level scheme for ^{76}Cu (left), and calculated energy levels with negative and positive parity from shell-model calculations with the A3DA-m interaction (right). More information on the states and transitions is listed in Table 3

states observed in the present experiment. Because a 3^- state would be populated by γ decay from higher-lying states, and because a 3^- state would decay by γ emission to a lower-spin ground state, the scenario proposed by Canete et al. is incompatible with the data from the present experiment.

A scenario in which the state at 65 keV has $I^\pi = 3^-$ and the ground state a spin $I \geq 3$ can also be excluded. In case of $I = 3, 4$, or 5 for the ground state, a 65 keV γ ray should have been observed in the present experiment. An even higher spin, e.g. $I^\pi = 6^-$, for the ground state would be incompatible with the feeding in two steps by the 480 and 1052 keV γ rays from the (1^+) state at 1532 keV. The assignment of $I^\pi = 3^-$ for the isomeric state can therefore be excluded based on the data from the present experiment. The state that was assigned $I = 3$ by laser spectroscopy can only be the ground state, and negative parity can be assumed based

on systematics. This assignment is furthermore consistent with the subsequent decay of ^{76}Cu , which in the present data shows an approximately equal population of the 2^+ and 4^+ states in ^{76}Zn .

The most likely spin assignment for the isomer is 6^- . This assignment is not only consistent with the decay data from Olaizola et al., but would also explain the non-observation of the isomer in the present experiment, as the population of a state with such high angular momentum following the β decay from the 0^+ state in ^{76}Ni would be highly unlikely. Even if a 6^- state was fed by γ transitions from above, an M3 decay to the 3^- ground state would be so strongly hindered that it could not compete with β decay. As was already pointed out by Olaizola et al., the laser spectroscopy data by de Groote et al. [27] seem to indicate some excess counts that would be compatible with a $I = 6$ state. This spin assignment

of (6^-) for the isomer and 3^- for the ground state is consistent with the stronger population of the isomeric state in the mass measurement of Canete et al. following proton-induced fission, as isomeric yield ratios typically favor the population of the higher-spin state [51]. It is also worth noting that the spin assignments proposed by Canete et al. are not supported by the LNPS or PFSDG-U shell-model calculations presented in their work [29]. Both the calculations reported by Canete et al. and our new calculations, to be discussed in the next section, are consistent with a 3^- ground state, while lower-spin states appear only at substantially higher excitation energies.

4.2 Shell-model calculations

In order to understand the nature of the experimentally observed states, shell-model calculations are necessary. Shell-model calculations were earlier performed for the negative-parity states in the odd-odd $^{70-78}\text{Cu}$ isotopes by Van Roosbroeck et al. [40] using an effective interaction derived from a nucleon-nucleon potential within a G-matrix approach, and a model space consisting of the $2p_{3/2}$, $2p_{1/2}$, $1f_{5/2}$, and $1g_{9/2}$ orbitals for both protons and neutrons. The calculations reflect a transition from particle-particle to particle-hole coupling as neutrons fill the $\nu 1g_{9/2}$ orbital, and also find a higher density of negative-parity states at very low energy in ^{74}Cu , consistent with a near degeneracy of the proton $2p_{3/2}$ and $1f_{5/2}$ orbitals. However, experimental data on excited states were lacking at the time, and the calculations were unable to predict the ground-state spins along the isotopic chain correctly. Later, Vingerhoets et al. [20] presented shell-model calculations for the odd-odd isotopes $^{70-74}\text{Cu}$ using the JUN45 and jj44b interactions, which again could not reproduce the correct ground-state spins.

More recently, large-scale shell-model calculations have been performed with the LNPS interaction [29], which predict 1^+ ground states for both ^{72}Cu and ^{74}Cu with low-lying 2^- excited states, at variance with the experimentally established 2^- ground states. For ^{76}Cu , the LNPS calculations yield a 4^- ground state with an almost degenerate 3^- excited level, whereas calculations with the PFSDG-U interaction, using the full $\pi pf - \nu sdg$ valence space outside a ^{60}Ca core predict a 3^- ground state [29], in agreement with the experimental assignment.

In the present work, we compare the experimental results with Monte Carlo shell-model (MCSM) calculations [10] using the A3DA-m effective interaction, which has successfully described the structure of nuclei in the ^{78}Ni region [5, 6, 11, 13]. The valence space comprised the full pf shell together with the $1g_{9/2}$ and $2d_{5/2}$ orbitals for both protons and neutrons without restrictions. States of both negative and positive parity are calculated. The negative-parity states originate primarily from the coupling of a proton in the

$1f_{5/2}$ and/or $2p_{3/2}$ orbital to a neutron in the $1g_{9/2}$ orbital, while positive-parity states arise from the coupling to a neutron in the $2p_{1/2}$ orbital. Because of the inversion of the $\pi 1f_{5/2}$ and $\pi 2p_{3/2}$ orbitals near neutron number $N = 48$ [5], it can be expected that their relative weight changes from ^{74}Cu to ^{78}Cu . It can be furthermore expected that mixing is reduced, and that the wave functions exhibit a purer single-particle character as the neutron degrees of freedom are reduced when approaching the $N = 50$ shell closure. The present experiment populated both negative- and positive-parity states. Their comparison to the MCSM calculations will be discussed in the following sections. The experimentally obtained level scheme for ^{78}Cu from the same experiment has already been published [33] along with A3DA-m calculations. For a more complete understanding of systematic trends along the isotopic Cu chain, results on ^{78}Cu are included in the discussion of experimental and theoretical results below.

The ground state of all three Cu isotopes can be explained as a member of the negative-parity multiplet based predominantly on the $\pi 1f_{5/2}\nu 1g_{9/2}$ configuration. The MCSM calculations were able to reproduce the experimentally known spins [27] of the ground states correctly: 2^- for ^{74}Cu , 3^- for ^{76}Cu , and (6^-) for ^{78}Cu . Furthermore, as more neutrons fill the $\nu 1g_{9/2}$ orbital, the occupation number for the $\pi 1f_{5/2}$ orbital in the ground state increases from 0.66 in ^{74}Cu to 0.71 in ^{76}Cu , and finally reaches 0.96 in ^{78}Cu . In contrast, the occupation number for the $\pi 2p_{3/2}$ orbital in the ground state decreases from 0.51 in ^{74}Cu to 0.48 in ^{76}Cu and to 0.24 in ^{78}Cu . This is consistent with the inversion of the $\pi 2p_{3/2}$ and $\pi 1f_{5/2}$ orbitals, which was previously confirmed in studies of the odd-mass isotopes ^{75}Cu and ^{77}Cu [3, 5, 13].

Calculated levels from the A3DA-m interaction are presented together with the experimental level scheme in Figs. 3 and 5, respectively. In both cases, the calculated levels are presented in the right part of the figures, with negative and positive-parity states separated for better readability. A similar figure for ^{78}Cu is presented in Ref. [33]. The calculations show that all low-lying excited states are negative-parity states, based on the coupling of a neutron in the $\nu 1g_{9/2}$ orbital and a proton in either the $\pi 2p_{3/2}$ or $\pi 1f_{5/2}$ orbital. For ^{74}Cu the $\pi 2p_{3/2}$ and $\pi 1f_{5/2}$ proton orbitals are mostly mixed, as shown by the doubling of spins at similar energies. This is in contrast to the ^{76}Cu calculations, which show a larger splitting between the two orbitals resulting in different ordering of the calculated states. It is interesting to note that the predictions for low-lying states in ^{76}Cu from the calculations with the PFSDG-U interaction [29] and the present calculations with the A3DA-m interaction are very similar, despite the differences between the models.

The calculations show that the lowest positive-parity states are based on the coupling between a neutron in the $\nu 2p_{1/2}$ orbital and a proton either in the $\pi 2p_{3/2}$ or the $\pi 1f_{5/2}$ orbital.

These configurations are expected to result in doublets of spin ($1^+, 2^+$) and ($2^+, 3^+$). However, the configurations are not pure and remain somewhat fragmented, leading to more positive-parity states with similar occupation numbers for different spin couplings as shown in Figs. 3 and 5. A (1^+) state is observed at 858.9 keV for ^{74}Cu and at 1531.8 keV for ^{76}Cu . The increased trend of these states from $N = 46$ to $N = 48$ can be related to the fact that they originate from the $\pi 2p_{3/2} \nu 2p_{1/2}$ configuration where the energy of the proton $2p_{3/2}$ state increases towards $N = 50$ due to the monopole tensor interaction [7]. A similar trend is reproduced by the MCSM calculations resulting in the states with the $\pi 2p_{3/2} \nu 2p_{1/2}$ configurations around 1 MeV for ^{74}Cu and 1.3 for ^{76}Cu .

Based on the shell-model calculations, the lowest-lying states can be associated with the negative-parity multiplets, although firm spin assignments are difficult to make. The states belonging to the multiplets are expected to be interconnected by γ -ray transitions, without receiving significant β feeding. Both of these expectations are in accordance with experimental observations for the low-lying states in both nuclei. In ^{74}Cu , the states at 147, 298, 511, and 718 keV are candidates to be negative-parity states, as no or little β feeding is observed. An assignment of negative parity and spin $I \geq 3$ is also consistent with the fact that the 859 keV (1^+) state only decays to the 2^- ground state, but not to the other low-lying states, which would be hindered by the large spin difference. The strong beta feeding to the 859 keV state is reproduced by the MCSM calculations, which find a large Gamow–Teller strength to the lowest 1^+ state with predominant $\pi 2p_{3/2} \nu 2p_{1/2}$ configuration. The calculations predict a second low-lying 1^+ state with similar configuration (but slightly higher occupation of the $\pi 1f_{5/2}$ orbital) and large Gamow–Teller strength. However, there is no indication for a second low-lying 1^+ state in the experimental data. The state at 694 keV is strongly fed by the states at 859 and 2590 keV, which are both assigned tentatively as (1^+) states. As it also decays to the 2^- ground state, the 694 keV state is a candidate for a low-spin, positive parity state, most likely 2^+ or 3^+ . The shell-model calculations predict the 3^+ state based on the $\pi 1f_{5/2} \nu 2p_{1/2}$ coupling to be the lowest positive-parity state, but other low-spin, positive-parity states are also predicted within approximately 300 keV and could be consistent with the observed decay pattern. The 819 keV state is also directly fed by the high-lying (1^+) states at 2590 and 2460 keV. However, unlike the 694 keV state, the 819 keV state is not feeding the 2^- ground state, but other low-lying negative-parity states with presumably higher spin. To bridge the angular momentum gap between high-lying (1^+) and low-lying $I \geq 3$ states with negative parity, the most consistent spin-parity assignment for the 819 keV state is therefore 3^+ .

For ^{76}Cu , the 171 and 483 keV states are candidates for low-lying negative-parity states. Fewer states are observed at

low energy compared to the ^{74}Cu case, which is consistent with the shell-model prediction of $I^\pi = 4^-, 5^-, 6^-$ for the lowest excited states, as such higher-spin states are harder to observe following the β decay of an even-even nucleus. The 1532 keV (1^+) state receives strong β feeding of similar intensity as the 859 keV state in ^{74}Cu , suggesting a similar structure for both states. The shell-model calculations find two 1^+ states with similar configuration at ~ 1.3 MeV, which are based on a mixed proton $2p_{3/2}$ and $1f_{5/2}$ configuration coupled to a neutron in the $2p_{1/2}$ orbital. The higher excitation energy of the 1^+ states in ^{76}Cu compared to ^{74}Cu is consistent in both experiment and theoretical calculations, although the energy difference between ^{74}Cu and ^{76}Cu is larger for the experimental states.

With the feeding from the (1^+) state at 1532 keV and its decay to the 3^- ground state, the state at 1052 keV is limited to $I \leq 3$. The shell-model calculations find the ($2^+, 3^+$) doublet based on the $\pi 1f_{5/2} \nu 2p_{1/2}$ configuration at 1.0 MeV excitation energy, making this configuration a good candidate for the structure of the 1052 keV state. In this scenario, the main decay path of ^{76}Ni would proceed via a $\nu 2p_{1/2} \rightarrow \pi 2p_{3/2}$ Gamow–Teller transition to the 1532 keV state in ^{76}Cu , followed by a $2p_{3/2} \rightarrow 1f_{5/2}$ proton de-excitation to the 1052 keV state, and a $1g_{9/2} \rightarrow 2p_{1/2}$ neutron de-excitation to the ground state. However, the shell-model calculations also find the 2^- member of the $\pi 1f_{5/2} \nu 1g_{9/2}$ multiplet at a similar energy of 755 keV, which could provide an alternative interpretation of the 1052 keV state. The 943 keV state, with its direct decay to the 3^- ground state, is another potential candidate for a state within a negative-parity multiplet, including the 2^- state, but also a candidate for the 2^+ or 3^+ state of the $\pi 1f_{5/2} \nu 2p_{1/2}$ doublet. Without clear evidence for other allowed Gamow–Teller transitions and other candidates for 1^+ states, it is difficult to constrain the spins of higher-lying states and draw further conclusions from the comparison with the results of the shell-model calculations.

4.3 Systematics of occupation numbers

Calculated proton and neutron occupation numbers for selected negative-parity states in $^{74,76,78}\text{Cu}$ are shown in Fig. 6. Note that the graphs show cumulative occupation numbers for 9 protons and 25 (^{74}Cu), 27 (^{76}Cu), and 29 (^{78}Cu) neutrons filling the orbitals of the shell-model valence space. The calculations for the 3_1^- and 3_2^- states indicate that the 3_1^- states have stronger occupation of the $\pi 1f_{5/2}$ orbital compared to the $\pi 2p_{3/2}$ orbital, while the opposite is true for the 3_2^- states. The two 4^- states in ^{74}Cu are calculated to lie very close in energy (see Fig. 3). The 4_1^- state in ^{74}Cu is dominated by the $\pi 2p_{3/2}$ configuration, while the 4_2^- state has stronger $\pi 1f_{5/2}$ occupation. For ^{76}Cu and ^{78}Cu , the character of the 4^- states is equivalent to the 3^- states, with the $\pi 1f_{5/2}$ configuration lower in energy than $\pi 2p_{3/2}$. The

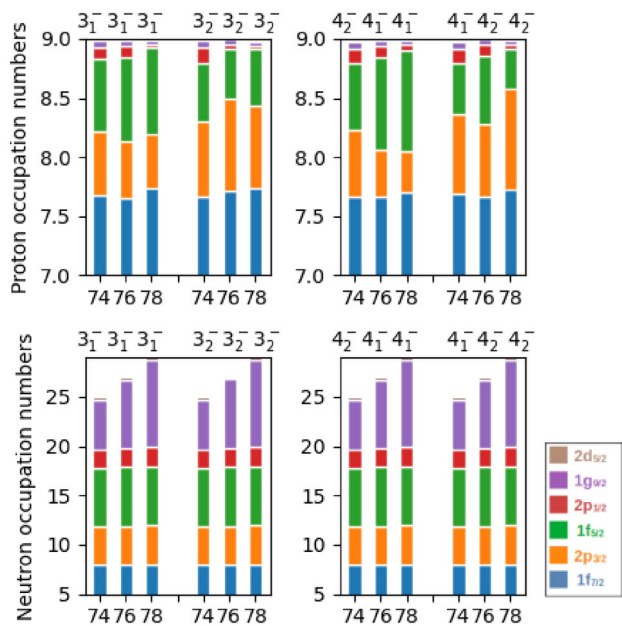


Fig. 6 Cumulative occupation numbers for protons (top) and neutrons (bottom) for selected negative parity states in ^{74}Cu , ^{76}Cu , and ^{78}Cu . Note that the occupancy of the $1f_{7/2}$ orbitals is not fully shown, with the y-axis starting at 7 for the protons and at 5 for the neutrons

proton occupation numbers calculated for the $3_{1,2}^-$ and $4_{1,2}^-$ states indicate a strong mixing between the $\pi 1f_{5/2} \nu 1g_{9/2}$ and $\pi 2p_{3/2} \nu 1g_{9/2}$ configurations in ^{74}Cu , which become purer toward ^{78}Cu . This is in accordance with the crossing of the $1f_{5/2}$ and $2p_{3/2}$ orbitals, which lie very close in energy for ^{74}Cu , and have increased separation when moving towards $N = 50$ due to the monopole tensor interaction [7]. The calculated neutron occupation numbers show that the last unpaired neutron fills the $\nu 1g_{9/2}$ orbital, while the pf orbitals are fully occupied for both $3_{1,2}^-$ and $4_{1,2}^-$ states.

Cumulative occupation numbers for a selection of low-lying positive-parity states are shown for both protons and neutrons in Fig. 7. The calculations show that all low-lying positive-parity states are based on a neutron excitation from the $\nu 2p_{1/2}$ to the $\nu 1g_{9/2}$ orbital, leaving an unpaired neutron in the $\nu 2p_{1/2}$ orbital, and 6, 8, and 10 neutrons in the $\nu 1g_{9/2}$ orbital for ^{74}Cu , ^{76}Cu , and ^{78}Cu , respectively. The 2_1^+ and 3_1^+ states are dominated by the $\pi 1f_{5/2} \nu 2p_{1/2}$ configuration, whereas the 1_1^+ and 2_2^+ states are predominantly based on the coupling of a $\nu 2p_{1/2}$ neutron with a $\pi 2p_{3/2}$ proton. However, the proton configurations are not pure and give rise to alternative spin couplings, notably additional 0^+ and 1^+ states, as can be seen in the calculated level schemes of Figs. 3 and 5. The occupation numbers indicate again that the purity of the proton configuration increases with neutron number, similar to what was found for the negative-parity states and consistent with the crossing of the $\pi 2p_{3/2}$ and $\pi 1f_{5/2}$ orbitals.

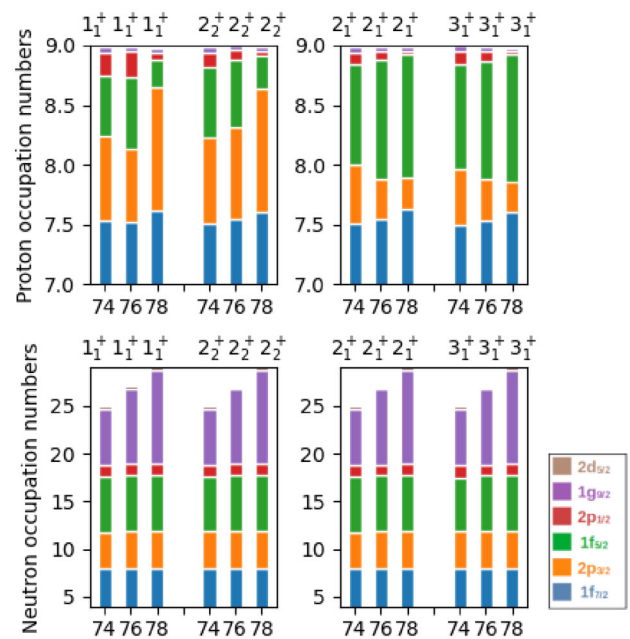


Fig. 7 Cumulative occupation numbers for protons (top) and neutrons (bottom) for selected positive-parity states in ^{74}Cu , ^{76}Cu , and ^{78}Cu . Note that the occupancy of the $1f_{7/2}$ orbitals is not fully shown, with the y-axis starting at 7 for the protons and at 4 for the neutrons

Figure 8 shows the excitation energies of negative- and positive-parity states from the MCSM calculations as a function of angular momentum for $^{74,76,78}\text{Cu}$. The calculated occupation numbers for states with negative parity were used to assign the states to multiplets with predominant $\pi 1f_{5/2} \nu 1g_{9/2}^{-1}$ or $\pi 2p_{3/2} \nu 1g_{9/2}^{-1}$ configuration. In the case of ^{78}Cu , the calculations also find a multiplet of states with relatively pure $\pi 1f_{5/2} \nu 2d_{5/2}$ configuration, which includes the isomeric 0_1^- state [33] as well as the 1_1^- , 2_2^- , 3_3^- , 4_3^- , and 5_3^- states. The corresponding states in ^{74}Cu and ^{76}Cu , with more vacancies in the $\nu 1g_{9/2}$ orbital, have a more mixed neutron configuration, and their $\nu 2d_{5/2}$ occupation number is smaller than in the case of ^{78}Cu . The low-lying positive-parity states from the MCSM calculations, shown in the lower part of Fig. 8, can be grouped into doublets of states with predominant $\pi 2p_{1/2} \nu 1f_{5/2}$ and $\pi 2p_{1/2} \nu 2p_{3/2}$ configuration. Experimental excitation energies of states with a tentative spin assignment based on experimental observations are included in Fig. 8 and marked with filled symbols. Experimental states with plausible spin assignments based on their feeding and decay pattern and the comparison with the shell-model calculations are shown with open symbols.

There is a relatively good agreement between the experimental excitation energies of the low-lying states and those found in the MCSM calculations, which supports their interpretation in terms of proton-neutron multiplets. The multiplets involving a hole in the $\nu 1g_{9/2}$ orbital for ^{76}Cu and ^{78}Cu show an approximate parabolic dependence on angular

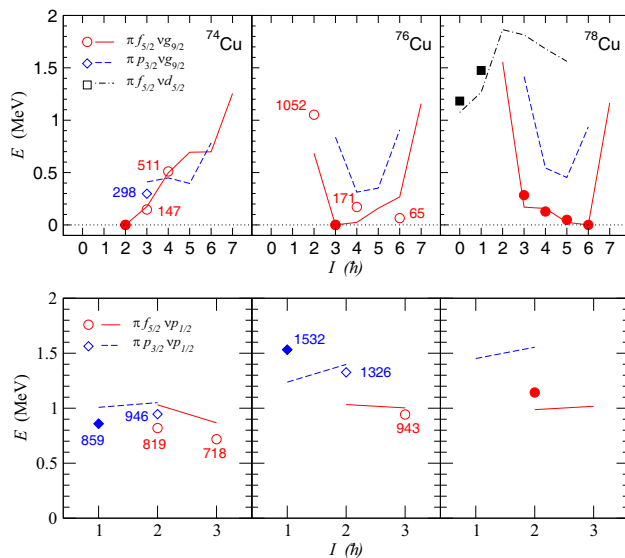


Fig. 8 Excitation energies of the negative-parity multiplets with predominant $\pi 1 f_{5/2} \nu 1 g_{9/2}$, $\pi 2 p_{3/2} \nu 1 g_{9/2}$, and $\pi 1 f_{5/2} \nu 2 d_{5/2}$ configurations (top) and positive-parity doublets with predominant $\pi 1 f_{5/2} \nu 2 p_{1/2}$ and $\pi 2 p_{3/2} \nu 2 p_{1/2}$ configuration from the MCSM calculations as a function of spin for ^{74}Cu , ^{76}Cu , and ^{78}Cu . The symbols indicate experimental excitation energies for states with tentative spin assignment (full symbols) and for states with a plausible spin assignment based on the comparison with the MCSM (open symbols)

momentum, with the extreme couplings $I = j_\nu \pm j_\pi$ having the highest energy, as expected for particle-hole coupling [52]. It can be noted that the separation between the two parabolas is larger for ^{78}Cu , consistent with an increasing separation between the $\pi 2 p_{3/2}$ and $\pi 1 f_{5/2}$ orbitals toward $N = 50$. In the case of ^{74}Cu , on the other hand, the states of the $\pi 1 f_{5/2} \nu 1 g_{9/2}$ multiplet exhibit a more or less linear increase with angular momentum. This can again be understood from the fundamental interaction between the odd proton and neutron. With the $\nu 1 g_{9/2}$ orbital half filled in ^{74}Cu , quadratic terms are expected to vanish, while the linear slope is expected to be positive for Nordheim number $\mathcal{N} = j_\pi - l_\pi + j_\nu - l_\nu = 0$ [52]. The deviation from the linear trend is likely due to the strong mixing between the $\pi 1 f_{5/2}$ and $\pi 2 p_{3/2}$ configurations. For the multiplet based on the latter, with $\mathcal{N} = 1$, one would in principle expect negative slope. However, this might be obscured by the strong mixing. The $\pi 1 f_{5/2} \nu 2 d_{5/2}$ multiplet in ^{78}Cu has particle-particle character, which favors (anti-)parallel coupling.

The overall agreement between experiment and MCSM calculations is very satisfactory also for the positive-parity states. The comparison between experiment and theory provides further support for the inversion of the $\pi 1 f_{5/2}$ and $\pi 2 p_{3/2}$ orbitals. The energy separation between the parabolas with predominant $\pi 1 f_{5/2}$ and $\pi 2 p_{3/2}$ configuration increases from near degenerate in ^{74}Cu to ~ 250 keV in ^{76}Cu and ~ 500 keV in ^{78}Cu , consistent with near degener-

ate single-particle states for ^{74}Cu and increasing separation with increasing neutron number. The calculations indicate furthermore that the occupancy of the $\nu 2 d_{5/2}$ orbital is not negligible, illustrating the need for a large valence space to correctly describe the neutron-rich Cu isotopes. The $\nu 2 d_{5/2}$ occupation numbers for the positive-parity states are typically in the range between 0.3 and 0.4.

5 Summary and conclusions

Excited states in ^{74}Cu and ^{76}Cu have been observed for the first time following the β decay of ^{74}Ni and ^{76}Ni , respectively. The neutron-rich Ni isotopes were produced at the Radioactive Isotope Beam Factory at RIKEN Nishina Center, Japan, by in-flight fission induced by a primary beam of ^{238}U at 345 MeV per nucleon incident on a ^9Be target. The secondary beams of fission fragments in the region of ^{78}Ni were separated by the BigRIPS separator and transported to the decay station, where they were implanted into the WAS3ABi detector. The HPGe detectors of the EURICA array were used to detect γ rays following the β decay of the short-lived Ni isotopes. Sufficient $\gamma\gamma$ -coincidence data allowed building partial level schemes for both odd-odd Cu isotopes under investigation. Spins and parities could be tentatively assigned for some of the states by using information on their β -decay feeding and γ -decay.

The non-observation of the isomeric state at 65 keV in ^{76}Cu and the observed decay scheme can only be explained if the ground state has $I^\pi = 3^-$ and the isomer has higher spin, most likely $I^\pi = 6^-$.

The experimental results were compared to large-scale MCSM calculations using the A3DA-m interaction and a valence space comprising the $1 f_{7/2}$, $2 p_{3/2}$, $1 f_{5/2}$, $2 p_{1/2}$, $1 g_{9/2}$, and $2 d_{5/2}$ orbitals for both protons and neutrons. The shell-model calculations show a very satisfactory agreement with the experimental results. In addition to the correct reproduction of the ground-state spins and parities, the calculations also reproduce many features of the observed excitation schemes for both isotopes. Combining the experimental results with the calculations, it was possible to interpret the low-lying states in terms of spin multiplets arising from the coupling of an odd proton in either the $\pi 1 f_{5/2}$ or $\pi 2 p_{3/2}$ orbital with an odd neutron in the $\nu 1 g_{9/2}$ or $\nu 2 p_{1/2}$ orbital. The results confirm the previously observed crossing between the $\pi 2 p_{3/2}$ and $\pi 1 f_{5/2}$ orbitals, which are near degenerate in ^{74}Cu , and provide quantitative information on their increased energy separation toward ^{78}Cu . The experimental results as a whole serve as benchmarks for shell-model calculations that will allow fine-tuning effective interactions to improve the accuracy in predicting the structure of nuclei beyond ^{78}Ni . In addition, experimental information on excited states can be relevant for astrophysical calcula-

tions. Many transitions that were observed in the present experiment could not be placed in the level schemes. Further experiments to complete the decay schemes and experiments using total absorption spectroscopy to determine β -decay intensities are therefore desirable. Extending the work to ^{80}Cu would represent an important step for investigating the proton-neutron interaction beyond ^{78}Ni .

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Data availability statement Data will be made available on reasonable request. [Author’s comment: The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request].

Code availability statement Code/software will be made available on reasonable request. [Author’s comment: The code/software generated during and/or analysed during the current study is available from the corresponding author on reasonable request].

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