Low energy levels in ^{72}Ni

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The yrast $J^{\pi}=8^{+}$ states in neutron-rich ^{70,72,74,76}Ni nuclei are predicted to be isomeric. The present paper describes two GANIL experiments. In the first of them a search was made for the 8^{+} isomeric states in ^{72,74}Ni nuclei via fragmentation of ^{76}Ge using the ion γ-decay correlation technique. Although these states were not observed, limits for their lifetimes were determined. In the second experiment the decay spectroscopy of ^{70,72}Co nuclei was performed using fragmentation of a ^{86}Kr^{36+} beam and the new LISE2000 spectrometer. The β delayed γ rays from the decay of ^{70,72}Co to ^{70,72}Ni were observed using the EXOGAM germanium detectors. The half life of ^{72}Co was measured to be 62(3) ms and the level sequence of the lowest excited states in ^{72}Ni was suggested, with the 2^{+} state at 1096 keV. An attempt to reproduce the level scheme in terms of shell-model calculations was undertaken. The reasons for the disappearance of the 8^{+} isomer in ^{72}Ni are discussed.

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I. INTRODUCTION

Experimental studies of the low energy structure of neutron-rich nickel isotopes provide information needed for the critical evaluation of theoretical models describing the properties of exotic nuclei close to $^{78}_{28}$Ni$_{50}$. Shell structure variations in this region may also occur for various reasons, as argued in several theoretical papers [1–4]. The systematic experimental data help to understand the trends of the structure changes. In particular, there has been a series of experiments [5–14] which directly or indirectly attempted to answer the question of magicity of the $^{68}_{28}$Ni$_{40}$ and $^{78}_{28}$Ni$_{50}$ nuclei. As a result of these experiments it has been established that although ^{68}Ni indeed appears to be a doubly magic nucleus [5,11], the $N=40$ closed shell is not robust and disappears as soon as the proton number changes. The existence of the 8^{+} isomeric state in ^{78}Zn [8] indicates that the $N=50$ closed shell persists. There is an agreement that a closed shell $Z=28$ is not being dramatically violated and the spherical shell-model calculation using a $^{56}_{28}$Ni$_{28}$ core can be applied for nuclei near $^{68}_{28}$Ni$_{40}$. This may create the illusion that these neutron-rich nuclei behave like their valence mirrors with $N=50$ (see Ref. [15]). In this paper we argue that this is not the case and we show significant departure of the experimental observations from the theoretical predictions. Since the observation of the $T_{1/2}=230(3)$ ns $I^{\pi}=8^{+}$ isomeric state in ^{70}Ni [7] the similar $(\nu g_{9/2})^{2}_{J=8^{+}}$ excitations in more neutron-rich nickel nuclei such as ^{72,74,76}Ni were sought for. All of these 8^{+} states are predicted to be isomeric. They should decay via a cascade of four stretched $E2$ transitions connecting the $8^{+},6^{+},4^{+},2^{+},0^{+}$ levels. The yrast 8^{+} level should be long lived because of the noncollective $E2$ transition [e.g., $B(E2)=0.693(9)$ W.u. for ^{70}Ni] and the small energy difference between the 8^{+} and 6^{+} levels ($\sim$100 keV). Such high-spin isomers resulting from the coupling of two identical nucleons in the same orbital j to a maximum allowed spin $J=2j-1$ are known across the chart of nuclei near closed shells. This general pattern arises as a consequence of the short-range nucleon-nucleon residual interactions [16]. The search for ^{72m,74m}Ni has been so far unsuccessful. This paper in its first part will summarize quantitative results of this search, and then present the new data obtained from the β decay of ^{72}Co and try to explain the relevance of this result to the problem of the disappearance of the 8^+ isomers. Two different experimental approaches are described. In the first one we attempted to observe the decay of the 8^+ isomeric states in ^{72}Ni and ^{74}Ni that are populated directly in the fragmentation reaction, using the same technique as applied for the discovery of ^{70m}Ni [7] and ^{78m}Zn [8]. In the second one we measured excited states in ^{72}Ni populated by β decay of ^{72}Co. The β decay of ^{70}Co was treated as the test case for the experimental technique as well as for the method of data analysis. This experimental task was difficult because these cobalt isotopes are even further away from stability and thus more difficult to produce than their nickel isobars. Parallel to the β decay measurements the isomeric spectroscopy was performed as well. The first results of that part—evidence for isomerism in ^{76}Ni—are reported in Ref. [17]. All experiments described below have been performed at the heavy ion fragmentation facility—GANIL.

II. SEARCH FOR AN 8^+ ISOMER IN ^{72}Ni

The search for isomers in ^{72,74}Ni produced directly in a fragmentation reaction was done with a 61.6 *A* MeV ^{76}Ge^{30+} beam at an average intensity of 330 nA. The microsecond ion-delayed γ-ray correlation method was used to search for the isomeric decay in each isotope [18]. The experiment was performed at the LISE separator [19] which was optimized for a maximum yield of ^{72}Ni. It employed a high efficiency and high resolution γ detection setup consisting of three HPGE detectors to search for an 8^+ isomer. The total full-energy peak efficiency was found to be 12% at 200 keV. The full description of the experiment is reported in Ref. [20]. During 74 h of acquisition time, a total number of 1.05×10^6 ^{72}Ni ions was implanted into the final detection setup. Despite such a large number of detected ions, no convincing evidence for the decay of the 8^+ isomer could be found. In the same setting, about 0.9×10^6 ions of ^{70}Ni were implanted and the decay of the known 8^+ isomer was clearly observed yielding 9025 counts in the 183-keV γ line and 1820 counts in the 1260-keV line. The γ intensity analysis yielded the population probability $F=13\%$ for the ^{70m}Ni isomer in agreement with the result reported previously [7].

Since the 8^+ state in ^{72}Ni should be populated in the reaction with a similar probability as the analogous state observed in ^{70}Ni, we conclude that the lifetime of the state searched for is either too short or too long to be identified with our technique. Assuming that the decay pattern of the 8^+ state in ^{72}Ni is the same as in ^{70}Ni, producing a similar sequence of four $E2$ γ transitions, and that the isomeric ratio is equal to 13% as measured in the same conditions for ^{70m}Ni, we can deduce the half-life limits for the unobserved isomer in ^{72}Ni. To obtain the short half-life limit, the γ spectrum correlated with ^{72}Ni was produced with the condition that the γ ray was detected less than 100 ns after the ion implantation. Such a spectrum allows us to deduce an upper limit for the number of counts in the expected peaks. From this the limit, $T_{1/2}<18$ ns was obtained. A similar procedure was used to derive the long half-life limit, with the correlation time $t=44$ μs and leading to $T_{1/2}>3.7$ ms. We conclude that under the above assumptions, the half life of the 8^+ state in ^{72}Ni is either shorter than 18 ns or longer than 3.7 ms. A similar analysis made for 3600 ions of ^{74}Ni yielded the limits $T_{1/2}<60$ ns and $T_{1/2}>0.2$ ms [21]. The presented results show clearly that the isomer spectroscopy in fragmentation is not a viable method to measure excited levels either in ^{72}Ni or in ^{74}Ni and one has to measure them with a different method. One way is via β delayed γ-ray spectroscopy.

III. β DECAY EXPERIMENT

A. Experimental method

In the experiment focused on β decay studies the ^{86}Kr^{36+} beam at energy of 58*A* MeV and the mean intensity of 2880 nA was impinging on a rotating ^{nat}Ta target of 30 μm thickness. Behind the target a 125 μm thick carbon stripper was used. The selection of the ions has been done using the new LISE2000 spectrometer [22]. The average time of flight of the reaction products was only about 200 ns, which was achieved by mounting the detector setup in the first achromatic point of LISE2000 only 19 m away from the target. A stack of four silicon detectors was placed at the implantation point. Their thickness amounted to 2×300 μm, 1 mm, and 3.5 mm. Selected ions were stopped in the third one—a double sided silicon strip detector (DSSD) with 16×16 strips of 3-mm pitch. The fourth Si (Li) detector acted as a veto counter for heavy ions and β particles. It detected beam particles not stopped in the third detector. This silicon telescope was surrounded by four clover-type EXOGAM Ge detectors. The total photopeak efficiency measured with calibration sources was found to be 6% at 1.3 MeV and 23% at the maximum around 120 keV. The energy resolution was found to be 4 keV at 1.408 MeV. The β detection efficiency of the DSSD was determined with the ^{66}Co decay using branching ratios from Ref. [23] and was found to be about 20%.

The standard method of identification, by measuring energy loss, total kinetic energy, and time-of-flight, has been applied for the assignment of mass *A*, atomic number *Z*, and charge *q* of each stopped ion [24–26]. During the whole measurement lasting about 100 h, approximately 200 000 heavy ions were implanted into the DSSD detector giving a rate of 0.03 ion per second per strip. Thus an average time between two implants is much longer than the average β decay lifetime, usually of the order of 100 ms for the nuclei of interest. The granularity of the strip detector provided a clean spatial correlation between the implanted ion and its detected β decay in the same strip. The average rate of the β particles correlated with the γ rays was 20 s^{-1}. The β background events were mainly coming from the decay of long-lived nuclei implanted in the same strips as the selected ions. In the measurement 3330 ions of ^{70}Co and 3290 ions of ^{72}Co have been implanted. The average rate of the β delayed γ rays correlated with the selected ions (^{70}Co or ^{72}Co) was 0.02 s^{-1}.

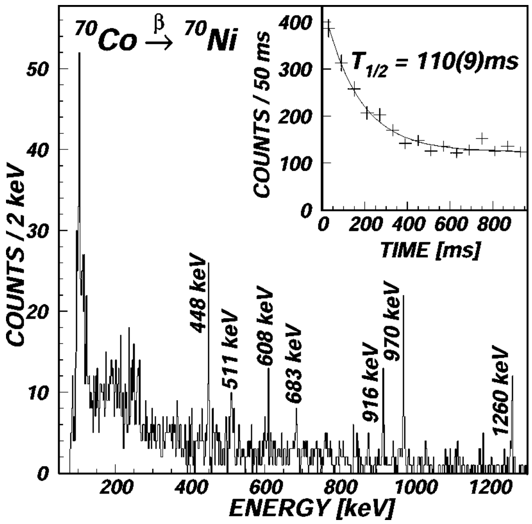

FIG. 1. The β delayed γ rays of ^{70}Ni. In the inset, the decay pattern of β-γ activity is shown. The 511-keV line is due to the long-lived contamination of the final focus system by the β^+ activity during previous experiments.

B. β^- decay of ^{70}Co

The spectrum of β delayed γ of ^{70}Co is shown in Fig. 1, revealing γ lines observed previously in a β decay experiment performed by Mueller *et al.* [23]. This provided a proof of the correct ion identification as well as of the data analysis technique. The half life of the β delayed γ rays from ^{70}Co has been determined by the least squares fitting procedure. The decay time spectrum (see inset of Fig. 1) was accumulated by taking into account all events of β-γ coincidences which occurred during the period 1 s after the implantation of the ^{70}Co ion. During this period, not only the decay of ^{70}Co but also of its daughter (^{70}Ni, $T_{1/2}$=6.0 s [27]) and granddaughter (^{70}Cu, $T_{1/2}$=4.5 s [28]) could, in principle, be recorded. Such a contribution, however, was found to be negligible due to long half lives of the descendant activities. Finally, we obtained $T_{1/2}$=110(9) ms which is compatible with the half life observed for the 7^- state decay in Ref. [23] $T_{1/2}$=120(30) ms. In addition to the strong 449-, 970-, 683-, and 1260-keV lines observed earlier in the β decay studies [23], we have identified an additional line at 916 keV. We tentatively place it at 3146 keV to feed the 4^+ state in ^{70}Ni at 2230 keV. We were able to identify also the decay of the 3^+ state in ^{70}Co which appears to be populated weakly in this reaction. The relative intensity of the 608-keV line is essentially weaker than reported in Ref. [23]. We could not observe the 1868-keV line from the decay of the second 2^+ state in ^{70}Ni to the ground state, identified in Ref. [23], which is consistent with the weak feeding of the 3^+ state in ^{70}Co see Fig. 2 and Table I.

C. β^- decay of ^{72}Co

The β delayed γ spectrum of ^{72}Co is shown in Fig. 3 revealing γ lines at 455, 845, 1096, and 1197 keV energy. Based on the intensity of these γ lines (see Table II) and expected similarities between the ^{70}Co and ^{72}Co β decays a

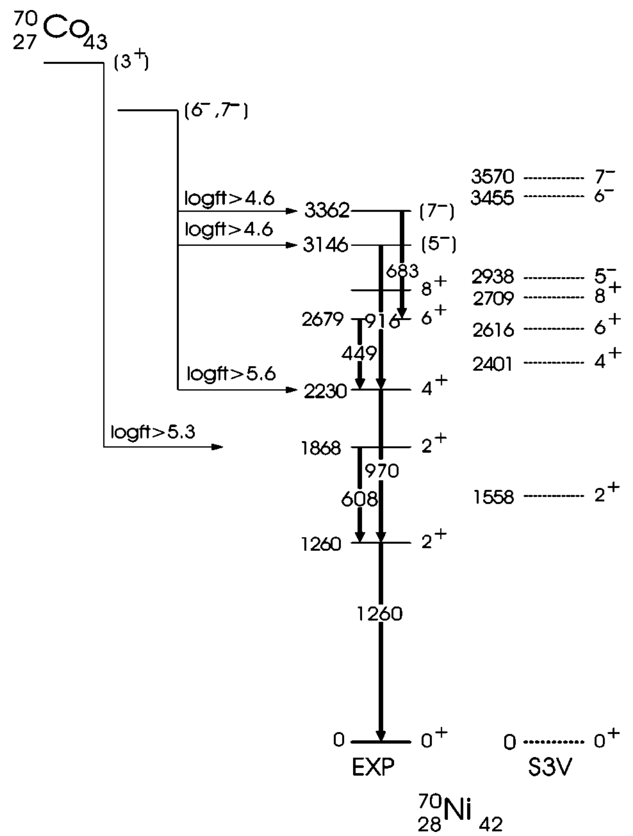

FIG. 2. The level scheme of ^{70}Ni, compared with the shell-model calculation using the S3V interaction [30].

tentative level scheme for ^{72}Ni has been proposed in Fig. 4. The decay has been attributed to the (6^-,7^-) state. The half life has been determined in the same way as for ^{70}Co (Sec. III B). The contribution of the daughter (^{72}Ni, $T_{1/2}$=1.5 s [27]) and granddaughter (^{70}Cu, $T_{1/2}$=6.6 s [28]) activities to the decay-time spectrum (see inset of Fig. 3) has been taken into account. This procedure yielded $T_{1/2}$=62(3) ms. The previously measured value is 90(20) ms [13]. We could not find conclusive evidence for the decay of a possible 3^+ state, likely because of its low population. We have attributed the strongest 1096-keV line as a transition between the first excited 2^+ state in ^{72}Ni and its 0^+ ground state. The observed level scheme does not reveal clear signatures of collective

TABLE I. Energies and relative intensities of β delayed γ lines from ^{70}Co decay for two different time ranges δt between the implantation and the β decay.

$\delta t \leqslant 0.6$ s		$\delta t \leqslant 2.5$ s	
Energy (keV)	Intensity (relative)	Energy (keV)	Intensity (relative)
449(1)	59(17)%	608(2)	≡100(40)%
683(2)	31(12)%	1260(2)	287(100)%
916(1)	50(16)%		
970(2)	≡100(30)%		
1260(2)	86(30)%		

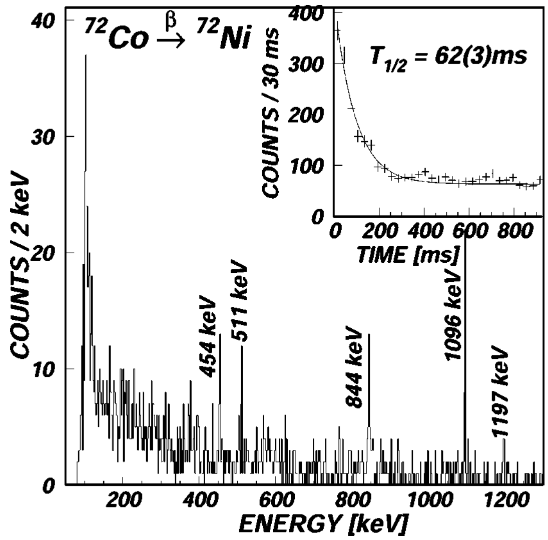

FIG. 3. The β delayed γ rays of ^{72}Ni. In the inset, the decay pattern of β-γ activity is shown. The 511-keV line originates from the long-lived β^+ contaminants implanted in the previous experiments.

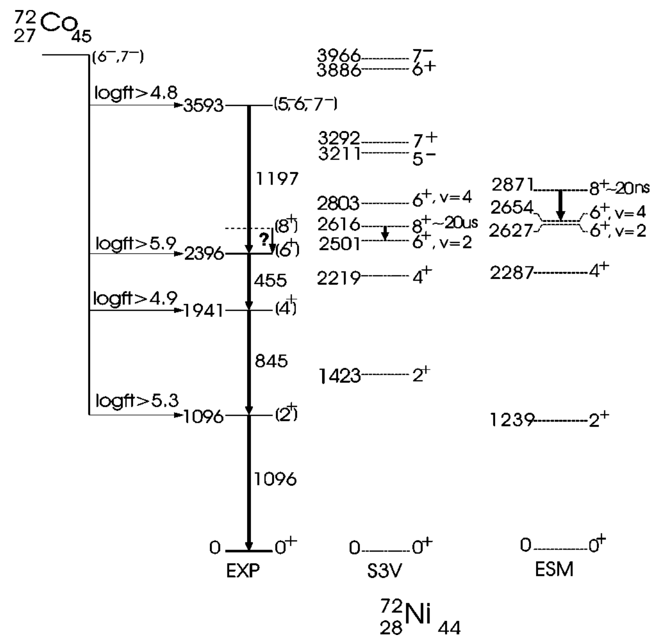

FIG. 4. Proposed decay scheme of ^{72}Co and shell-model predictions of ^{72}Ni levels using the S3V interaction and full $f_{5/2}$, p, $g_{9/2}$ model space and the empirical ESM residual interaction [30], restricted only to $g_{9/2}$ shell. The searched for $8^+ \rightarrow 6^+$ isomeric transition is marked by an arrow.

excitations. The previously used shell-model calculation with the S3V [29] realistic interaction predicts an energy spectrum similiar to the one observed experimentally, see Fig. 4.

IV. DISCUSSION

The limits on the half life of the 8^+ isomeric state in ^{72}Ni, as deduced from the isomer spectroscopy experiment (Sec. II), are at variance with the shell-model predictions. For example, the calculation [30] performed according to Ref. [31] using a ^{56}Ni core and a full $f_{5/2}$, p, $g_{9/2}$ neutron shell with a realistic S3V interaction from Ref. [29], adopted for the nickel region at $N=40$, predicted very small $B(E2)$ values for the $8^+ \rightarrow 6^+$ transition. This would result in isomeric lifetimes of the order of tens of microseconds, which is well within experimental sensitivity (see Fig. 4). The expected $B(E2)$ quenching is due to a mid-shell effect [32] for states with good seniority $\nu=2$ in the $\nu g_{9/2}$ shell and can be observed, e.g., for the $N=50$ isotones in the ^{100}Sn region, which are dominated by $g_{9/2}$ protons.

From the obtained results it can be concluded that there is a different hitherto not considered structure feature which causes the disappearance of isomerism for these mid-shell nuclei. That could happen if the strong neutron $g_{9/2}$ polarizing effect would result in a reduction of the $Z=28$ shell gap leading to deformation and collectivity. A recent estimate, however, results in an only marginal reduction of the proton gap from $N=40$ to 50 [33].

TABLE II. Energies and relative intensities of β delayed γ lines from ^{72}Co decay. The time interval δt between the implantation and the β decay is given.

$\delta t \leqslant 0.3$ s	
Energy (keV)	Intensity (relative)
455(1)	33(10)%
845(2)	75(17)%
1096(1)	≡100(26)%
1197(3)	29(21)%

The β-delayed γ-ray spectroscopy of ^{72}Co could shed light on the problem of disappearance of the 8^+ isomer in ^{72}Ni. In particular, the observation of rotational-type structures would suggest the onset of collectivity and provide a simple explanation for the nonexistence of isomers, and more importantly would be an evidence for a dramatic breaking of the $Z=28$ shell closure. There is however no evidence for such rotational-like structure in the observed level sequence. The intensities of the observed γ rays, the analogy to ^{70}Ni and the high-spin parent state make it very unlikely that an yrast rotational sequence with $J \leqslant 6$ could have escaped observation. On the other hand, observation of shell-model-type excitations would suggest to look for more subtle effects within the shell-model approach. Unfortunately the 8^+ state seems to be marginally populated in the ^{70}Co decay and also in the ^{72}Co decay. At present the attempt can be made to consistently reproduce the observed level scheme with the shell-model calculations and from these calculations try to infer the decay properties of the 8^+ level. This has been done by Grawe *et al.* [30] using empirical shell-model calculations (ESM) with two-body interactions derived from the ^{70}Ni data. Only the excitations involving $g_{9/2}$ neutrons have been allowed. For the valence mirror $N=50$ isotones between $Z=40$ and 50 it was shown a long time ago that the ESM provides an excellent interpolation and extrapolation scheme with high predictive power for level energies [34,35]. The empirical two-body matrix elements (TBME) have been used to calculate the ^{72}Ni level scheme, Fig. 4 (ESM). There is the expected similarity of ^{70}Ni and ^{72}Ni in the predicted level schemes for S3V and ESM calculations. The striking difference is however the presence of the low lying seniority $\nu=4$ $J^{\pi}=6^{+}$ state which is predicted to be below the seniority $\nu=2$ $J^{\pi}=8^{+}$. This opens another deexcitation branch for the isomer with a larger $B(E2)$ value of 2.7 W.u. The lifetime predicted by this calculation is about 10–20 ns, which is just at the limits of the experimental sensitivity. This level is placed well above the $J^{\pi}=8^{+}$ state by the S3V calculations. It can be shown that the lowering of the $\nu=4$ $J^{\pi}=6^{+}$ state is related to the lowering of the $J^{\pi}=2^{+}$ excitation energies in ^{70,72}Ni, as the $g^2_{9/2}$, 2^{+} TBME enters with a large weight in the $\nu=4$ interaction energies, which do not contain the 0^{+} pairing TBME at all [36]. This suggests that the ESM scenario is relevant to explain the experimental data. The dramatic lowering of the 2^{+} energies beyond $N=40$, which due to the $A^{-1/3}$ scalling and the missing Coulomb repulsion in the ground-state should be larger than in the $N=50$ valence mirror isotones, awaits further clarification.

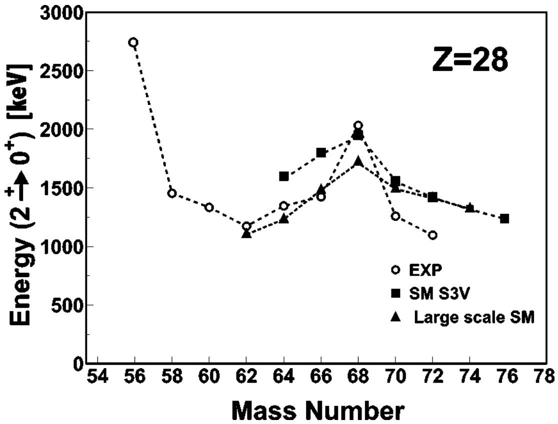

FIG. 5. Systematic reference of the 2^{+} level energies in the even-even nickel isotopes. Experimental results are marked by the open points. The squares represent the S3V shell-model predictions [30] and the triangles the results of the large scale shell-model calculations taken from Ref. [11].

V. CONCLUSIONS

A systematic search for the $J^{\pi}=8^{+}$ isomer in ^{72}Ni has been performed. It has been concluded that the lifetime of this isomer, if it exists, is too short or too long to be observed within the applied experimental methods. The derived lifetime limits (smaller than 20 ns or larger than about 3 ms) are in direct contradiction with previous shell-model calculations which predict the existence of this isomer well within the observation time window. The spectroscopy of β decay of ^{72}Co yielded for the first time information on excited levels in ^{72}Ni. The spin and parity of energy levels have been suggested based on the comparison with the ^{70}Co β decay. The proposed 2^{+} level energy of 1260 keV in ^{70}Ni and of 1096 keV in ^{72}Ni are lower than predicted by the shell-model calculations based on the realistic interactions, see Fig. 5. A possible explanation for the disappearance of 8^{+} isomers is provided. Namely, the calculation with ESM parameters predicts near degeneracy of the $J^{\pi}=6^{+}$ state with seniority $\nu=2$ and $\nu=4$ which can be the reason for such a disappearance of an 8^{+} isomer in ^{72}Ni. The same mechanism as for ^{72}Ni discussed in this paper may be responsible for the disappearance of 8^{+} isomerism in ^{74}Ni. No evidence for significant deformation in ^{72}Ni was found.

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