# Evidence for a $\beta$-decaying $1/2^-$ isomer in $^{71}$Ni

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(Received 22 January 2009; published 30 April 2009)

We report on the investigation of the population mechanism for the 454-keV level in $^{71}$Cu. This level was identified for the first time in a recent Coulomb excitation measurement with a radioactive beam of $^{71}$Cu. The selective nature of the Coulomb-excitation process as well as nuclear-structure considerations constrain the possible spin values for the newly observed state to $I^\pi = 1/2^-$. A reexamination of the data set obtained in a $\beta$-decay study at the Leuven isotope separator on-line mass separator (LISOL) revealed that this state is also populated in the decay of $^{71}$Ni, most probably by direct feeding from a newly identified $1/2^-$ $\beta$-decaying isomer having a $T_{1/2} = 2.3(3)$ s. In this paper, we investigate the proposed scenario by reanalyzing the $\beta$-$\gamma$ and $\gamma$-$\gamma$ coincidences obtained in the $\beta$-decay study at LISOL.

DOI: 10.1103/PhysRevC.79.044325 PACS number(s): 23.35.+g, 21.10.Ky, 25.70.De, 27.50.+e

## I. INTRODUCTION

Isomeric states in nuclei around closed shells can occur as a result of the large spin difference between the valence orbitals (single-particle isomers) or when the maximum amount of angular momentum created in a single-particle configuration is reached (seniority isomers). Depending on the transition probabilities involved, an isomeric state can decay by, e.g., $\gamma$ transitions to lower lying states or $\beta$ radiation to the ground or excited states of the daughter nucleus. The investigation of nuclear isomers gives important information regarding the evolution of the shell structure in a specific mass region.

The identification of isomeric states in the neutron-rich nuclei with $Z \sim 28$ and $N \sim 40$–50 constitutes a field of great current interest. These states store key information about the structural changes induced by increasing the neutron number and especially by the filling of the unique parity $\nu g_{9/2}$ orbital. An experiment employing the fragmentation of a $^{86}$Kr$^{34+}$ beam with an energy of 60.3 MeV/nucleon led to the identification of 13 new $\mu$s isomers in the neutron-rich nuclei from Sc ($Z = 21$) to As ($Z = 33$) [1]. Spin and parity assignments were based on the observed $\gamma$-decay pattern and comparisons with the systematics. Most of the identified isomers were found to originate from the stretched $\nu g_{9/2}^n$ configurations and decay to the lower lying states via $E2$ or $M2$ $\gamma$ transitions [1].

In recent years, $\beta$-decaying isomers in the neutron-rich nuclei around $^{68}$Ni have been extensively studied as well [2–6]. Such isomers, arising from the large spin difference between the opposite parity orbitals $\nu p_{1/2}$ and $\nu g_{9/2}$, are expected to be found at low excitation energies in the odd-odd and odd-$N$ nuclei with N$\sim$ 40. Among these, the odd-$N$ Ni isotopes are of special interest since their low-energy levels are expected to arise mainly from neutron single-particle excitations whose investigation offers important information concerning the core properties of $^{68}$Ni.

Low-lying states in the neutron-rich $^{67,69,71,73}$Ni were identified in the $\beta$ decay of their Co isobars obtained in proton-induced fission combined with resonant laser ionization [2,7] and in fragmentation reactions [1,3,8,9]. $1/2^-$ and $9/2^+$ spins and parities were proposed for the ground states of $^{67}$Ni and $^{69,71,73}$Ni, respectively, based on the observed $\beta$-decay pattern and shell-model calculations [2,3,7–10]. In $^{69}$Ni, the $1/2^-$ state originating from two-particle–one-hole (2p-1h) excitations $\nu(p_{1/2}^{-1} g_{9/2}^2)$ across the $N = 40$ subshell was found to be a long-lived isomer [$T_{1/2} = 3.5(5)$ s] decaying via a fast Gamow-Teller $\beta$ transition [$\log ft = 4.3(2)$] to the first excited $3/2^-$ state at 1298 keV in $^{69}$Cu [2,3,11,12]. The observed weak branch to the $3/2^-$ ground state of $^{69}$Cu was explained by invoking some mixing of the wave function, dominated by the $\pi p_{3/2}^{+1} \nu g_{9/2}^{+0}$ component, with the $\pi p_{3/2}^{+1} \nu p_{1/2}^{-2} g_{9/2}^{+2}$ configuration proposed for the excited $3/2^-$ level at 1298 keV [2,3]. No feeding of the isomer to the single-particle $1/2^-$ state at 1096 keV in $^{69}$Cu was observed, suggesting a rather pure $\pi p_{1/2}^{+1} \nu g_{9/2}^0$ structure for this level.

Level schemes of the neutron-rich odd-$A$ Ni isotopes beyond $^{69}$Ni are still poorly known. In all odd-$A$ Ni isotopes with masses from 71 to 77, the shell model predicts a spin-parity of $9/2^+$ for the ground state and a low-lying $1/2^-$ level dominated by the $\nu p_{1/2}$ neutron-hole configuration [10]. Sawicka *et al.* [8] reported four $\gamma$ transitions in each of the $^{71,73}$Ni isotopes observed in the $\beta$ decay of the $^{71,73}$Co isobars. Because of the poor statistics, $\gamma$-$\gamma$ coincidences could not be constructed. Therefore, the observed transitions were placed in a level scheme based on shell-model predictions [8].

Most of the $\gamma$ rays reported by Sawicka *et al.* [8] were recently confirmed by the results of a decay-spectroscopy experiment performed at National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University [9]. In that experiment, the $^{71,73}$Co isotopes were produced in the fragmentation of a $^{86}$Kr beam with an energy of 140 MeV/nucleon onto a thick $^{9}$Be target. The secondary fragments were implanted in a double-sided silicon strip detector surrounded by the NSCL Ge detector array SeGA used to detect the $\gamma$ rays. The good statistics obtained in that measurement allowed the analysis of $\gamma$-$\gamma$ coincidences, which provided the basis for the placement of the observed transitions in the decay schemes of $^{71,73}$Co given in Fig. 4 of Ref. [9]. The two strong peaks observed at energies 566 and 774 keV did not show any coincidence relationship with each other nor with any of the other transitions observed in the $\gamma$ spectrum associated with the $\beta$ decay of $^{71}$Co. Based on a comparison with the systematics and shell-model predictions, both transitions were tentatively placed to feed the $1/2^-$ level, suggested to be a $\beta$-decaying isomer [9].

The present study was prompted by the observation of a new state located at 454 keV populated in a recent Coulomb excitation experiment with a postaccelerated radioactive beam of $^{71}$Cu produced at the CERN on-line isotope mass separator (ISOLDE) facility. The results of that measurement are presented in Ref. [13]. The low beam energy ($\sim$3 MeV/u) used in that experiment ensured that the population of the excited states proceeded mainly via $E2$ excitations from the $3/2^-$ ground state, therefore only levels with spins $1/2^-$, $3/2^-$, $5/2^-$, and $7/2^-$ were expected to be populated. The top of Fig. 1 shows the $\gamma$ spectrum after Coulomb excitation obtained with the beam of $^{71}$Cu. The spectrum is Doppler corrected for the mass of the projectile. The newly observed $\gamma$ ray of 454 keV and the known $5/2^- \rightarrow 3/2^-_{\mathrm{g.s.}}$ transition of 534 keV [11,12,14] are clearly visible in the spectrum.

In the lighter Cu isotopes, an $1/2^-$ state dominated by the $\pi 2p_{1/2}$ single-particle orbital was identified at low excitation energies. Its energy is very close to that of the $5/2^-$ level found to contain a large component from the $\pi 1 f_{5/2}$ orbital [15]. The Coulomb excitation experiment mentioned above included also a measurement with radioactive beam of $^{69}$Cu [13]. A portion of the Doppler-corrected particle-$\gamma$ coincidence spectrum obtained in that run is shown at the bottom of Fig. 1. The two peaks present in the selected energy range were identified as the transitions depopulating the first and second excited states in $^{69}$Cu, namely, the $1/2^-$ and $5/2^-$ levels at 1096(6) [16] and 1213.5(1) keV [12], respectively. Population of the closely lying $3/2^-$ state at 1297.9(1) keV was not observed in the aforementioned Coulomb excitation measurement.

As pointed above, the $E2$ excitation from the $3/2^-$ ground state of $^{71}$Cu constrains the spin of the newly identified state to values $I^\pi \leqslant 7/2^-$. A spin $7/2^-$ would imply a pure $E2$ character for the $7/2^- \rightarrow 3/2^-$ depopulating transition. The calculated Weisskopf estimate for the partial decay lifetime indicates that an $E2$ transition of 454 keV will proceed in $\sim 2$ ns, more than three orders of magnitude slower than an $M1$ transition. The observation of a Doppler broadened 454-keV peak in our Coulomb excitation spectrum suggests a half-life in the picosecond range for the emitting level and therefore an $M1$ character for the depopulating $\gamma$ ray. This restricts the spin of the 454 keV level to values $I^\pi \leqslant 5/2^-$. In Ref. [13], spin and parity $(1/2^-)$ were assigned to the newly observed state at 454 keV, based on the systematics

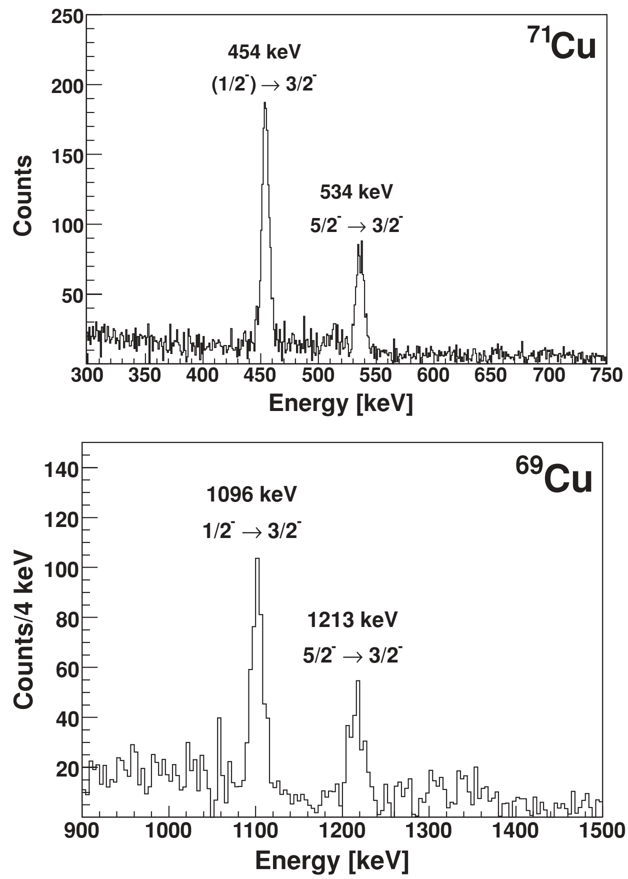


FIG. 1. Particle-$\gamma$-ray coincidence spectra obtained after Coulomb excitation experiment with radioactive beams of $^{71}$Cu and $^{69}$Cu. The spectra are Doppler corrected for the mass of the projectile.

of the lighter Cu isotopes and comparison with the Coulomb excitation spectrum with beam of $^{69}$Cu. Such a spin assignment is also in agreement with the shell-model and particle-core coupling calculations [12,17–19]. It is worth mentioning that in $^{71}$Cu, the second $3/2^-$ state is still unknown. Shell-model and particle-core calculations predict this state around 1900, 1662, and 1100 keV, respectively [12,17,19].

It is also worthwhile to mention that isomeric $1/2^-$ states originating from 2p-1h excitations across $Z = 40$ have been observed in the valence partner of $^{71}$Ni, $^{93}_{43}$Tc$_{50}$ [20]. In fact, the $1/2^-$ isomer was found to be the first excited state in the $N = 50$ isotones from Nb ($Z = 41$) to Rh ($Z = 45$) with a half-life ranging from 60.9 days to 1.96 min, respectively [20]. In $^{93}$Tc, however, the $\beta$ decay from the $1/2^-$ isomer ($T_{1/2} = 43.5$ min) was found to compete with an $M4$ transition to the $9/2^+$ ground state [20].

This paper focuses on the possible decay modes of the $1/2^-$ state in $^{71}$Ni. We analyze and discuss the experimental evidence indicating that this state is a $\beta$-decaying isomer feeding the newly observed $(1/2^-)$ state at 454 keV in $^{71}$Cu [13]. The data sets used in the present study were obtained in two different $\beta$-decay experiments performed at the Leuven isotope separator on-line (LISOL) facility. In the first measurement, the $\beta$-decay study of $^{71}$Ni was used to investigate the low-lying level scheme of $^{71}$Cu [11,12]. The

TABLE I. Half-lives of the mother nuclei, specific implantation-decay cycles, measuring times with and without laser radiation, beam intensities, and productions rates for $^{71}$Ni and $^{71}$Co. During experiment I, the lasers were tuned on nickel, while during experiment II they were tuned on cobalt.

| Exp. $N_0$ | Nucleus | $T_{1/2}$ (s) | Cycle (impl./decay) | Laser ON | Laser OFF | $I_{beam}$ ($\mu$A) | Yield (ions/$\mu$C) |
|---|---|---|---|---|---|---|---|
| I | $^{71}$Ni | 2.56(3)[a] | 6 s/10 s | 35 h 09 min | – | 6.1 | 3.0(6) |
| II | $^{71}$Co | 0.079(5)[b] | 0.6 s/1 s | 16 h 02 min | 12 h 57 min | 6.7 | 0.032(8) |

[a]Reference [12].
[b]Reference [8].

second experiment was dedicated to the identification of the energy levels in $^{71}$Ni populated in the decay of the $^{71}$Co isobar.

## II. EXPERIMENTAL DETAILS

The $^{71}$Ni and $^{71}$Co beams were produced in two separate measurements at the LISOL facility by colliding a 30-MeV proton beam with two thin $^{238}$U foils mounted inside a gas cell [21]. The cell was filled with 500 mbar of argon gas. The radioactive Ni and Co atoms were resonantly photoionized, mass separated, and implanted in a movable tape surrounded by $\beta$ and $\gamma$ detectors arranged in a close geometry. Table I gives a summary of the experimental conditions in both measurements.

In the first experiment, $^{71}$Ni was implanted in a Mylar tape surrounded by two high-purity germanium (HPGe) detectors positioned in the horizontal plane and at 90° and 270° with respect to the beam axis. The relative efficiency of the detectors reached 70% and 75%, respectively. The emitted $\beta$ particles were recorded in a plastic $\Delta E$ scintillator located between the two Ge detectors, in forward direction. A detailed description of the experimental setup can be found in Ref. [12].

In the second experiment, the $\beta$ decay of $^{71}$Co was observed by means of four plastic $\Delta E$ detectors, while the emitted $\gamma$ rays were recorded with three HPGe detectors of 70%, 75%, and 90% relative efficiency located at 90°, 0°, and 270°, respectively, with respect to the beam axis. Measurements with and without laser radiation were performed to disentangle the $\gamma$ rays emitted by the nuclei of interest from the nonresonant transitions.

## III. EXPERIMENTAL RESULTS

### A. $\beta$ decay of $^{71}$Ni

The $\beta$-gated $\gamma$ spectrum obtained in the experiment with $^{71}$Ni beam is presented in Fig. 2. In the inset, the region around 500 keV is enlarged, showing the transition of 454 keV. $\gamma$ rays attributed to the decay of $^{71}$Ni (see Ref. [12] for details) are marked with an asterisk. Open circles label the transitions arising from the $^{71}$Cu decay.

In Ref. [12], the 454-keV transition was found not to be in coincidence with any of the $\gamma$ rays attributed to $^{71}$Cu, therefore it was not further discussed in that paper. The proposed spin value ($1/2^-$) for the 454-keV level out of the Coulomb excitation study rules out the possibility of a direct $\beta$ branch from the $9/2^+$ ground state of $^{71}$Ni. Furthermore, the lack of $\gamma$-ray coincidences in the $\beta$-decay study of Ref. [12] also excludes indirect feeding from the ground state of $^{71}$Ni, see further. Therefore, the alternative scenario that this state is fed by a $1/2^-$ $\beta$-decaying isomer in $^{71}$Ni is investigated.

The time evolution of the $\gamma$ intensity of the 454-keV transition is shown in Fig. 3. The data were fitted with a single exponential. The poor statistics forced us to take bins of 2 s each, resulting in three and five data points for the implantation and decay periods, respectively (see Table I). The last two seconds of the decay period were excluded because of the very low number of counts observed in the peak. A value of $T_{1/2} = 2.3(3)$ s was extracted from the fit.

Figure 4 compares the $\gamma$-$\gamma$ spectra gated with the 447-keV transition and the 454-keV line. The 447-keV transition deexcites the level at 981 keV, which is populated both directly in the $\beta$ decay of the $9/2^+$ ground state of $^{71}$Ni and from feeding from higher lying states in $^{71}$Cu [12]. As can be seen from the inset of Fig. 2, the 447-keV line is twice as strong as the peak at 454 keV. The observation of the 472- and 534-keV transitions in the spectrum coincident with the 447-keV $\gamma$ ray provided the basis for its placement in the level scheme of $^{71}$Cu as shown in Fig. 7 of Ref. [12]. In the spectrum gated with the 454-keV $\gamma$ ray shown in the bottom of Fig. 4, no clear peak can be distinguished

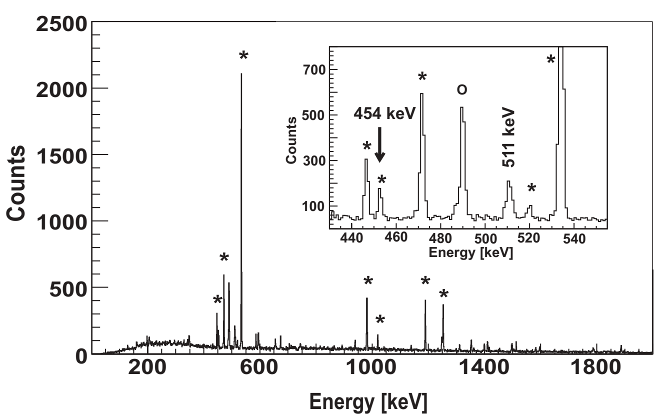


FIG. 2. $\beta$-gated $\gamma$ spectrum for mass $A = 71$ obtained from the data set reported in Refs. [11,12]. The $\gamma$ rays following the $\beta$ decay of $^{71}$Ni are marked with an asterisk. In the inset, the region around 500 keV is enlarged, showing the 454-keV line. The peak marked with a circle was assigned to the $\beta$ decay of the daughter nucleus $^{71}$Cu.

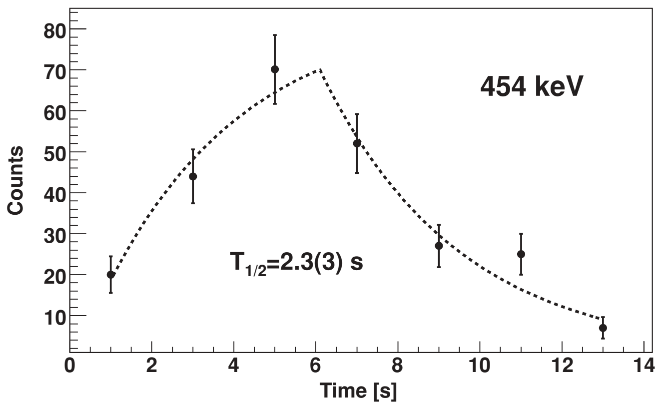


FIG. 3. Time evolution of the intensity of the 454-keV $\gamma$ ray fitted with a single exponential function yielding to a half-life of $T_{1/2} = 2.3(3)$ s.

from the background, indicating that $\gamma$ feeding from higher lying states has a negligible contribution to the population of the 454-keV level. The observed background is due to true coincidences with $\beta$ particles interacting with the Ge detectors. The nonobservation of any coincident $\gamma$ ray supports the scenario that this state is directly fed by a $1/2^-$ isomer in $^{71}$Ni.

From the observed number of counts in the 454-keV peak and taking into account the absolute $\gamma$-ray branching from the $(1/2^-)$ $\beta$-decaying isomer (see Sec. III B), we extract a production rate of 0.2(1) atoms/$\mu$C of the $1/2^-$ isomer in experiment I. With a ground-state yield of 3.0(6) atoms/$\mu$C, see Table I, this results in an isomeric ratio of 7(4)%. Within the same experimental conditions, a lower limit of 0.74 atoms/$\mu$C was reported for the production of the $(1/2^-)$ isomer in $^{69}$Ni, which was found to represent nearly 20% of the total production rate of $^{69}$Ni [12].

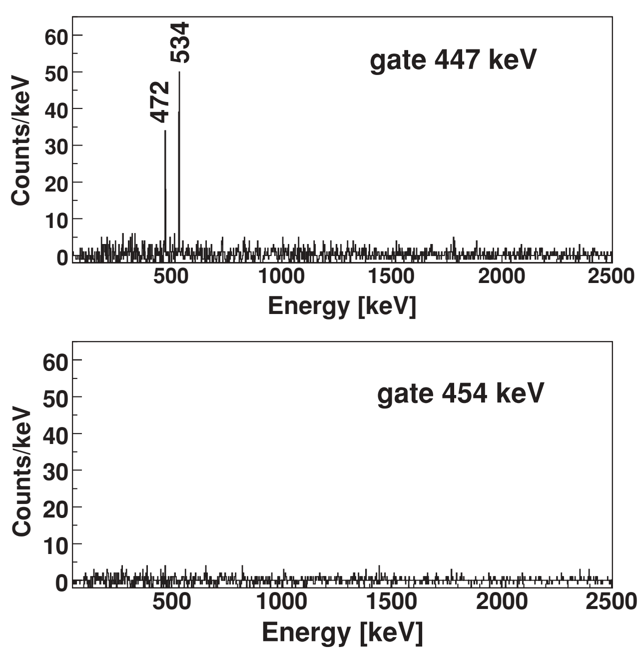


FIG. 4. Background-subtracted $\gamma$-$\gamma$ coincidence spectra gated on the 447-keV transition and 454-keV $\gamma$ ray.

### B. $\beta$ decay of $^{71}$Co

Figure 5 shows part of the $\beta$-gated $\gamma$ spectra observed in the measurement with the lasers tuned to ionize Co and without laser radiation. Transitions belonging to the $A = 71$ decay chain are labeled on the figure. The contaminant lines, marked by open circles, were found to be emitted by the $^{142}$La or $^{102}$Nb fission products. $^{142}$La as well as $^{102}$Nb in the form of a molecule with $^{40}$Ar could reach the detection setup in a $2^+$ charge state and therefore with the same $A/q$ ratio as the ions of interest. Another source of contamination found to give a nonresonant signal in the $\beta$-gated $\gamma$ spectra shown in Fig. 5 was $^{112}$Ag, produced in the decay of $^{112}$Rh, which was implanted next to the tape during the optimization of the laser-ion source.

With the lasers tuned on the Co resonance, the transitions of 281, 566, and 774 keV, assigned to the decay of $^{71}$Co in Refs. [8,9], are clearly visible in Fig. 5 (top).

The lasers-off spectrum (Fig. 5, bottom) shows the presence of the 534-keV line from the nonresonant production of $^{71}$Ni. The upper limits of the $\gamma$ intensities of the other lines from the decay of $^{71}$Ni are consistent with Ref. [12]. However, in the Co on resonance spectrum (Fig. 5, top), an excess of 35(11) counts in the 454-keV line was observed when using the intensity ratio $I_\gamma(534)/I_\gamma(454)$ from Ref. [12], see Fig. 2. This difference in relative intensities between the transitions in $^{71}$Cu in the decay of $^{71}$Ni, directly (lasers on Ni) or through the $\beta$ decay of $^{71}$Co (lasers on Co), indicates the presence of a low-spin $\beta$-decaying isomer in $^{71}$Ni. A good candidate for this isomer is the $(1/2^-)$ state at 499 keV, as suggested in Ref. [9]. In the $\beta$ decay of $^{71}$Co, the 566- and 774-keV lines feed the $(1/2^-)$ isomer [9,22], and this allows us to deduce an absolute $\gamma$-ray branching of 40(15)% to the 454-keV transition in the decay of $^{71}$Ni$^m$. In the absence of other $\gamma$-ray transitions, this absolute $\gamma$-ray branching is taken as the direct $\beta$ branching to the 454-keV level, and the remaining intensity of 60(15)% is attributed to the direct feeding of the ground state of $^{71}$Cu, see Fig. 6. Because weaker $\gamma$ transitions to both the 454-keV level and ground state might have been missed, the $\beta$-branching values should nonetheless be considered as upper limits. The value extracted for the feeding to the excited state corresponds to a $\log ft$ of 5.6(2), assuming that the $(1/2^-)$ isomer in $^{71}$Ni is indeed located at 499 keV [9,22].

## IV. DISCUSSION

Let us now discuss the implications of the present findings on the evolution of the nuclear structure in this mass region. Figure 6 shows the comparison between the $\beta$-decay chains $^{69}\text{Co} \rightarrow ^{69}\text{Ni} \rightarrow ^{69}\text{Cu}$ [2,12] and $^{71}\text{Co} \rightarrow ^{71}\text{Ni} \rightarrow ^{71}\text{Cu}$ [9,12]. Both $^{69,71}$Co isotopes are assumed to have a $7/2^-$ ground state dominated by the $\pi f_{7/2}^{-1}$ proton-hole configuration for which the major decay path is the Gamow-Teller decay of a $f_{5/2}$ core neutron to fill the $f_{7/2}$ proton orbital. In $^{69}$Ni, the strong $\beta$-decay branches from $^{69}$Co observed to the levels at 915 and 1518 keV suggest dominant $\nu f_{5/2}^{-1} \otimes 0^+(^{70}\text{Ni})$ and $\nu f_{5/2}^{-1} \otimes 2^+(^{70}\text{Ni})$ configurations, respectively, although the latter is considerably mixed up with a $\nu p_{1/2}^{-1} \otimes 2^+(^{70}\text{Ni})$ component

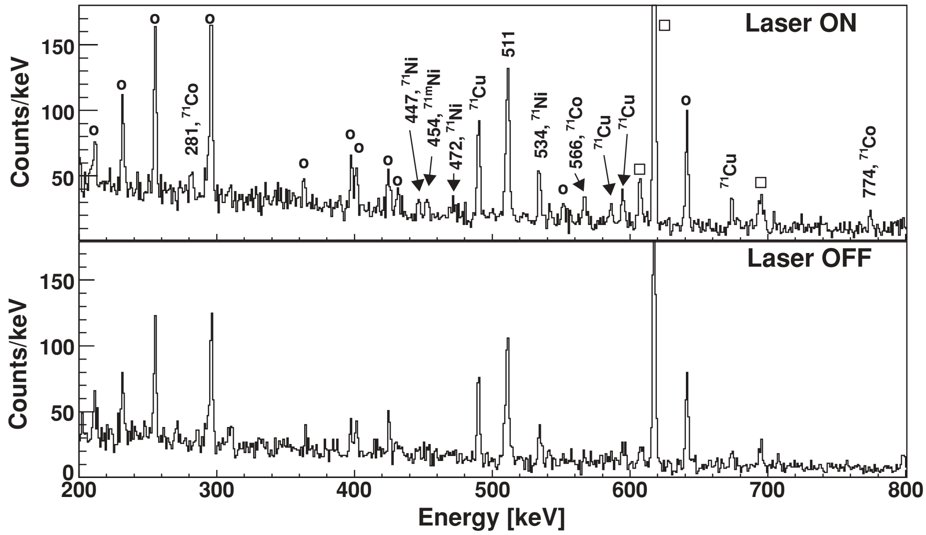


FIG. 5. $\beta$-gated $\gamma$ spectrum for $A = 71$ when lasers are on (top) Co resonance and lasers are off (bottom). Transitions belonging to the decay of $^{71}$Co (see text), $^{71}$Ni, and $^{71}$Cu are labeled; contaminant $\gamma$ lines are marked with open circles. The open squares mark $\gamma$ lines belonging to the decay of $^{112}$Ag, which originates from $^{112}$Rh isotopes implanted next to the tape during the optimization of the laser-ion source.

[2]. As discussed in Ref. [9], the expected strong Gamow-Teller $\beta$-decay branch from the $7/2^-$ ground state of $^{71}$Co restricts the spins and parities of the excited states populated in the $^{71}$Ni daughter nucleus to $9/2^-$, $7/2^-$, and $5/2^-$. Based on shell-model predictions and the observed systematics, spin and parity $5/2^-$ were assigned to the levels at 1065 and 1273 keV in $^{71}$Ni, see Ref. [9] and Fig. 6.

In both $^{69,71}$Ni nuclei, the $5/2^-$ states receiving the main $\beta$ feeding are assumed to decay via $E2$ transitions toward the $(1/2^-)$ isomer. In $^{71}$Ni, however, the shell model predicts that the first excited level is $7/2^+$ [10]. The presence of such a state below the $(1/2^-)$ level reduces the spin difference between the $5/2^-$ levels populated in $\beta$ decay and the $9/2^+$ ground state and increases the probability for $\gamma$ decay $5/2^- \to 7/2^+ \to 9/2^+_{\text{g.s.}}$, bypassing the $(1/2^-)$ isomer. Based on the analysis of $\gamma$-$\gamma$ coincidences, the observed 813–252 keV cascade was assigned to this spin sequence in Ref. [9].

The $\beta$ decay of the $(1/2^-)$ isomer in $^{69}$Ni was found to populate essentially the state at 1298 keV in $^{69}$Cu, see Fig. 6. From the comparison of the $\gamma$ intensity feeding into the 321-keV level in $^{69}$Ni with the intensity of the 1298-keV transition in $^{69}$Cu, a $\beta$ branching of 74(9)% was determined in Ref. [2] for the level at 1298 keV. This branching corresponds to a $\log ft$ value of 4.3(2), see Ref. [2] and Fig. 6. Spin and parity $3/2^-$ were assigned to the 1298-keV state, viewed as the $p_{3/2}$ proton coupled to the 2p-2h, $0^+$ state at 1770 keV in the $^{68}$Ni core [2]. Such configuration implies very low collectivity for the $3/2^-$state, in agreement with its nonobservation in the Coulomb excitation spectrum shown in Fig. 1. In contrast to the $3/2^-$ single-particle level at 1298 keV in $^{69}$Cu, the state at 454 keV in $^{71}$Cu was found to exhibit large collectivity [$B(E2; 1/2^- \to 3/2^-_{\text{g.s.}}) = 20.4(22)$ W.u. as determined in Ref. [13]]. By relating the number of counts in the peaks at 1096 and 1213 keV observed in the bottom spectrum of Fig. 1 with the corresponding $B(E2)$ values reported in Ref. [13], an upper limit of 1.4 W.u. can be extracted for the $B(E2)$ value for the 1298-keV transition. Thus, the decay of the $(1/2^-)$ isomer in $^{69,71}$Ni populates states with very different character in the daughter nuclei.

In $^{71}$Ni, however, our evidence shows that the $\beta$-decaying isomer feeds mainly the proposed $(1/2^-)$ state at 454 keV in $^{71}$Cu. As discussed in Ref. [13], the large $B(E2)$ value measured for the 454-keV transition excludes a single-particle character of $\pi p_{1/2}$ type for the 454-keV level. The increased collectivity indicates significant deformation setting in with increasing the number of $g_{9/2}$ neutrons, as also suggested by the results of recent Coulomb excitation experiments with radioactive beams of $^{70}$Ni [25]. The onset of collectivity was associated with the quenching of both $Z = 28$ and $N = 40$ gaps through the combined effect of the attraction and repulsion between the $fp$ protons and $g_{9/2}$ neutrons [25–27]. Thus, the observed $\beta$-decay branch from the $(1/2^-)$ isomer in $^{71}$Ni to the 454-keV level in $^{71}$Cu can be explained by assuming that

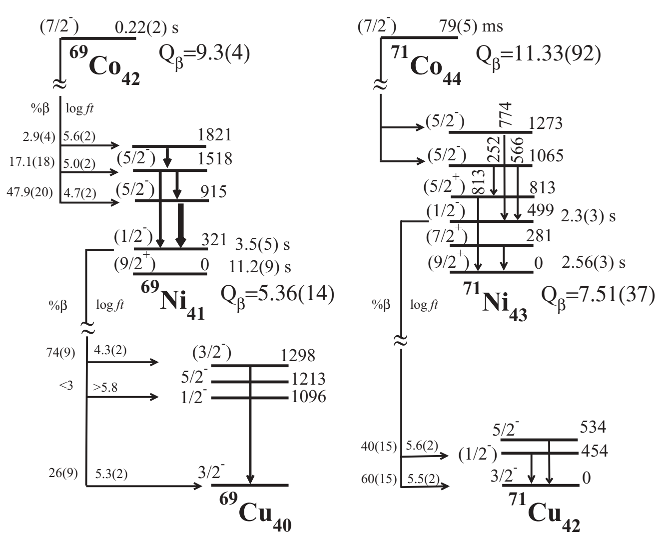


FIG. 6. Observed $\beta$-decay chain $^{69}$Co $\to$ $^{69}$Ni $\to$ $^{69}$Cu [2,12] and $^{71}$Co $\to$ $^{71}$Ni $\to$ $^{71}$Cu as proposed in Ref. [22] and present work. $Q_\beta$ values (given in MeV) of the $A = 69$ and $A = 71$ decay chains are taken from AME1995 [23] (as presented in Refs. [2,12]) and from AME2003 [24], respectively.

the odd proton occupies the $K$=1/2 downsloping orbit of the $p_{3/2}$ orbital, on the prolate side, while the neutron part of the wave function is, depending on deformation, dominated by $\nu p_{1/2}^{+2} g_{9/2}^{+2}$ or $\nu p_{1/2}^{-2} g_{9/2}^{+4}$ configurations. This indicates that in both $^{69,71}$Ni isotopes, the $\beta$ decay of the $(1/2^-)$ isomer proceeds via a fast Gamow-Teller transition; but in the case of $^{71}$Ni, the spin of the final state in the daughter nucleus is changed by the deformation. Interesting to note is that a similarly deformed $\pi 1/2^-[321]$ has been observed in $^{67}$Co, stemming from a $\pi$(1p-2h) proton excitation across $Z = 28$ [6].

## V. CONCLUSIONS

In this paper, the results of the investigation of the decay of the proposed $(1/2^-)$ $\beta$-decaying isomer in $^{71}$Ni are presented and discussed. The key observable for this study is the newly observed level at 454 keV in $^{71}$Cu reported recently in Ref. [13] and for which the comparison with the systematics and model calculations predict a spin and parity of $1/2^-$. The experimental evidence discussed here combines the results of the Coulomb excitation measurement with radioactive beams [13] with the results of two decay experiments aimed at investigating the $\beta$ decay of $^{71}$Co and $^{71}$Ni. The analysis of the $\beta$ decay of $^{71}$Ni indicates that the 454-keV state observed in $^{71}$Cu is fed by the $(1/2^-)$ $\beta$-decaying isomer in $^{71}$Ni, for which a half-life of $T_{1/2} = 2.3(3)$ s was determined in the present work.

The large $B(E2)$ value measured in Ref. [13] for the 454-keV transition depopulating the $(1/2^-)$ state in $^{71}$Cu indicates a deformed structure for this level. This indicates that in both $^{69,71}$Ni isotopes, the main $\beta$-decay branch of the $(1/2^-)$ isomer goes to the level dominated by the $\pi p_{3/2} \nu (p_{1/2}^{-2} g_{9/2}^{2})$ configuration in the daughter nuclei. In $^{71}$Cu, however, due to deformation, the nuclear properties of the level receiving the main $\beta$ feeding are dictated by the $K$=1/2 downsloping orbit of the $\pi p_{3/2}$ orbital.

## ACKNOWLEDGMENTS

We gratefully thank J. Gentens and P. Van den Bergh for running the LISOL separator. This work was supported by FWO-Vlaanderen (Belgium), GOA/2004/03 (BOF-K. U. Leuven), the 'Interuniversity Attraction Poles Programme–Belgian State-Belgian Science Policy' (BriX network P6/23), the European Commission within the Sixth Framework Programme through I3-EURONS (Contract RII3-CT-2004-506065), and the US Department of Energy.

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