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Unambiguous identification of three β-decaying isomers in ^{70}Cu

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Abstract

Using resonant laser ionization, β-decay studies and for the first time mass measurements, three β -decaying states have been unambiguously identified in ^{70}Cu. A mass excess of -62976.1(1.6) keV and a half-life of 44.5(2) s for the (6^-) ^{70}Cu ground state isomer have been determined. The level energies of the (3^-) isomer at 101.1(3) keV with $T_{1/2} = 33(2)$ s and the 1^+ isomer at 242.4(3) keV with $T_{1/2} = 6.6(2)$ s are confirmed by high-precision mass measurements. The low-lying levels of ^{70}Cu populated in the decay of ^{70}Ni and in transfer reactions compare well with large-scale shell-model calculations and the wave functions appear to be dominated by one proton - one neutron configurations outside the closed $Z = 28$ shell and $N = 40$ subshell.

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Recent studies of the nuclear structure of ${}^{68}_{28}\mathrm{Ni}_{40}$ aiming to establish a doubly magic character have resulted in a controversial situation [1]. This stems essentially from the poorly known residual interaction between the (quasi) particle and hole states. It was shown that stellar core collapse models also suffer from this lack of knowledge as these interactions influence the electron capture rates in unstable neutron-rich nuclei far from stability [2].

Crucial information to resolve this deficiency lies in the structure and β-decay of the odd-odd neighboring nuclei of ${}^{68}\mathrm{Ni}$. The structure of these nuclei is particularly sensitive to the single-particle spacings between the neutron orbitals and to the specific residual interactions amongst the valence proton (π) and neutron (ν) holes and/or particles. The single (quasi) particle components in the states of these nuclei are direct indications for the properties of ${}^{68}\mathrm{Ni}$ as a core nucleus. However, the specific shell-model states involved give rise to isomerism – in the case of ${}^{70}_{29}\mathrm{Cu}_{41}$ three β-decaying isomers – which complicates significantly the study of these nuclei. The case of ${}^{70}\mathrm{Cu}$ is particularly interesting due to a persisting uncertainty as to the identity of the ground state.

We report a series of measurements in which resonant laser ionization has been combined with β–γ coincidence studies and with high-resolution mass spectrometry in order to achieve the selectivity needed to elaborate the low-energy structure of ${}^{70}\mathrm{Cu}$. In earlier work, two β-decaying isomers were suggested in ${}^{70}\mathrm{Cu}$ [3–5]; a ground state isomer with $I^{\pi} = (1^{+})$ and $T_{1/2} = 4.5(1.0)\,\mathrm{s}$, and an isomeric state at 140(80) keV with $I^{\pi} = (4^{-})$ and $T_{1/2} = 47(5)\,\mathrm{s}$ [6]. Sherman *et al.* [7] reported five resonances from (t,^{3}He) studies at 0, 100(6), 226(6), 366(6), and 506(6) keV.

The ${}^{70}\mathrm{Ni}$ and ${}^{70}\mathrm{Cu}$ nuclei were produced in a proton-induced fission reaction on uranium. Data on the β-decay of ${}^{70}\mathrm{Ni}$ were obtained at the LISOL facility at Louvain-la-Neuve using the same setup as described in [8]. In-source laser spectroscopy, β-decay studies and mass measurements of ${}^{70}\mathrm{Cu}$ were performed at the ISOLDE/CERN facility [9].

The mass measurements on ${}^{70}\mathrm{Cu}$ were performed with the Penning trap mass spectrometer ISOLTRAP [10]. The setup consists of three traps. The first two traps serve for deceleration, cooling, bunching, and isobar purification of the continuous 60-keV ion beam delivered by ISOLDE. The third trap is a precision Penning trap. Here, the mass measurement is carried out by use of a time-of-flight detection technique to determine the cyclotron frequency $\nu_{\mathrm{c}} = 1/2\pi \cdot q/m \cdot B$ for an ion with mass m and charge q. Cyclotron excitation times of $T_{\mathrm{RF}} = 0.9\,\mathrm{s}$ were used resulting in a linewidth $\Delta\nu_{\mathrm{c}}(\mathrm{FWHM}) \approx 0.9/T_{\mathrm{RF}} \approx 1\,\mathrm{Hz}$.

TABLE I: Frequency ratios relative to ^{85}Rb$^+$ ($m(^{85}\text{Rb}) = 84.911789732(14)\,\text{u}$ [12]) and mass excesses D for the three β-decaying states in ^{70}Cu as determined in this work. For comparison, literature values are given from [12]. The energies of the three isomeric states deduced from the mass measurements and the decay studies are compared.

^{70}Cu	$T_{1/2}$ (s)	Frequency ratio ν_c^{ref}/ν_c	D_{lit} (keV)	D_{exp} (keV)	E(from mass) (keV)	E(from decay) (keV)
gs (6^-)	44.5(2)	0.8235875816(199)	-63202(15)	-62976.1(1.6)	0	0
1st is (3^-)	33(2)	0.8235888547(258)	-63101(16)	-62875.4(2.0)	100.7(2.6)	101.1(3)
2nd is 1^+	6.6(2)	0.8235906419(272)	-62960(16)	-62734.1(2.1)	242.0(2.7)	242.4(4)

This yielded a resolving power $R = \nu_c/\Delta\nu_c(\text{FWHM})$ of more than $1 \cdot 10^6$, mandatory to clearly resolve the ^{70}Cu isomers. The magnetic field strength B was determined via the ^{85}Rb$^+$ cyclotron frequency. By appropriate excitation of the ion motion, a dedicated cleaning procedure can be employed removing a possible remaining contamination from the trap. Cleaning excitation times of 3 s were used.

In the decay of ^{70}Cu two γ-rays from internal decay were identified with energies 101.1 and 141.3 keV. Careful scanning over the frequency of the first laser transition (Fig. 1, top) and investigation of the intensities of these two γ-lines and of the individual γ-rays in the β-decay of ^{70}Cu revealed distinct groups of γ-rays belonging to three different hyperfine-structure patterns, evidencing the existence of three β-decaying isomers in ^{70}Cu with spin (6^-) for the lowest, (3^-) for the intermediate and 1^+ for the highest lying isomer. Tentative spin values were deduced from the magnetic moments [11].

For the mass measurements of the three isomers the laser frequency was tuned to the positions indicated by arrows in the upper part of Fig. 1. The obtained cyclotron resonances are shown in the lower part of Fig. 1. While for the positions a and b the selectivity of the laser ionization was high enough to obtain almost pure samples of the (6^-) and (3^-) β-decaying states, in the case of position c an additional mass selective cleaning of the other isomers was required to obtain an isomerically clean cyclotron resonance. These data

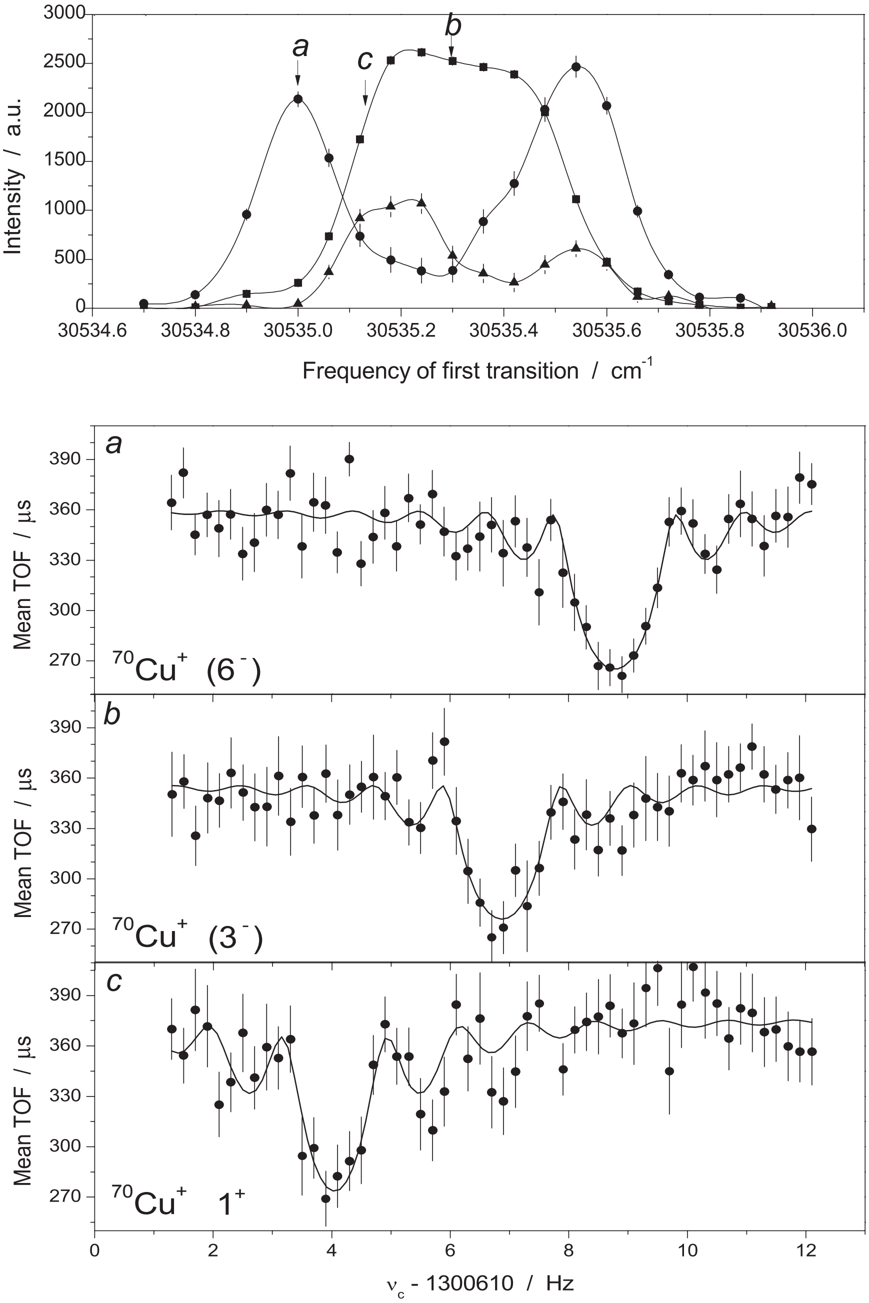

FIG. 1: Top: Intensity of the 101.1 keV (●) and 141.3 keV (▲) internal transitions summed with the associated β-delayed γ-rays as a function of laser frequency. The γ-rays associated with the decay of the (6^-) ground state are indicated by (■). Bottom: Time-of-flight resonance curves as a function of cyclotron frequency for the laser settings marked with arrows (a, b, c) in the top figure. The solid lines are fits of the theoretically expected line shape to the data points.

exemplify the strength of this combined technique to produce isomerically pure samples of short-lived radioactive nuclei.

Table I gives the frequency ratios $\nu_c^{\mathrm{ref}}/\nu_c$ with respect to the reference mass ^{85}Rb$^+$ for all three ^{70}Cu states and the resulting mass excesses and literature values [12] (for details of the analysis and the residual systematic uncertainty see [13]). The mass differences between the β-decaying states obtained with ISOLTRAP are in excellent agreement with those obtained from the decay studies of ^{70}Ni and ^{70}Cu and unambiguously confirm the assignments given in Fig. 2. The new mass data reveal that the literature mass excess values of all states are incorrectly evaluated by 226 keV, possibly due to a former incorrect state assignment.

These results, the decay study of ^{70}Ni and its daughter ^{70}Cu, and the results from the (t,^{3}He) reaction [7] were combined to construct the level scheme of ^{70}Cu (see Fig. 2) and to determine both half-life and branching ratio of each β-decaying state [14]. Five 1^+ states are populated through allowed Gamow-Teller (GT) β-decay of ^{70}Ni and proceed to the 1^+ isomer via one or at most two γ-transitions. Of particular interest is the unanticipated decay of the (1^+) state at 1980.1 keV that is populated by an allowed β-decay branch (log$ft = 4.5$). In contrast to all other (1^+) levels, it feeds only a level at 368.9 keV and surprisingly not the 1^+ state at 242.4 keV.

In the extreme shell model picture, $^{70}_{29}$Cu$_{41}$ can be viewed as having one valence proton outside the $Z = 28$ closed shell and one valence neutron outside the closed $N = 40$ subshell, as shown in the left part of Fig. 2. In ^{70}Cu, the valence proton and neutron will couple, giving rise to a multiplet of states that due to the residual interaction split up in energy [15, 16]. The most important π-ν-coupling schemes assuming a pure quadrupole proton-neutron interaction are schematically drawn in Fig. 2. This simplified approach serves as a guideline for the different configurations of the low-lying states observed.

The ^{70}Cu ground state and its first excited isomeric state at 101.1 keV were already attributed to the 6^- and 3^- members of the $\pi 2p_{3/2}\nu 1g_{9/2}$ multiplet [11]. The states at 226(6) and 506(6) keV are most probably the other members [7, 17]. Based on the γ-feeding and decay pattern of the states at 229 and 369 keV, we associate the latter with the (2^-) member and the former to the (4^-) member of the $\pi 1f_{5/2}\nu 1g_{9/2}$ multiplet. The state at 320.7 keV can be associated to the 2^+ member of the $(1{,}2)^+$ doublet having the $\pi 2p_{3/2}\nu 2p_{1/2}^{-1}$ configuration.

To further explore this configuration we have performed large-scale shell-model calculations using a realistic effective interaction as given by G-matrix calculations [18] with the modified monopole part [19]. The model space consists of the $(1f_{5/2}2p_{3/2}2p_{1/2}1g_{9/2})$ orbitals outside the ^{56}Ni-core.

The results of the diagonalization, performed with the shell-model code ANTOINE [20], are in good agreement with the experimental data (Fig. 2). Although the calculations show mixing between the different configurations, the contribution of the proposed $\pi 2p_{3/2}\nu 1g_{9/2}$ configuration in the first 6^-, 3^-, 4^-, and 5^- states is more than 50% (grey area in Fig. 2), which lends support to calculations that use a more schematic force [14]. The neutron 2p-2h excitations across $N = 40$ represent in these states about 33–38%, which is in line with the 35% admixture in the ground state of ^{68}Ni deduced from large-scale diagonalization shell model calculations [1].

The structure of the lowest 1^+ and 2^+ states is dominated by the $\pi 2p_{3/2}\nu(2p^{-1}_{1/2}1g^{2}_{9/2})$ configuration, with the second largest component being $\pi 2p_{3/2}\nu(2p^{-1}_{1/2}1f^{-2}_{5/2}1g^{4}_{9/2})$. All other states are predicted to have a strongly mixed wave function; none of them contains a single component contributing more than 16%.

The 1^+ states lying within the Q_{EC}-window will be populated in the β-decay of ^{70}Ni through allowed GT decay leading to neutron hole states in the $2p_{1/2}, 2p_{3/2}, 1f_{5/2}$ orbitals or neutron particle states in the $1g_{9/2}$ orbital. Because of the strong mixing the subsequent γ-decay of the excited states should proceed to the 1^+ isomer in ^{70}Cu and not to the negative parity states. The (1^+) state at 1980 keV clearly does not follow this pattern; it only decays towards the (2^-) state. This indicates that the main configuration for the 1980 keV state is most probably the $\pi 1g_{9/2}\nu 1g_{9/2}$ configuration which is indeed expected around this excitation energy (see left part of Fig. 2). Its decay towards the 1^+ isomer then involves both a proton and a neutron single-particle transition and will therefore be strongly retarded. This particular pure configuration is in contradiction with the shell-model calculations (a rather large logft value of 6.02 results). In view of this problem, it is important to investigate the two-body matrix elements for this particular configuration $< \pi 1g_{9/2}\nu 1g_{9/2}; J^\pi |V| \pi 1g_{9/2}\nu 1g_{9/2}; J^\pi >$ in more detail for nuclei in the Ni region near mass $A = 70$.

In conclusion, the unique combination of resonant laser ionization, ion manipulation in Penning traps, precise mass measurements and selective β- and γ-decay studies has allowed for the first time the selection and study of isomerically pure samples from an ensemble of

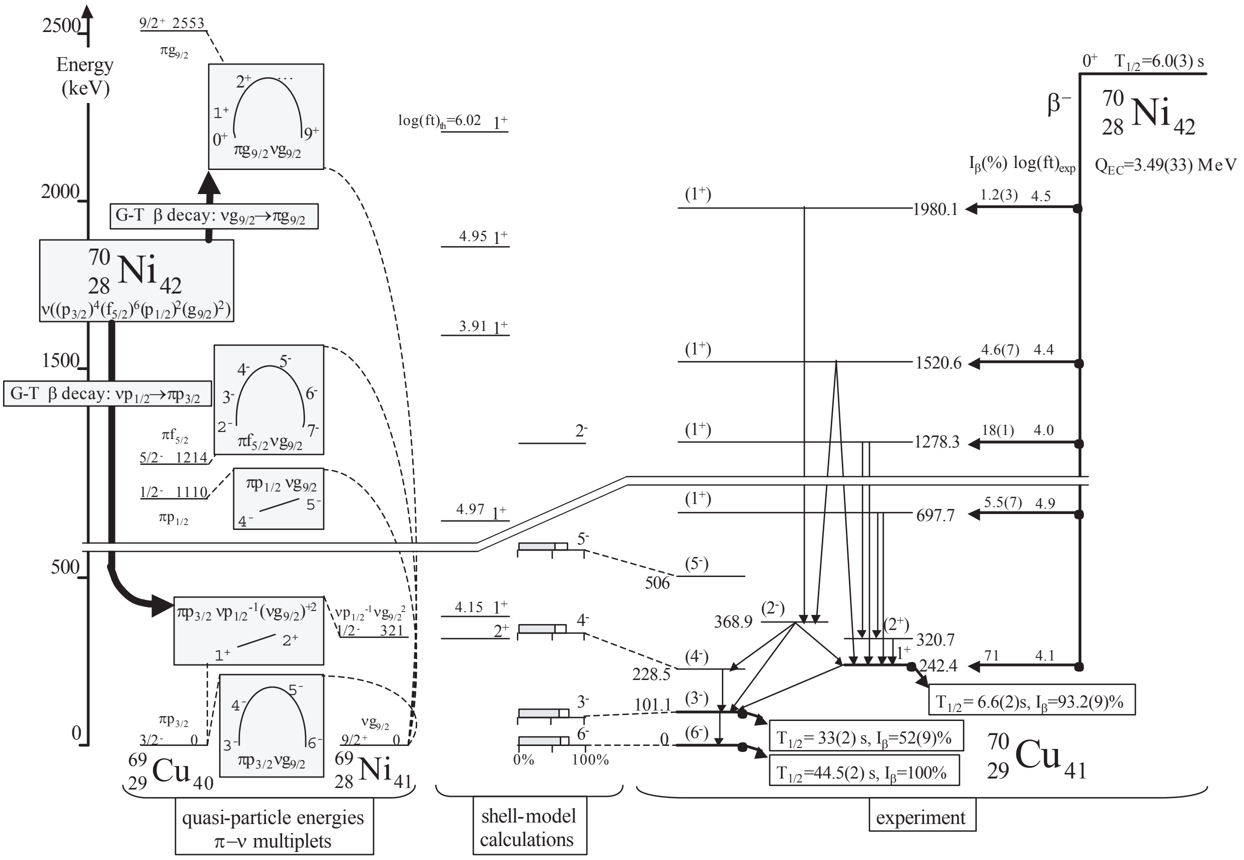

FIG. 2: Left: Schematic presentation of the experimental quasi-particle energies of the orbitals involved for ^{69}Cu and ^{69}Ni [6], the schematic p-n coupling schemes, and the GT β-decay modes of ^{70}Ni. Middle: large-scale shell-model calculations. The grey area on top of the $3^- - 6^-$ multiplet indicates the contribution of the proposed $\pi 2p_{3/2}\nu 1g_{9/2}$ configuration, the white area indicates the $\pi 2p_{3/2}\nu(1f^{-2}_{5/2}1g^{3}_{9/2})$ configurations and the total neutron 2p-2h admixture represents 33% − 38%. Right: partial decay scheme of ^{70}Ni. The (5^-) state is from [7].

three different isomeric states of short-lived radioactive nuclei. A further exploration of these techniques, including post acceleration of isomerically pure beams using schemes like *e.g.* REX-ISOLDE at ISOLDE [21], will create a large potential for reaction studies, of interest for nuclear structure and nuclear astrophysics investigations. Using these complementary techniques, the unambiguous identification and assignment of three β-decaying isomers in ^{70}Cu has been accomplished and has led to corrected mass assignments for the three isomers as well as to further conclusions by comparisons with models for the structure of ^{70}Cu and the β-decay of ^{70}Ni. This is an important step towards understanding the complex nuclear structure of the exotic nuclides in the region of the $N = 40$ subshell closure. Mass measurement and nuclear spectroscopy results are in excellent agreement on the energy position of the ^{70}Cu isomers. The calculations show that for the lowest multiplet the main component of the low-lying states is a 1π-1ν configuration outside the closed $Z = 28$ shell and $N = 40$ subshell, but that a substantial neutron 2p-2h configuration contributes with at least 33%. This indicates a weak subshell closure at $N = 40$.

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