Beta Decay of $^{68-74}$Ni and Level Structure of Neutron-Rich Cu Isotopes

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The isotopes $^{68-74}$Ni, of interest both for nuclear physics and astrophysics, have been produced in proton-induced fission of ^{238}U and ionized in a laser ion guide coupled to an on-line mass separator. Their β decay was studied by means of β-γ and γ-γ spectroscopy. Half-lives have been determined and production cross sections extracted. A partial level scheme is presented for ^{73}Cu and additional levels for ^{71}Cu, providing evidence for a sharply lowered position of the $\pi 1 f_{5/2}$ orbital as occupancy of the $\nu 1 g_{9/2}$ state increases. The latter may have a clear impact on the predicted structure and decay properties of doubly magic ^{78}Ni. [S0031-9007(98)07340-2]

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Exotic nuclei situated far from stability and exhibiting high isospin values have gained increased interest. The reason for this is twofold. Recent theoretical developments predict novel features when one moves away from the valley of stability towards the neutron drip line [1]. A few examples of these features are the altering of the traditional shell gaps and magic numbers, weakening of the spin-orbit interaction, and dilute neutron matter. Understanding the structure of nuclei under extreme conditions will shed new light on the choice of effective nucleon-nucleon interactions in the nuclear medium. Next to this, neutron-rich exotic nuclei are believed to play an important role in explosive nucleosynthesis scenarios like the different *r*-processes in supernovae events [2].

One of the regions in which there is much interest lies around ^{78}Ni, with a magic number both for protons ($Z = 28$) and neutrons ($N = 50$). Large-scale shell-model calculations are presently being carried out in the fp-shell [3], while much experimental effort is put into the investigation of neutron-rich nuclei. Nevertheless, only recently was ^{78}Ni discovered at the GSI fragment separator [4], but no spectroscopic information on excited states nor on decay characteristics towards the copper daughter is yet available.

This holds equally for the lighter nickel nuclei with $A > 69$, of which until two years ago only the half-lives with large uncertainties were determined [5,6]. Different yet complementary experiments at GANIL, Caen, and GSI, Darmstadt, exploiting the production of isomers in fragmentation reactions [7], have meanwhile revealed the first excited states in ^{71}Cu and ^{70}Ni, while multiparticle transfer studies have uncovered states in ^{68}Ni and ^{69}Cu [8,9]. Knowledge of the excited states of the copper isotopes obtained through β decay of nickel remained restricted to $A \leq 69$. The evolution of the single-particle levels along the $Z = 28$ line towards $N = 50$, however, is of utmost importance for predictions of the structure and decay properties of ^{78}Ni and other nuclides of interest to astrophysics beyond the $N = 50$ shell closure.

This lack of information is primarily due to the difficulties with which the nickel isotopes are produced. For on-line isotope separation using conventional high-temperature target-ion source systems the delay time is too long and the short-lived nickel nuclei decay in the target-ion source system before being mass analyzed [10]. Furthermore these ion sources do not provide the necessary selectivity for the nickel isotopes, which in the fission reaction are overwhelmed by isobars nearer stability.

In order to overcome these limitations, an ion-guide laser ion source (IGLIS) has been developed over the last years at the Leuven Isotope Separator On-Line (LISOL). It takes optimum advantage of the selectivity and efficiency inherent to laser ionization and the fast extraction times due to gas flow evacuation [11–13]. This laser ion source made possible the first high-precision measurements of the β and γ decay of ^{68}Ni–^{74}Ni, five nuclei more rich in neutrons towards ^{78}Ni, that reveal significant changes in the single-particle structure.

The nuclei of interest were produced in the proton-induced fission of ^{238}U. The 30 MeV proton beam was pulsed and an averaged intensity between 3 and 6 μA was used. Two ^{238}U targets of 15 mg/cm^2 were installed in a gas cell, filled with 500 mbar of Ar. The reaction recoil products were thermalized and neutralized in the buffer gas. The gas flow transported the atoms into the beam paths of two excimer-pumped dye lasers, that selectively ionized the nickel atoms in a two-step process. At the exit hole of the gas cell, the ions were injected into a sextupole

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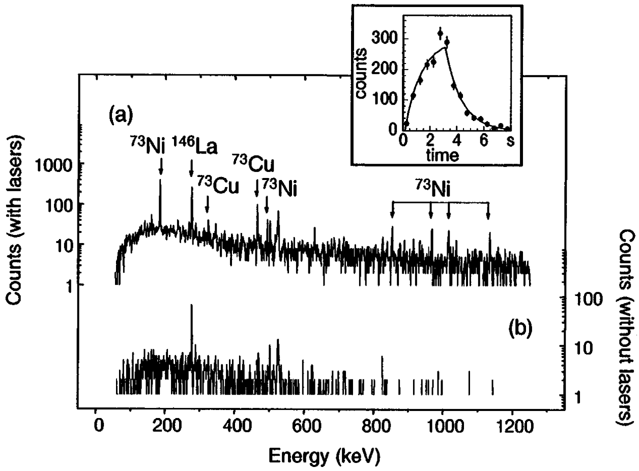

FIG. 1. Part of the γ spectrum at mass 73 obtained (*a*) with and (*b*) without laser light irradiating the gas cell. The integrated proton beam dose was 1.6×10^5 and 5.7×10^4 μC, respectively. The time evolution of the γ intensity attributed to the decay of ^{73}Ni is given in the inset.

ion guide (SPIG) [14], connecting the high pressure area of the gas cell to the low pressure zone of the mass separator.

The mass-separated nickel ions were implanted in a tape for given intervals, alternated with periods during which the proton beam was off and the separator beam deflected. The tape regularly moved away the daughter activity. Two high-efficiency germanium detectors were placed around the source and a thin plastic detector was used for detecting the β particles. The detection efficiencies were determined with intensity calibrated radioactive sources as well as GEANT [15] simulations, to take into account the scattering of β particles into the germanium crystals and the multiplicity of the γ rays.

As an example we present in Fig. 1 part of the β-gated γ spectra for mass 73. The spectrum, when the gas cell was irradiated with the lasers, is drawn on top, while the bottom part shows the spectrum when the laser light was blocked. Comparing both, one clearly notices γ rays of which the presence is directly related to the laser irradiation. Most of the background arises from the decay of $^{146}La^{2+}$ ions, that were abundantly produced in the fission reaction. A substantial fraction of these ions survived in the 2^+ charge state and was mass separated at $A/Q = 73$.

Since the laser ionization exclusively selected the nickel isotopes, we could attribute the resonant lines to the β decay of nickel and its daughters. Relying on the different time behavior of the γ-ray intensity for the mother nucleus and its daughters, of which the most intense γ transitions are known, it was then possible to identify γ lines belonging to the decay of ^{68}Ni up to ^{74}Ni. The strongest transitions are given in Table I.

It is most intriguing that a γ ray of 166.1(1) keV was observed both at masses 73 and 74. Mass contamination is ruled out because of the excellent mass resolving power of the separator, $M/\Delta M \sim 1400$. Moreover, the γ spectrum obtained at mass 73, apart from the 166.1(1)-keV line, is completely different from the spectrum at mass 74. Furthermore, the 166.1(1)-keV line at mass 74 is coincident with a γ ray of 694.3(2) keV of equal intensity, which is not the case for the 166.1-keV transition at mass 73. Since the 605.7(1)-keV line from the known decay of the daughter nucleus ^{74}Cu [16] is clearly seen at mass 74, we can state that ^{74}Ni is β decaying to ^{74}Cu. The present data, however, do not exclude that the decay of ^{74}Ni feeds also, through β-delayed neutron emission, levels in ^{73}Cu. Assigning the 166.1–694.3-keV γ-ray cascade to this decay mechanism would lead to a P_n value for ^{74}Ni of 30(8)%, considerably larger than the calculated prediction of 4.5% [17].

From the intensities of the γ lines in the β decay of the copper daughter nuclei, production rates for the nickel isotopes are obtained as soon as one of the γ branchings of the β-decaying daughters is known. In most cases, these branchings were adopted from literature [18]. For the production of ^{69}Ni, we could rely on the known γ intensities in the decay of nickel itself. The level scheme we constructed for ^{70}Zn is strongly at variance with the literature [19] and for deducing the production rate of ^{70}Ni, we supposed that no ground-state feeding occurs in the decay of ^{70}Cu. For the intensity of the 449.8(2)-keV γ ray in the β decay of ^{73}Cu we took 43(2)% [20], while for the 605.7(1)-keV transition in the decay of ^{74}Cu a value of 79(15)% was used [21].

Figure 2 summarizes the experimental production rates and compares them with theoretical calculations [22]. The slope of the experimental cross section curve was measured over a range of five mass units. Its shape is well reproduced by a Gaussian fit with a width of 2.8(3), which is consistent with the theoretical width of 3.0. The

TABLE I. Measured half-lives for $^{68-74}$Ni, compared to literature values taken from Refs. [5,6,18]. The two most intense γ lines for every isotope are given as well.

	^{68}Ni	^{69}Ni	^{70}Ni	^{71}Ni	^{72}Ni	^{73}Ni	^{74}Ni
This work	29(2) s	11.2(9) s	6.0(3) s	2.56(3) s	1.57(5) s	0.84(3) s	0.9(2) s
Literature	19^{+3}_{-6} s	11.4(3) s	···	1.9(4) s	2.1(3) s	0.6(1) s	0.5(2) s
γ rays (keV)	758.3(1)	1213.5(1)	1035.5(2)	534.4(1)	376.4(1)	166.1(1)	166.1(1)
	84.2(1)	1871.3(2)	78.3(1)	2015.6(2)	94.0(1)	1010.0(2)	694.3(2)

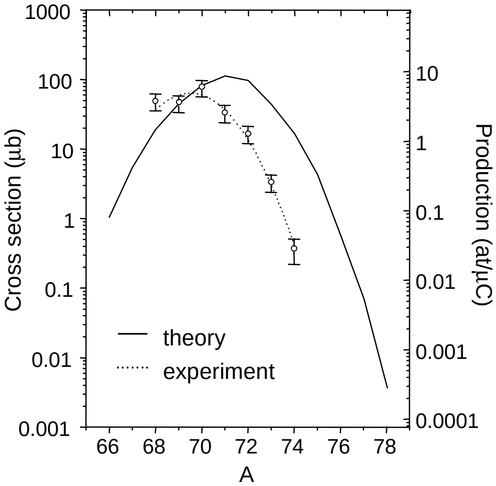

FIG. 2. Comparison of experimental production yields for $^{68-74}$Ni and cross section calculations for 30 MeV protons on ^{238}U [22]. A possible β-delayed neutron branch in ^{74}Ni is not taken into account.

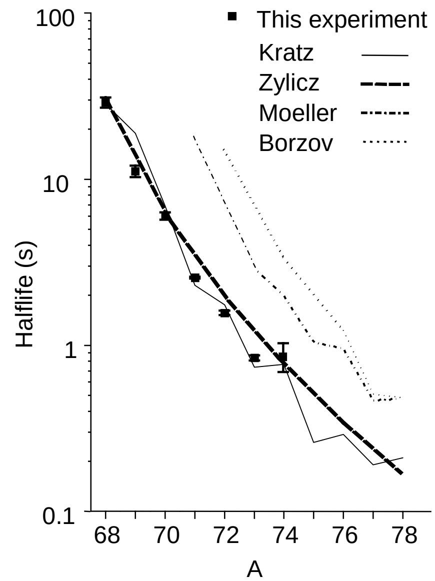

FIG. 3. Obtained half-lives, compared to predictions by Möller [17], Borzov [24], Zylicz [25], and Kratz [26].

maximum, however, is found at mass 69.5(3), instead of the theoretical centroid at 71.

From the time behavior of the characteristic γ rays that were unambiguously assigned to the decay of a specific nickel isotope, we extracted the half-lives listed in Table I. The specific data for ^{73}Ni are shown in Fig. 1. For the β decay of ^{68}Ni, we observed only two weak transitions at 758.3(1) and 84.2(1) keV. Since we produced a monoisotopic source of ^{68}Ni, we were able to fit the half-life of ^{68}Ni out of the time behavior of the γ-ray intensity of the ^{68}Cu to ^{68}Zn β decay, using a mother-daughter relation and the known half-life of 31.1(15) s for ^{68}Cu [18].

Upon examining Table I, the deviation for ^{68}Ni becomes clear immediately. A possible explanation for the discrepancy could be the limited purity of the source in the previous measurements [23]. Also the agreement for ^{71}Ni to ^{74}Ni is out of the 1σ limit. It might point to problems in the earlier experiments when deducing half-lives out of time correlations between implanted ions and detected β particles [5,6]. The precision obtained in this work is a factor 3 to 10 better than the literature values.

In Fig. 3 the half-lives are compared to theoretical predictions. The QRPA calculations by Möller [17] and ETFSI-based values from Borzov [24], which are both global evaluations, overestimate the measured half-lives considerably. The recent spherical TDA predictions by Zylicz [25], using single-particle levels from a HFB model, and the older QRPA calculations by one of the authors [26], that took into account the locally known nuclear structure, are in remarkable agreement with the data. For ^{68}Ni, the newly measured half-life corresponds much better to these expectations than the literature value. An extrapolation of the last two models towards ^{78}Ni yields a half-life for this nucleus of the order of 0.2 s.

The systematics of the excited states in ^{69,71,73}Cu are drawn in Fig. 4. The proposed schemes for ^{71}Cu and ^{73}Cu were deduced from the γ-γ coincidences recorded. Because of the limited statistics, weak γ rays might be missing and the $\log ft$ values quoted below will have to be regarded as lower limits.

The levels at 534.4, 981.3, 1189.5, and 1786.1 keV in ^{71}Cu have been observed in decay studies of high-spin isomers as well [27]. The first excited state in ^{69}Cu has been identified as the $\pi 1f_{5/2}$ single particle level while the ground state is the $\pi 2p_{3/2}$ orbital. For all odd ^{57}Cu to ^{69}Cu isotopes, this $1f_{5/2}$ state has an excitation energy near 1 MeV. In ^{71}Cu, however, the first excited level appears at 534.4 keV and in ^{73}Cu at only 166.1 keV. Assuming a spin of $9/2^+$ for ^{71}Ni and ^{73}Ni, the β decay

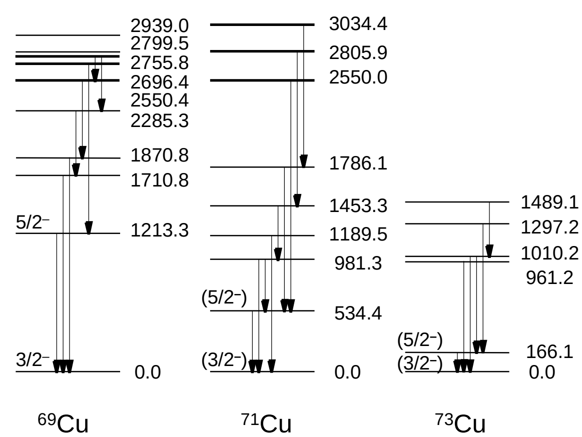

FIG. 4. Energy level systematics for ^{69,71,73}Cu. Energies are given in keV. The data for ^{69}Cu are taken from Ref. [18].

will not feed the $\pi 2p_{3/2}$ state. On the other hand, we did detect β decay to both the 534.4 and 166.1-keV levels with a branching up to 6.3% and 24%, respectively, corresponding to $\log ft$ values of 6.0 and 5.7. Hence we suggest that these two levels correspond to the $1f_{5/2}$ particle excitation, while the ground state in both isotopes is still the $2p_{3/2}$ orbital. A similar shift downwards in energy of the $\pi 1f_{5/2}$ level was proposed as well in earlier shell-model calculations [28,29] in order to reproduce properly experimental level energies and electromagnetic transition probabilities of the $N = 50$ isotones.

Most β feeding in ^{69}Cu proceeds through three states at 2550.4, 2696.4, and 2755.8 keV with $\log ft$ of 4.8, 4.2, and 4.2, respectively [18,30]. Three analogous states are found in the level scheme of ^{71}Cu at 2550.0, 2805.9, and 3034.4 keV with $\log ft$ values of 4.8, 4.9, and 4.8, respectively. The β decay to these levels arises from allowed Gamow-Teller transformation of a $p_{1/2}$ core neutron into the empty $p_{3/2}$ proton orbital [9]. The final states with $(\nu 1g_{9/2}\nu 2p_{1/2}\pi 2p_{3/2})$ configurations result in a $(7/2^+, 9/2^+, 11/2^+)$ triplet. This particular decay path is expected to dominate the decay of the heavy nickel nuclides [31]. A fourth relatively highly fed state in ^{71}Cu with a $\log ft$ of 5.4 occurs at 1786.1 keV. All observed levels in ^{73}Cu show $\log ft$ values between 5.5 and 5.7. However, a strongly fed triplet with $\log ft \approx 5.0$ at higher excitation energies analogous to ^{69,71}Cu cannot be excluded, due to the limited statistics.

In conclusion, the laser ion-guide setup has been used to perform significantly improved measurements for the decay of five very neutron-rich nickel nuclides further out from stability and determine new level structures for heavy copper isotopes. The structure for ^{73}Cu, in particular, reveals the dramatic and sudden lowering of the $\pi 1f_{5/2}$ state through the monopole interaction with the increased occupancy of the $\nu 1g_{9/2}$ orbital. This reordering of the single-particle levels could have profound effects on shell structure for nuclei near and beyond the doubly magic ^{78}Ni.

With the current setup, a production rate of 0.1 atoms per day is to be expected for ^{78}Ni. Although out of reach at present, planned improvements both in the efficiency and selectivity of the laser ion source, and in the detection efficiency by installation of part of the germanium Miniball detector [32], will allow extension of this study to $^{75-76}$Ni in the near future.

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