β decay of ^{67}Co

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The β-decay properties of ^{67}Co produced in proton-induced fission of ^{238}U were measured by the detection of β-delayed γ rays emitted from an isotopically pure mass-separated source obtained by laser ionization. The measured half-life of 0.425(20) s is more accurate than previous values. New γ transitions were observed, and corresponding branching ratios and log *ft* values were deduced. The ^{67}Co decay scheme is discussed in terms of the single-particle shell model. [S0556-2813(99)04904-3]

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I. INTRODUCTION

Recently several studies of the semimagic nucleus $^{68}_{28}\mathrm{Ni}_{40}$ and of nuclei in its neighborhood have been performed [1–3]. Because of the $Z=28$ proton shell and the $N=40$ neutron subshell closures, these nuclei form a good testing ground for shell-model calculations in this region [4]. As far as astrophysics is concerned, the measurements of half-lives of neutron-rich nuclei in the Fe group are relevant for explosive *r*-process nucleosynthesis scenarios [5,6].

For decades nuclei far from stability have been studied at on-line mass separators (see Ref. [7] and references therein). The main difficulty of these experiments is high isobaric contaminations, which sometimes have production yields orders of magnitude higher than the yield of the nuclei of interest. A further complication comes from the fact that Co is a difficult element for conventional ion sources as its extraction time in the ion source can be considerably longer than the nuclear half-lives of short-living isotopes, leading to decay losses. To overcome this problem a laser ion source, selectively ionizing the reaction products of interest stopped in a gas cell, was developed at the Leuven Isotope Separator On-Line mass separator (LISOL) [8,9]. As a result of the short evacuation time of the gas and the high selectivity of the resonant photoionization process, very pure radioactive sources of short-living Co nuclei can be produced and studied. We report in this work on a decay study of ^{67}Co feeding levels in ^{67}Ni.

Very little information exists on ^{67}Co and its daughter nucleus ^{67}Ni. The ^{67}Co half-life value was reported by three different groups [10–12] as $T_{1/2}=420(70)$ ms, 310(20) ms, and 440(70) ms, respectively. All of these measurements are distinctly longer than the results based on a quantum random phase approximation (QRPA) calculation using both nuclear mass and ground state deformation from the finite-range droplet model (FRDM) theoretical model [13], $T^{\mathrm{th}}_{1/2}=104.7$ ms.

An interpretation in a extreme single-particle shell-model framework involves the following possible single-particle states: the ground state of $^{67}_{27}\mathrm{Co}_{40}$ is expected to be a $(\pi f_{7/2})^{-1}$ hole in the $Z=28$ closed shell; possible single-particle states for $^{67}_{28}\mathrm{Ni}_{39}$ are a $(\nu f_{5/2})^{-1}$, $(\nu p_{1/2})^{-1}$, and $(\nu p_{3/2})^{-1}$ hole in the $N=40$ closed subshell or one-$\nu g_{9/2}$-particle–two-hole excitation through the $N=40$ subshell. The first excited state $J^{\pi}=(5/2^{-})$, $E=694$ keV of ^{67}Ni was observed in [10]. The spectroscopy of ^{67}Ni was studied using the ^{70}Zn(^{14}C,^{17}O)^{67}Ni transfer reaction [14]. Unfortunately, this measurement had large uncertainties in the deduced excitation energy values and the spin assignments were also rather tentative. For example, the spin and parity of the first excited state was assigned as $9/2^{-}$ instead of $5/2^{-}$. This makes the spin assignment of higher-lying levels in [14] also doubtful. In a more recent in-beam experiment [15], a second excited state at 1007 keV was detected by a γ-γ coincidence relation between the 694.1- and 313.1-keV

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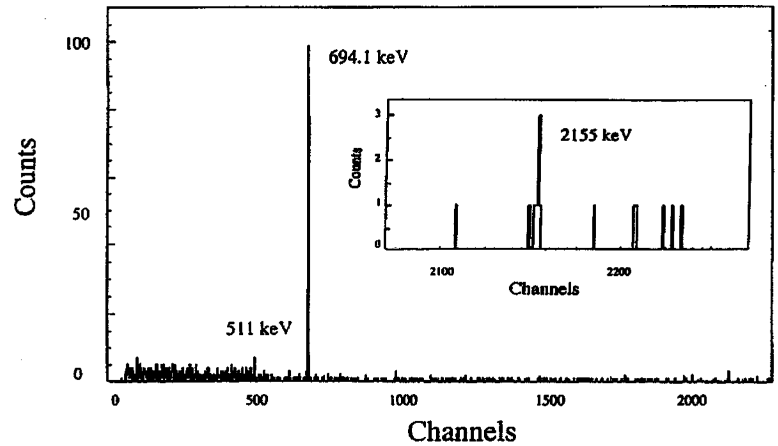

FIG. 1. β-gated γ spectrum measured at mass value $M=67$ when the lasers were tuned on Co resonance. The high-energy 2155-keV transition is indicated in the inset.

transitions. The 1007-keV isomeric level [$T_{1/2} \geqslant 13.3(2)\ \mu$s [2]] was interpreted as a $\nu g_{9/2}$ configuration $I^{\pi}=(9/2^{+})$, decaying to the $(1/2^{-})$ ground state via the $(5/2^{-})$ excited state at 694.1 keV. The $1/2^{-}$ ground state and $5/2^{-}$ excited state were interpreted as the $(\nu p_{1/2})^{-1}$ and $(\nu f_{5/2})^{-1}$ shell-model single-particle states [15]. The long lifetime of the 1007 isomeric state prevented the observation of transitions feeding this state. The 1007-keV excited state is in agreement with the 1020(20)-keV level measured from the ^{70}Zn(α,^{7}Be)^{67}Ni transfer reaction study [16] and maybe also corresponds to the 1.14(10)-MeV level observed in the ^{70}Zn(^{14}C,^{17}O)^{67}Ni transfer reaction [14].

In a recent experiment at the LISOL facility, new information regarding the ^{67}Co β decay to levels in ^{67}Ni was obtained.

II. EXPERIMENT AND RESULTS

The Co isotopes were produced in a 30-MeV proton-induced fission reaction of a ^{238}U target. The proton beam was produced at the Louvain-la-Neuve cyclotron facility. The fission products were thermalized in a gas cell filled with argon buffer gas (500 mbar). The Co atoms were selectively ionized using two-step resonant photoionization [8] by lasers with wavelengths of 232.903 and 481.90 nm, respectively. The Co ions were extracted using a sextupole ion guide [9] and after subsequent mass separation implanted into a tape. To avoid a buildup of long-lived daughter activity, the tape was periodically moved with a time cycle optimized for the ^{67}Co lifetime. The time cycle consisted of 1.2 s of implantation followed by a 2-s decay period. During the latter period, the proton and separator beams were blocked. The implantation time consisted of a few microcycles, which consisted of a proton beam on and off period, with a typical time of 50–200 ms [8].

Details on the detector setup can be found elsewhere [17], and here we give only a short description. Two Ge detectors with relative efficiencies of 70% and 75% were installed opposite to each other close to the implantation point and were used for γ-ray detection. Thin plastic scintillators were used for β-particle detection. The total efficiency for β detection, measured by comparing intensities of γ lines in single and β gated γ spectra, was found to be 55%. The efficiencies of the Ge detectors and β detectors were calculated by GEANT simulations and checked with on-line sources [17]. Energy calibration was performed using off-line sources. The data acquisition was triggered by γ-γ or β-γ coincidence events. A β-gated γ spectrum measured at mass $M=67$ with lasers tuned to the cobalt resonance is shown in Fig. 1. The spectrum exhibits a prominent 694-keV transition. The time to digital converter (TDC) spectrum of β-γ coincidences gated by the 694-keV transition is shown in Fig. 2. From these data a half-life for ^{67}Co of 0.425(20) s is obtained, which is in agreement with two of the three previous measurements [10–12].

The γ spectrum of one Ge detector gated by the 694-keV transition in the opposite Ge detector is shown in Fig. 3. This spectrum exhibits a weak 313.1-keV transition, which gives evidence of β feeding of the level at 1007 keV. Because of the isomeric nature of this level [$T_{1/2} \geqslant 13.3(2)\ \mu$s] and the 1-$\mu$s β-γ correlation time window, the 313.1-keV transition could not be observed in β-γ coincidences.

A high-energy 2155-keV transition was observed in the β-gated γ spectra (inset of Fig. 1). The high selectivity of the laser ion source, the mass $M=67$ condition, and the time behavior of the γ-ray intensity provide evidence that the 2155-keV γ ray belongs to the β decay of ^{67}Co. The number of β-triggered counts in the 2155-keV peak does not change if a condition of nonobservation of γ-γ coincidences between two Ge detectors is applied. This means that the 2155-keV transition most probably decays directly to the ground state of the ^{67}Ni.

III. DISCUSSION

The tentative scheme of the ^{67}Co decay is presented in Fig. 4 together with calculated branching ratios and log ft values for each level. The Q value is taken from [18]. This scheme can be compared with QRPA theoretical calculations of Gamow-Teller decay properties of Co isotopes, using two versions of the model described in [19]. The first model implies single-particle Nilsson wave functions and BCS pairing

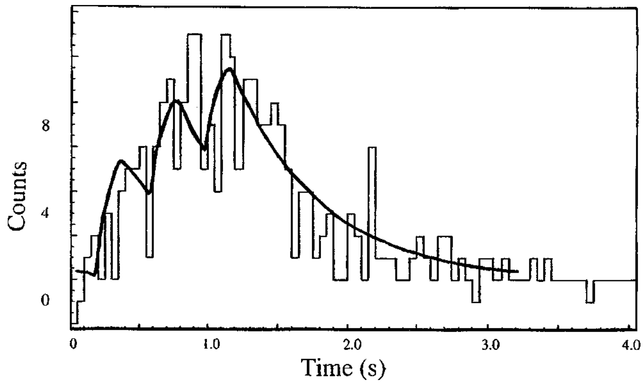

FIG. 2. TDC spectrum of β-γ coincedences gated by the 694-keV transition. The fit includes a 1.2-s implantation period with three beam-on–beam-off microcycles of 200 ms and a 2-s decay period.

[20]; the second one is based on folded Yukawa wave functions and Lipkin-Nogami pairing [13]. The results of calculated single-particle energies and neutron-occupation numbers v_n^2 are summarized in Table I. Using the calculated single-particle energies and occupation numbers, the main features of Gamow-Teller (GT) decay can be obtained (Table II). As is seen from the tables, the calculations provide only a qualitative agreement to the measured β-decay properties with a dominating $\nu f_{5/2} \rightarrow \pi f_{7/2}$ GT transition. The measured $\log ft$ values exhibit a considerable retardation of the decay compare to the calculations.

The high $\log ft$ value ($\approx$6.3) for β decay to the 1007-keV level suggests a *l*-forbidden transition and could give further support for the suggested $\nu g_{9/2}$ [one-particle–one-hole (1p-2h)] character of this state [2]. The observation of this *l*-forbidden decay indicates an admixture of the $\pi f_{7/2}^{-1}$ ground and the excited $\pi f_{7/2}^{-1} \nu g_{9/2}^{2} p_{1/2}^{-2}$ configurations in ^{67}Co. This is supported by the calculated $g_{9/2}$ neutron occupancy, as presented in Table I. The decay of the $\nu g_{9/2} \rightarrow \pi f_{7/2}$ type would then lead to the $\nu g_{9/2}^{1} p_{1/2}^{-2}$ configuration. The $g_{9/2}$ single-particle states are known in the lighter Ni nuclides,

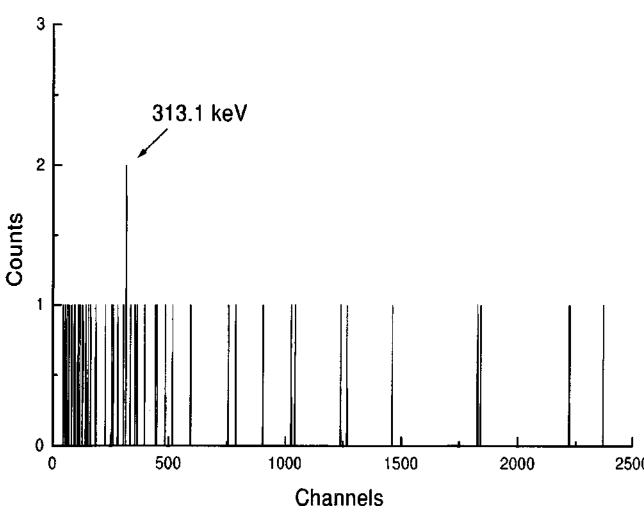

FIG. 3. γ spectrum gated by the 694-keV transition in the opposite Ge detector. The 313.1 keV from the second excited state of ^{67}Ni is observed.

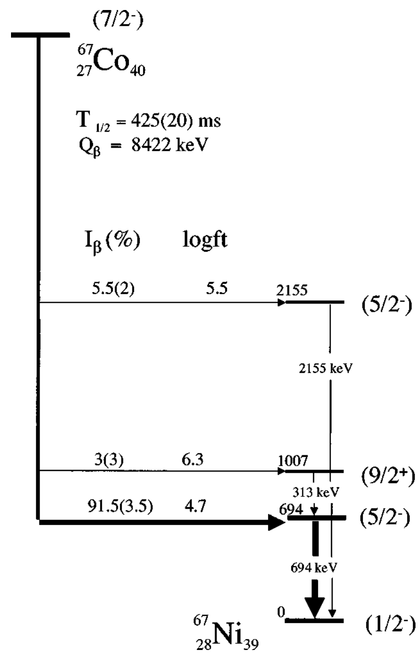

FIG. 4. Tentative level scheme for ^{67}Co decay.

but no such transition has been observed in the β decays of Co isotopes. Note that for such type of β decay, which was classified as ''even-jumping'' [21], the *ft* is proportional to a $(v_p v_n)^{-2}$ value [21]. Hence the present measurement can be used for the estimation of β-decay rates of hitherto unobserved more neutron-rich Co nuclides using the calculated neutron occupation numbers (Table I).

As the level at 2155 keV in ^{67}Ni appears to be populated in allowed β decay and also depopulates to the $1/2^-$ ground state, it can only be a $5/2^-$ level.

There are two possible configurations for the 2155-keV $5/2^-$ level, one in which the $p_{1/2}$ neutron hole of the ground state of ^{67}Ni is coupled to the 2^+ level at 2033 keV in the ^{68}Ni core and a second where the the second excited $f_{5/2}$ hole state at 694 keV is coupled to the 0^+ level at 1770 keV in the ^{68}Ni core [1]. Strong β decay to the former core-coupled

TABLE I. Quasiparticle energies E_{QP} and occupation numbers (v^2) of neutron (ν) levels for the decays of ^{65,67,69}Co for two different models [18]: (A) Nilsson wave function and BCS pairing and (B) folded Yukawa wave functions, Lipkin-Nogami pairing.

	E_{QP} [keV]			v^2		
ν levels	^{65}Co	^{67}Co	^{69}Co	^{65}Co	^{67}Co	^{69}Co
(A)						
$\nu p_{1/2}$	g.s.	g.s.	745	0.517	0.787	0.917
$\nu f_{5/2}$	240	565	1450	0.763	0.900	0.955
$\nu g_{9/2}$	1410	475	g.s.	0.065	0.110	0.241
$\nu p_{3/2}$	1435	1975	2955	0.937	0.967	0.981
(B)						
$\nu p_{1/2}$	g.s.	g.s.	360	0.514	0.721	0.845
$\nu f_{5/2}$	240	585	1180	0.754	0.879	0.931
$\nu g_{9/2}$	1135	410	g.s.	0.000	0.148	0.271
$\nu p_{3/2}$	975	1410	1980	0.898	0.942	0.960

TABLE II. Main features of ^{67}Co decay obtained with QRPA calculations with two different wave functions and pairing parameter sets [18]: (1) Nilsson wave functions and BCS pairing and (2) folded Yukawa (FY) wave functions and Lipkin-Nogami pairing.

Nilsson/BCS	FY/Lipkin-Nogami	Experiment	Comments
$T_{1/2}=75$ ms	$T_{1/2}=84$ ms	$T_{1/2}=0.425(20)$	Calculated half-life is shorter by factor 5
$E^*=565$ keV	$E^*=585$ keV	$E^*=694$ keV	GT decay dominated by a single spin-flip transition
$I_\beta=99.2\%$	$I_\beta=99.6\%$	$I_\beta=91.5\%$	$(\nu f_{5/2}\rightarrow\pi f_{7/2})$
log ft=3.77	log ft=3.81	log ft=4.7	
$\nu p_{1/2}\rightarrow\pi p_{3/2}$			
$E^*=5.49$ MeV	$E^*=5.59$ MeV		
$I_\beta=0.6\%$	$I_\beta=0.25\%$		All other decays take less than 1%
log ft=4.2	log ft=4.4		
$\nu f_{7/2}\rightarrow\pi f_{7/2}$			
$E^*=5.88$ MeV	$E^*=5.54$ MeV		
$I_\beta=0.2\%$	$I_\beta=0.2\%$		
log ft=4.3	log ft=4.8		

state would require mixing of the ground state with the $f_{5/2}$ single-hole state at 694 keV. Because of the large separation in energy between these two states, such significant mixing would be unexpected. In contrast, the excited 0^+ state at 1770 keV is expected to be dominated by a shift of a pair of neutrons from the $p_{1/2}$ orbital across the subshell gap into the $g_{9/2}$ orbitals. Hence the dominant configuration of a $5/2^-$ level in ^{67}Ni coupled to this 0^+ level would also include significant occupancy for the $g_{9/2}$ neutron orbitals. As the allowed β decay in which this state is populated does not involve change in the occupancy of the $g_{9/2}$ neutron orbitals, the probability of observing this β transition would be directly related to the occupancy of the $g_{9/2}$ orbitals in the ^{67}Co ground state. As we show in Table I, the calculated $g_{9/2}$ occupancy for the ground state of ^{67}Co ranges from 11% up to 15%. Hence the observation of β population with a ft^{-1} of the order of 15% of that of the $5/2^-$ (694 keV) level population rate supports the interpretation of the configuration of the 2155-keV level in ^{67}Ni as having a strong component in which the $f_{5/2}$ single-neutron hole level in ^{67}Ni is coupled to the 0^+ pair excitation state at 1770 keV in ^{68}Ni. Unfortunately, no theoretical predictions exist for the excitation energy of the $\nu g_{9/2}^2 p_{1/2}^{-2} f_{5/2}^{-1}$ configuration.

Let us now compare the level scheme obtained from our β-decay work with spectra from pickup reaction studies [14,16]. In the ^{70}Zn(^{4}He,^{7}Be)^{67}Ni study [16], peaks were observed that indicated excited states at 720, 1020, and 1710 keV, with the first two easily identified with the levels established at 694 and 1003 keV. In the ^{70}Zn(^{14}C,^{17}O)^{67}Ni study [14], peaks indicated levels at 770, 1140, 1970, 2390, and 3680 keV. We note that the energy assigned to the first peak is 10% higher than that now established. If the other values reported in that work are also high by 10%, then the level suggested at 1140 keV can be identified with the $9/2^+$ level at 1003 keV, the 1970 level identified with the level previously observed at 1710 keV [16], the 2390-keV peak would indicated a level near 2150 keV, and the peak at 3680 keV could indicate a peak at 3300 keV. In that case, the level identified at 1710 keV could be the missing single-neutron $p_{3/2}$ hole level or the $p_{1/2}$ ground state coupled to the second 0^+ level in ^{68}Ni that lies at 1770 keV. In both cases this level will not be populated in the β decay of ^{67}Co. The level at 2150 keV could be the level we identify at 2155 keV. The level at 3300 keV could be the deep $f_{7/2}$ neutron hole state below the $N=28$ closed shell.

Finally, let us mention that we confirmed in this measurement the longer half-life of ^{67}Co in comparison to the available theoretical QRPA predictions ([12] and the present work). It is interesting to note, however, that similar calculations provide a good agreement for the case of the neutron-rich Ni isotopes [3]. On the other hand, the older predictions of microscopic and gross theory quoted in [22] give much longer half-lives of 1.9 and 3.7 s, respectively.

IV. CONCLUSION

We observed two new branches of the ^{67}Co β decay to 1007- and 2155-keV excited states of ^{67}Ni. The existence of these decay modes seems to indicate a significant admixture of $\pi f_{7/2}\nu g_{9/2}^2 p_{1/2}^{-2}$ configuration to the $\pi f_{7/2}$ ground state of ^{67}Co. This conclusion is in agreement with the calculated occupancy of $\nu g_{9/2}$ orbitals for the ground state of ^{67}Co.

The measured half-life time disagrees with all available theoretical calculations ([12,22] and the present work). This contradiction between experimental half-life values and the different theoretical calculations seems to be quite common for the nuclei in this region [23]. This raises new demands for further theoretical efforts, since half-lifes of neutron-rich isotopes in the Fe region are important parameters for nucleosynthesis r-process calculations.

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