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Beta-decay of ^{71}Co and ^{73}Co

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Abstract. A decay spectroscopy study of the neutron-rich cobalt isotopes has been performed using fragmentation of a ^{86}Kr^{36+} beam and the new LISE2000 spectrometer at GANIL. For ^{71}Co and ^{73}Co, the β-delayed γ radiation has been observed for the first time, and the half-lives were found to be 79(5) ms and 41(4) ms, respectively. Features of the decay are discussed qualitatively in terms of nuclear models.

PACS. 25.70.Mn Projectile and target fragmentation – 21.10.Tg Lifetimes – 23.20.Lv γ transitions and level energies – 27.50.+e $59 \leq A \leq 89$

The structure of neutron-rich nuclei has attracted growing interest with the development of modern techniques enabling access to the exotic regions of the nuclides chart. According to theoretical studies, large neutron excess in nuclear systems can affect the nucleon-nucleon interaction and result in a rearrangement of traditional shell gaps and magic numbers [1–4].

To verify these predictions beyond the neutron-rich $0p$ and $(1s, 0d)$ nuclei, experiments have been performed close to the $N = 40$ and $N = 50$ neutron shells. The medium-mass neutron-rich nuclei around $Z = 28$ have been treated as a test case for the evolution of the nuclear structure above $N = 40$ [5–11]. One way to obtain information on nuclear structure is the study of microsecond isomers. Such isomers have been identified and studied in ^{69,70}Ni [7] and ^{76}Ni [12]. However, for the intermediate nickel isotopes $^{71-75}$Ni, no evidence of isomerism has been found (although this may be due to shorter half-lives that are beyond the range of sensitivity of the method). On the other hand, a search for γ transitions in ^{70}Ni and ^{72}Ni following the β-decay of ^{70}Co and ^{72}Co has been successful [13]. This has encouraged the search for γ-rays in the β-decay of ^{71}Co and ^{73}Co. These two odd-A cobalt isotopes have been identified in earlier experiments using the fragment separator FRS at GSI. The isotope ^{71}Co was found among the fragmentation products of a 500 MeV/u ^{86}Kr beam [14]. In another experiment [15], the spatial and time correlation between fragments and the subsequent β-particles were recorded resulting in a half-life for ^{71}Co of 0.21(4) s. We note, however, that in a recent experiment focused on the β-decay of neutron-rich $_{21}$Sc-$_{27}$Co produced by the fragmentation reaction of a ^{76}Ge^{30+} beam, a different half-life value of 97(2) ms was reported for ^{71}Co [16]. The isotope ^{73}Co was identified for the first time following the projectile fission of a 750 MeV/u ^{238}U

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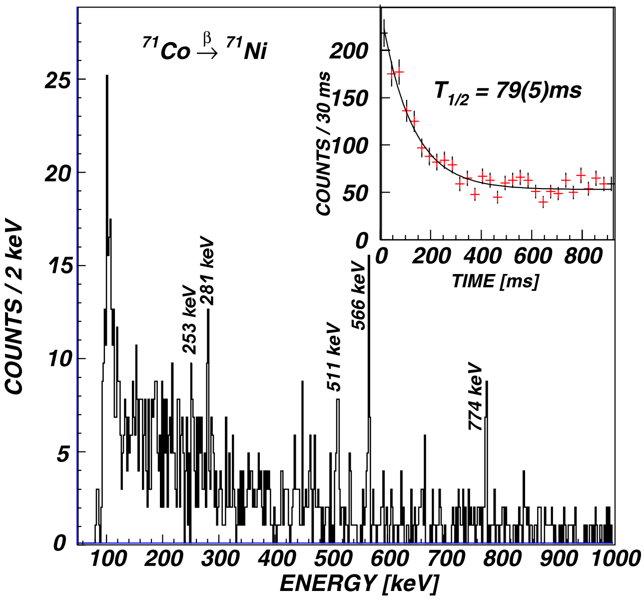

Fig. 1. The β-delayed γ-rays of ^{71}Co occurring up to 400 ms after the implantation of the ion. In the inset, the decay pattern of the β-γ activity is shown. A weak 511 keV line is consistent with the presence of a large background of long-lived β^+ emitters implanted at LISE2000 final focus during previous experiments, and does not belong to the ^{71}Co decay.

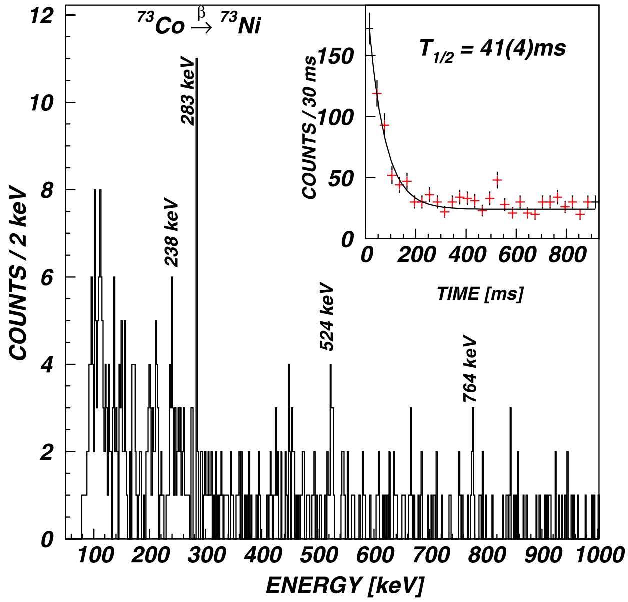

Fig. 2. The β-delayed γ-rays from ^{73}Co occurring up to 200 ms after implantation of the nucleus. In the inset, the decay pattern of the β-γ activity is shown.

beam [17] but no half-life value could be determined. In none of these experiments γ-ray detection was performed.

The experiment discussed in this article was performed at GANIL and was focused on the β-decay of neutron-rich nuclides close to ^{74}Ni produced by the fragmentation of a 60 MeV/u ^{86}Kr beam. The primary beam, in a charge state $q = 36^+$ with a mean intensity of 2880 enA, hit a rotating $^{\text{nat}}$Ta target. The LISE2000 spectrometer [18] was used to select the reaction products. A stack of four silicon detectors was placed at the implantation point. Selected reaction products were passing through the first two detectors and finally were stopped in the third one —a double-sided silicon-strip detector DSSD with two sets of 16 strips oriented perpendicularly. For the individual reaction products, the energy deposited in these three detectors together with the measured time-of-flight and $B\rho$ values were used to assign the mass A, the atomic number Z, and the ionic charge state q [19–21]. During the whole measurement, lasting about 100 hours, approximately 200000 heavy ions were implanted into the DSSD detector giving a rate of 0.03 ions 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 silicon-strip detector allowed the recording of ion–β-particle correlations. The average rate of the β-particles correlated with the γ-rays was 20 per second. The detection efficiency for the β-particles, determined from the measurement of the ^{66}Co activity where branching ratios are known [22], was found to be about 20%. The background β events were mainly coming from the decay of long-lived nuclei implanted in the same strips as the selected ions. The fourth Si(Li) detector acted as a veto counter for ions and β-particles not stopped in the silicon-strip detector. The silicon telescope was surrounded by four clover-type EXOGAM germanium detectors. The total photopeak efficiency of this array, measured with standard calibration sources, was found to be 6% at 1.3 MeV and 23% at the maximum around 120 keV. A full description of the experimental set-up is reported in ref. [13]. In course of the data acquisition, 5150 ions of ^{71}Co and 1352 ions of ^{73}Co were implanted into the strip detector.

The spectrum of γ-rays coincident with β events spatially correlated with the ^{71}Co implants is shown in fig. 1. The spectrum reveals γ lines at 253, 281, 566, and 774 keV. A similar spectrum shown in fig. 2 obtained for ^{73}Co shows γ lines at 238, 283, 524, and 764 keV. Relative intensities of γ transitions are given in table 1 and table 2. The half-lives of β-delayed γ-rays from ^{71}Co and ^{73}Co have been determined by the least-squares fitting procedure. For each case, the decay time spectrum (see insets in fig. 1 and fig. 2) was obtained by recording all β-γ events coincident within 10 μs, which occurred during a period of 1 s after the implantation of the selected ion. During this period, not only the decay of the particular ion, but also of its daughter and granddaughter, could in principle be recorded. The half-lives of ^{71}Ni and ^{73}Ni, the daughters of ^{71}Co and ^{73}Co, are 1.86 s and 0.9 s [23], respectively, and were taken into account in the $T_{1/2}$ calculation. The granddaughter activities of ^{71}Co and ^{73}Co have longer half-lives (19.5 s and 3.9 s, respectively [24]) and were neglected. Finally, the half-lives of ^{71}Co and ^{73}Co were determined to be $T_{1/2} = 79(5)$ ms and $T_{1/2} = 41(4)$ ms, respectively.

The half-life of ^{71}Co appears to be three times shorter than the value obtained by Ameil *et al.* [15]. We note,

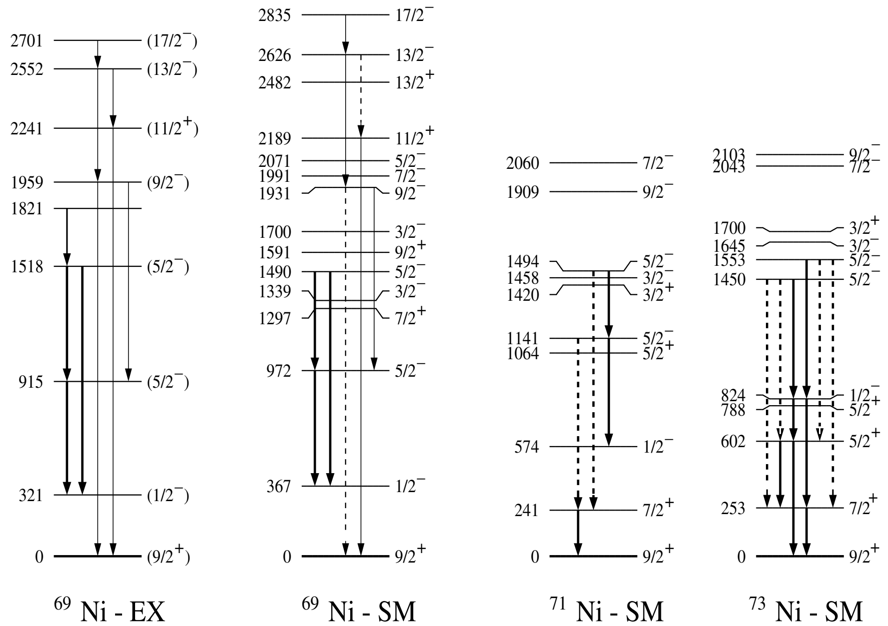

Fig. 3. Experimental and SM γ-decay schemes for ^{69}Ni and SM predictions for the γ-decay of $5/2^-$ β-decay daughter states in ^{71,73}Ni. In the ^{69}Ni experimental decay scheme the thick lines indicate transitions observed in β-decay, while those following direct fragmentation and μs isomer decay are shown by thin lines. In the schemes predicted by the SM the dashed lines indicate $E1$ transitions.

Table 1. Energies and relative intensities of β-delayed γ lines of ^{71}Co.

E_γ (keV)	Intensity (relative)
774(2)	85(20)%
566(1)	100%
281(2)	40(30)%
253(3)	54(10)%

Table 2. Energies and relative intensities of β-delayed γ lines of ^{73}Co.

E_γ (keV)	Intensity (relative)
764(2)	60(40)%
524(1)	100%
283(1)	57(30)%
238(2)	35(40)%

however, that a similar disagreement between values reported in ref. [15] and alternative measurements was found before [25,26]. For example, the half-life of ^{59}V measured by Sorlin *et al.* [26] is smaller by a factor of almost two than that determined by Ameil *et al.* [15]. For the case of ^{64}Mn, Hannawald *et al.* [25] reported the half-life value which is in a good agreement with the earlier measurement of Sorlin *et al.* [27] but is significantly smaller than the result given in ref. [15]. These findings may indicate systematic errors in the results reported in ref. [15].

In the following we discuss our results in the frame of various nuclear models. We include also the less exotic ^{67}Co and ^{69}Co isotopes for which some elements of the decay scheme have already been established [10,28,29]. First, we assume a spherical shape for all nuclei of concern and we consider $^{56}_{28}\mathrm{Ni}_{28}$ as a core. The ground state of the odd-A parent cobalt nuclei corresponds to a $\pi f^{-1}_{7/2}$ proton hole in the $Z = 28$ shell. The states of the daughter nuclei ^{67,69,71,73}Ni are related to the neutron $\nu g_{9/2}$ particle as well as to the $\nu p^{-1}_{1/2}$ and $\nu f^{-1}_{5/2}$ hole states. To estimate energies of these states, the shell model calculations were performed in the $\nu(p_{3/2}, p_{1/2}, f_{5/2}, g_{9/2})$ model space. A new interaction fitted to states in $A = 57$–72 Ni isotopes was recently derived [30] and used in the present work. The level scheme of low-lying low-spin states resulting from this approach are shown in fig. 3 for $^{69-73}$Ni and compared to the experimental data in the well-studied ^{69}Ni. The dominating γ-decay pattern of the β-decay daughter states as predicted by theory is shown, too. Effective charge of 1.0 e and g-factor $g_s^{\mathrm{eff}} = 0.7 g_s^{\mathrm{free}}$ were used to calculate $E2$, $E3$, $M1$ and $M2$ transition strenghts in the neutron valence space. For the $E1$ transition a common value of 10^{-5} W.u. was assumed as estimated from the $E1/E2$ branching ratios in the γ-decay of the $(13/2^-)$ and $(9/2^-)$ states in ^{69}Ni adopting the shell model $E2$ strengths. The agreement for ^{69}Ni is excellent for the β-decay daughter states [10,29] and the levels observed directly in fragmentation [7]. This implies that the tentative $13/2^+$ assigment for the $E_x = 2241$ keV state is changed to $(11/2^+)$, which fits with the experimental evidence [7]. The 1821 keV level in ^{69}Ni from ^{69}Co β-decay, reported by W. Mueller et al. [29], was assigned to the $7/2^-$ state

Table 3. SM calculations compared with the experimental values (EXP) for the level energies (in keV) in odd-A nickel isotopes.

	STATE					
	$9/2^+$		$1/2^-$		$5/2^-$	
Isotopes	SM	EXP	SM	EXP	SM	EXP
^{67}Ni	931	1007	0	0	650	694
^{69}Ni	0	0	367	321	972	915
^{71}Ni	0	0	574	~ 475	1141	~ 1040
^{73}Ni	0	0	824	–	1450	≥ 1288

orginating from the coupling of an $f_{5/2}$ neutron hole to the 2_2^+ proton core excitation of ^{70}Ni. This configuration is outside of the considered SM model space and therefore not taken into account.

In view of the poor statistics for the exotic ^{71,73}Ni daughters, a level scheme could not be constructed from γ-γ coincidences. The theoretical γ-decay pattern, however, is consistent with the observed γ-rays listed in table 1 and table 2. For ^{71}Ni this implies tentatively assigned excited states at 253/281 keV ($7/2^+$), 461/489 keV ($1/2^-$), 1027/1055 keV ($5/2_1^-$) and 1308 keV ($5/2_2^-$). The ambiguity is due to the low-energy γ-rays, which are close in energy, and the large uncertainties in the relative intensities. It is interesting to note that the $1/2^-$ β-decaying spin-trap in ^{69}Ni apparently ceases to exist in ^{71,73}Ni. Nevertheless, the slow $1/2^- \to 7/2^+$ $E3$ transition in ^{71}Ni, even if enhanced to about 10 W.u. would correspond to a partial half-life that exceeds the observational limit of 10 μs in the present experiment. A weak γ-decay branch cannot be excluded.

In ^{73}Ni due to the low-lying $5/2^+$ state enabling $E1$ branchings, that are highly unpredictable, and due to possible nonobservation of γ-rays beyond 1 MeV for efficiency reason (see fig. 3), the situation is less obvious. The possible $M2$ and $E3$ decay of the $1/2^-$ state would result in a 2.7 μs half-life as calculated in the shell model approach. This is well in the observational time range, but on the other hand, a search for isomers in this nucleus [12] yielded a negative result. Therefore no estimate can be made for the position of the $1/2^-$ state, whereas a limit $E_x \geq 1288$ keV can be given for the $5/2^-$ level. In table 3 the experimentally known or estimated values for level energies are compared to the shell model results.

Although our γ-ray data are not complete enough for the construction of decay schemes for ^{71}Co and ^{73}Co, the half-life values, combined with model considerations shed some light on the Gamow-Teller (GT) decay of these isotopes. The $^A\text{Co} \to {}^A\text{Ni}$ beta-decay is expected here to feed mainly the $5/2^-$ state in the nickel daughter via a Gamow-Teller transition. In the extreme single-particle shell model (ESPSM) this approximation would be a $\pi f_{7/2}^{-1} \otimes^{A+1}\text{Ni} \to \nu f_{5/2}^{-1} \otimes {}^{A+1}\text{Ni}$ transition with the strength given by $B(GT) = 12/7$. This strength can be converted to the half-life. Decay energies have been taken from the Nubase evaluation [31] for the first three cobalt isotopes and from a theoretical estimate by Aboussir *et al.* [32] for ^{73}Co. The excitation energies of the $5/2^-$ states in the daughter nickel nuclei we have taken from the shell model (SM) calculation, given in table 3. Finally, the obtained half-lives for ^{67,69,71}Co, and ^{73}Co are an order of magnitude shorter than the experimental ones. All these values are given in table 4. The discrepancy would be even more pronounced if other possible transitions were included. These are especially Gamow-Teller transitions related to the transformation of a neutron from an orbital other than $\nu f_{5/2}$. They lead to three-particle configurations with spin and parity I^π equal to $5/2^-$, $7/2^-$ or $9/2^-$.

Table 4. Experimental and theoretical half-lives (in ms).

Isotopes	^{67}Co	^{69}Co	^{71}Co	^{73}Co
$T_{1/2}$(exp)	425(20)	220(20)	79(5)	41(4)
$T_{1/2}$(ESPSM)	34	21	12	9
$T_{1/2}$(Möller)	105	77	39	26

To get a better agreement with experiment, one has to take into account nuclear-structure effects which result in a mixing of the simple shell model configurations and in a shift of the transition strength towards the GT resonance. Such calculations were performed for a large number of nuclides by Möller *et al.* Ground-state masses and deformations were studied using the finite-range droplet model and folded Yukawa potential [33]. From differences in the calculated masses, predictions for the decay energies were obtained. In the next step, a quasi-particle random phase approximation with single-particle levels and wave functions corresponding to the ground-state shape was applied [34] to predict decay half-lives. Predictions for the odd-A neutron-rich cobalt isotopes are compared to the experimental data in table 4. Clearly, the agreement between model prediction and the experiment is better here than in the case of the ESPSM estimate, and improves with increasing mass number A. The calculations done by Möller *et al.* indicate some small deformation of the considered cobalt and nickel nuclei. For the ground states of ^{71}Ni and ^{73}Ni, the β_2 deformation is predicted to be 0.045 and 0.053, respectively (as well as small β_4 and β_6 deformation values). As a consequence of this deformation, instead of $I^\pi = 9/2^+$ (implied by the assumption of a spherical shape), the predicted assignments are $3/2^+$ and $5/2^+$, respectively.

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