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Precision mass measurements of $^{67}$Fe and $^{69,70}$Co: Nuclear structure toward $N = 40$ and impact on r-process reaction rates

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Accurate mass measurements of neutron-rich iron and cobalt isotopes $^{67}$Fe and $^{69,70}$Co have been realized with the JYFLTRAP double Penning-trap mass spectrometer. With novel ion-manipulation techniques, the masses of the $^{69,70}$Co ground states and the $1/2^-$ isomer in $^{69}$Co have been extracted for the first time. The measurements remove ambiguities in the previous mass values and yield a smoother trend on the mass surface, extending it beyond $N = 40$. The moderate $N = 40$ subshell gap has been found to weaken below $^{68}$Ni, a region known for shape coexistence and increased collectivity. The excitation energy for the $1/2^-$ intruder state in $^{69}$Co has been determined for the first time and is compared to large-scale shell-model calculations. The new mass values also reduce significantly mass-related uncertainties for the astrophysical rapid neutron-capture process calculations.

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Nuclear mass is an intrinsic property of atomic nuclei. It provides a way to determine nuclear binding energy, which holds the nucleons together and reflects subtle changes in the inner structure of nuclei (see, e.g., Ref. [1]). As such, binding energies are used to test predictions of the nuclear shell model [2], such as evolution and magnitude of shell closures at magic neutron (N) and/or proton (Z) numbers (see, e.g., Refs. [3–6]). Nucleons can also arrange themselves to form long-living excited states known as isomers. The binding energies of isomers, i.e., their excitation energies, can provide relevant data for nuclear structure and shape coexistence as well. Resolving isomers from the ground states (g.s.) is essential not only for studying nuclear structure far from stability, but also accurate mass values are the main nuclear inputs for the rapid neutron-capture process (r process) [7–9] which produces around half of the elements heavier than iron. Sensitivity studies [10] have shown that the neutron-capture rates $^{67}$Fe($n,\gamma$) $^{68}$Fe and $^{68}$Co($n,\gamma$) $^{69}$Co have a particularly strong impact on the calculated abundances in the weak r process, which produces lighter r-process elements most likely at several astrophysical sites [11–16]. These rates, and, in particular, their inverse photodissociation rates depend sensitively on the reaction Q value, i.e., on nuclear masses.

In this Rapid Communication, we report precision mass measurements of neutron-rich iron (Z = 26) and cobalt (Z = 27) isotopes. The studied nuclei lie below $^{68}$Ni (Z = 28, N = 40), which exhibits typical doubly magic characteristics: The first 2$^+$ state has a high excitation energy of 2033 keV [17] and a low reduced transition probability of $B(E2;0^+_1 \rightarrow 2^+_1) = 260(50) e^2fm^4$ [18,19]. The observed values, however, have not been interpreted as evidence for a strong N = 40 closure [20,21]. So far, precision mass measurements on nickel, copper, and gallium isotopes have indicated only a localized weak subshell closure at N = 40 [22,23]. Below nickel, cobalt and iron isotopes up to $^{69}$Co [24,25] and $^{66}$Fe [24,26] have been studied at the LEBIT Penning trap, but the overall trend after N = 40 has remained unclear, partly due to long-living isomers.

The N = 40 region is known for shape coexistence [27]. Several low-lying 0$^+$ states with different shapes have been observed in $^{68}$Ni [28–32] and $^{70}$Ni [32–34]. These states and many isomers in the region stem from particle- (p) or hole (h) excitations across the Z = 28 and/or N = 40 shell closures. The presence of neutrons in the g9/2 orbital makes proton excitations more likely due to the tensor force which decreases the gap between the 1f5/2 and the 1g9/2 proton orbitals [35–37]. These so-called intruder states can even become the ground state when strong quadrupole correlations drive them lower in energy, and an “island of inversion” can occur [38].
Shape coexistence and isomeric (isom.) states have been observed in neutron-rich cobalt isotopes [39–41]. The (7/2−) ground state in 67Co has been described as a proton hole coupled to the spherical 68Ni ground state [41] and the (1/2+) isomeric state at 491.6(10) keV with a half-life of 496(33) ms [39] as a prolute [321]1/2+ proton intruder state where one proton from the f7/2 shell has been excited across Z = 28 [39]. Two long-living states have also been observed in 69Co [42], but the energy of the deformed 1/2− state has remained unknown. It has been estimated to be less than 467 keV based on the unobserved 1/2− → 7/2− M3 transition [42].

The shorter-living (7/2−) state in 69Co (T1/2 = 180(20) ms [42]) strongly feeds (5/2−) states in 69Ni and has been observed in several studies [42–46] whereas only Ref. [42] reports on a longer-living 750(250)-ms state, based on a fit to the total decay curve of 69Fe. Further evidence for the existence of two long-living states are the γ transitions at 1128, 1319, 1343, 1545, and 1642 keV, which were unplaced in Ref. [44] but found to be much more populated via β decay of 69Fe (1/2−) than via prompt 69Co production in Ref. [42]. Therefore, the longer-living state is likely 1/2−, similar to the proton-intruder states at 491.6(10) keV in 67Co [39] and at 1095.0 keV in 65Co [40]. In this Rapid Communication, we employ Penning-trap mass spectrometry to determine the location of the (1/2−) state beyond the N = 40 subshell closure.

In 70Co, the ground state has been predicted to be the shorter-living high-spin state with spin and parity (6−, 7−) and T1/2 = 112(7) ms, studied in many fragmentation experiments [33,47–49]. Recently, a β-decay study of 70Fe [50] and Monte Carlo shell-model calculations based on the A3DA Hamiltonian [51] suggest the ground state of 70Co to be a (1+, 2+) state with T1/2 = 508(7) ms. The long half-life is explained by the stabilizing effect of the type-II shell evolution [37]. The minimum of the potential-energy surface of 70Co has been assigned to correspond to deformed single-particle orbitals analogous to Nilsson π[321]1/2− and ν[301]1/2− orbitals [50]. The 1/2− isomer in 68Fe has also been interpreted as ν[301]1/2−, however, the isomers in 69Fe [52,53] are too short living (submillisecond) for Penning-trap mass spectrometry.

In this Rapid Communication, we investigated long-living ground and isomeric states in the N = 40 region via Penning-trap mass spectrometry. The neutron-rich iron and cobalt isotopes were produced by 35-MeV protons impinging on a 15-mg/cm2-thick 26Al target at the IGISOL facility [55]. The reaction products were purified by extraction in helium gas, extracted out from the gas cell, transported using a sextupole ion guide [56], and accelerated to 30 keV before mass separation with a dipole magnet. A radio frequency quadrupole (RFQ) cooler and buncher [57] was used to convert the continuous mass separator beam to short ion bunches that are injected into the double Penning-trap mass spectrometer JYFLTRAP [58]. The ions were first purified via the buffer gas cooling technique [59] before the transfer to the precision trap for high-precision mass measurements. The ion’s cyclotron resonance frequency νc = \( \frac{1}{2π} \frac{q}{m} B \), where \( q \) and \( m \) are the charge and mass of the ion, respectively, was measured using the time-of-flight ion cyclotron resonance (TOF-ICR) technique [54,60] (see Fig. 1). The magnetic field strength \( B \) was determined with 85Kr+ ions as a reference. For 69,70Co, quadrupolar excitation times of 50 and 100 ms were employed. The 67Fe data were collected using Ramsey’s method of time-separated oscillatory fields [61–63] with an excitation pattern of 25–50–25 ms (on-off-on). Systematic errors due to temporal fluctuations in the magnetic-field \( σ_B/Vc,ref/Lc,ref = [8.18(19) × 10^{−12}/\text{min}] Δt [64] \) and the mass-dependent uncertainty \( σ_m(r)/r = [2.2(6) × 10^{−10}] Δm [65] \) were quadratically added to the statistical uncertainties.

The results are summarized in Table I. For 69Co, it was not possible to separate the two long-living states from each other using the TOF-ICR technique. Since the half-lives of the two states are significantly different, the composition of the ion bunches was manipulated by changing the waiting time \( t_{\text{wait}} \) from the moment the ion-beam accumulation in the cooler was stopped to the extraction toward JYFLTRAP. The two measurement sets for 69Co had otherwise identical measurement schemes except for \( t_{\text{wait}} = 500 \) ms in the long cycle, which lasted in total 726 ms after the ion-beam production had stopped. There was no waiting time in the short 226-ms cycle. Due to the much longer half-life of the (1/2−) state, it is likely that the measurements using the long cycle. Based on the ratio of the average number of ions in the short- and long-cycle measurements \( R = N_{\text{short}}/N_{\text{long}} = 2.6(4) \), the fraction of the longer-living state in the beam (\( f_l \)) was determined at the moment the production stopped (\( f_l = 33(10)% \)) as well as 226 ms (\( f_l = 49(13)% \)) and 726 ms (\( f_l = 81(9)% \)) after it, assuming the shorter-living state contributes \( f_s = 1 − f_l \) of the beam. The mass-excess values for the longer- and shorter-living states \( (Δ_t),Δ_s \) were determined from the measured mass-excess values \( Δ_\text{meas}(t = 226 \text{ ms}) = −50.296(15) \text{ keV} \) and \( Δ_\text{meas}(t = 726 \text{ ms}) = −50.238(20) \text{ keV} \) using \( Δ_\text{meas}(t) = [1 − f_l(t)]Δ_s + f_l(t)Δ_l \). The obtained mass-excess value for 69Co, −50.383(44) keV agrees well with the most recent Atomic Mass Evaluation (AME16) [67] value based on measurements using the TOF1 spectrometer [68,69], \( Bp- \) TOF method [70,71], and isochronous mass spectrometry [72]. The obtained mass-excess value for the isomer 69Co+, −50.207(36) keV is in perfect agreement with the ground-state value of −50.214(14) keV [25], reported recently from the LEBIT Penning trap, suggesting they have actually measured the isomer.
TABLE I. The half-lives, spins, parities for the ions of interest based on Ref. [66], measured frequency ratios \( r = \nu_{\text{ref}}/\nu \), and mass-excess values \( \Delta \) in comparison with the literature values from Refs. [66,67]. "#" denotes a value based on extrapolations or systematics. Singly charged ions of \(^{84}\text{Kr} \) \(( m = 83.911497729(4) \text{amu} [67] \) were used as a reference for all studied cases.

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>( T_{1/2} ) (ms)</th>
<th>( I^m )</th>
<th>( r )</th>
<th>( \Delta_{\text{JYFL}} ) (keV)</th>
<th>( \Delta_{\text{m}} ) (keV)</th>
<th>Difference (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{67}\text{Fe} )</td>
<td>394(9)</td>
<td>(1/2(^-))</td>
<td>0.797874190(8)</td>
<td>-45709.1(3.8)</td>
<td>-45610(270)</td>
<td>-99(270)</td>
</tr>
<tr>
<td>(^{69}\text{Co} )</td>
<td>180(20)</td>
<td>7/2 #</td>
<td>0.82164914(428)(^a)</td>
<td>-50383(44)</td>
<td>-50280(140)</td>
<td>-103(147)</td>
</tr>
<tr>
<td>(^{69}\text{Co} )</td>
<td>750(250)</td>
<td>1/2 #</td>
<td>0.821651504(291)(^a)</td>
<td>-50207(36)</td>
<td>-49780(240)#</td>
<td>-430(240)#</td>
</tr>
<tr>
<td>(^{70}\text{Co} )</td>
<td>508(7) [50]</td>
<td>(1+, 2(^+)) [50]</td>
<td>0.833615937(21)</td>
<td>-46525(11)</td>
<td>-46430(360)#</td>
<td>-95(360)#</td>
</tr>
</tbody>
</table>

\(^a\)Calculated based on the isomeric fractions \( f_i \) for the longer-living state and the frequency ratios determined from the files using the 226-ms cycle \([ f_i = 49(13)\%, \ r = 0.821650299(36) \] and the 726-ms cycle \([ f_i = 81(9)\%, \ r = 0.821651055(92) \), see the text for details.

\(^b\)Assigned as the ground state in Ref. [50]. Considered as a 3\(^+\) isomer 200(200)# keV above a (6\(^-\), 7\(^-\)) state, \( T_{1/2} = 112(7)\)-ms state in Ref. [66].

We have determined the excitation energy \( E_x = 176(57) \) keV for the longer-living (1/2\(^-\)) state in \(^{69}\text{Co} \) for the first time. The (1/2\(^-\)) state is interpreted as a deformed \( 1p-2h \) proton-intruder state for which the role of neutron excitations across \( N = 40 \) is essential as they model correlation energies to overcome the \( Z = 28 \) shell gap. Shell-model calculations employing the Lenzi-Nowacki-Poves-Sieja interaction with minor modifications in the \( pf-sdg \) space \([73]\) predict that the 1/2\(^-\) intruder state becomes the ground state in \(^{69}\text{Co} \) instead of the spherical 7/2\(^-\) proton-hole state (see Fig. 2). Here, we confirm the proximity of the coexisting deformed intruder and spherical states in \(^{69}\text{Co} \), and the decreasing trend from \( N = 40 \) to \( N = 42 \), similar to the intruder states observed in nickel and copper isotopes (see Fig. 2).

The phase-imaging ion-cyclotron-resonance (PI-ICR) technique \([76]\), recently commissioned at JYFLTRAP \([77]\) was used to determine the composition of the \(^{70}\text{Co} \) beam. Unfortunately, there was no sign of another long-lived state at a statistically significant level. The production rates and determined mass-excess values for \(^{70}\text{Co} \) changed only moderately when the measurement cycle was increased from 232 to 513 ms, supporting that the measured state was the 508(7)-ms (1\(^+\), 2\(^+\)) state [50]. This is consistent with the previous \(^{70}\text{Co} \) experiment [78] employing the same production method where the longer-living low-spin state was favored as well. Using the PI-ICR data, an upper limit for the (6\(^-\), 7\(^-\)) state contribution could be set. This was \( \leqslant 17\% \) for the short-cycle values and \( \leqslant 5\% \) for the long cycles. For the final result, the value determined with the long cycle was adopted.

Our mass-excess value for \(^{70}\text{Co} \) agrees with the extrapolation given in AME16 [67] and is 295(280) keV above the only previous experimental value [70] which has been rejected in AME16 as an anomalous point since it, e.g., introduces a kink at the \( N = 43 \) state on the \( S_{2n} \) values. A much smoother trend is obtained with our new value as shown in Fig. 3 giving further support that the \((1^+, 2^+)\) is the ground state as suggested in Ref. [50]. If we had measured the isomer, then the \( S_{2n} \) value for \(^{70}\text{Co} \) would be larger, introducing a kink at \( N = 43 \). We also noted that using the value from Ref. [25] for \(^{68}\text{Co} \) introduces an anomaly.

![FIG. 2. Experimental level schemes for \(^{67}\text{Co} \) [39,41] and \(^{69}\text{Co} \) in comparison with the shell-model calculations for the spherical (SB) and 1/2\(^-\) intruder (IB) bands in \(^{67}\text{Fe} \), \(^{69}\text{Co} \). The 1/2\(^-\) states in Co (in blue and in red from this Rapid Communication) follow a similar trend as the 2\(^+\) and prolate 0\(^+\) [31,33,34,74] intruder states in Ni (in magenta) and 7/2\(^-\) [75] states in Cu isotopes (in green).](image)

![FIG. 3. Two-neutron separation energies based on experimental values from AME16 [67] (in blue) and including the results from this Rapid Communication (in red). The recent \(^{68}\text{Co} \) measurements at LEBIT [25] (in green) introduce a kink, the same is true if only the result for \(^{69}\text{Co} \) from Ref. [25] is included, indicating that it is likely to belong to the isomer \(^{69}\text{Co} \). For \(^{70}\text{Co} \), AME16 is based on extrapolations (indicated with an open symbol), and our value is for the (1\(^+\), 2\(^+\)) state.](image)
LEBIT (in green) or only $^{68}$Co (in black) results in a kink at $D_n$ around 1 MeV. This is higher than $D_n$ of $^{58}$Fe. Moreover, the decreasing trend in the two-neutron separation energy flattens the trend in the two-neutron parameter decreases. Our measurements bring the $D_{2n}$ values for $^{66}$Fe and $^{67}$Co 100 keV lower than in AME16 [67], but the values are still at about 1 MeV. This is higher than $D_{2n}$ $\approx$ 0.7 MeV observed for the most neutron-rich Cr and Mn isotopes [67,86,87]. Moreover, the decreasing trend in the $D_{2n}$ values seems to stop at $N$ $\approx$ 38 for the Fe and Co chains. Santamaria et al. [84] have observed that the $2^+$ and $4^+$ excitation energies in the Fe isotopic chain decrease until $N$ = 40 after which a plateau is reached. This has been interpreted as an extension of the $N$ = 40 island of inversion toward $N$ = 50 [84] that could lead to a disappearance of the magicity of $N$ = 50 below $^{58}$Ni.

Masses of neutron-rich nuclei close to $N$ = 40 are also relevant for astrophysics. Neutron-capture rates $N_A(\sigma v)$ for $^{66}$Fe($\gamma, n$) $^{65}$Fe and $^{68}$Co($\gamma, n$) $^{69}$Co have been highlighted as among the most influential for the $r$-process calculations with impact factors $F = 15.8$ and $F = 11.6$, respectively, on the abundances when the rates were varied by a factor of 100 [10]. In this Rapid Communication, we determined the mass of $^{65}$Fe (see Table I) with a 70 times higher precision than before. It was found to be around 100 keV lower than the recommended value [67] based on less precise methods [68–71,88–89]. The mass of $^{69}$Co was also found to be around 100 keV lower and three times more precise than in AME16 [67]. The mass values affect the calculated neutron-capture rates, and even more importantly, their inverse photodissociation rates $\lambda_{\gamma,n}$ which depend exponentially on the reaction $Q$ value: $\lambda_{\gamma,n} \propto N_A(\sigma v) \exp[-Q/(kT)]$ for temperature $T$. Figure 5 shows a comparison of photodissociation rates and mass-related uncertainties for $^{68}$Fe($\gamma, n$) $^{67}$Fe and $^{66}$Co($\gamma, n$) $^{65}$Co from this Rapid Communication and from REACLIB V1.0 [90] used for the sensitivity study in Ref. [10]. The new rate calculated with $Q = 5.85(37)$ MeV, determined from the masses of $^{65}$Fe from this Rapid Communication and $^{68}$Fe from AME16 [67], is significantly higher than the rate obtained with REACLIB V1.0, which relies on NON-SMOKER [91,92] neutron-capture rates with $Q = 6.86(82)$ MeV, based on the experimental AME95 value [93] for $^{67}$Fe and the theoretical FRDM1995 value [94] for $^{68}$Fe. At 1.5 GK, the mass-related uncertainties have been reduced by a factor of $\approx$ 30, and the photodissociation rate is around 2500 times higher. The $Q$ value for $^{68}$Co($\gamma, n$) $^{69}$Co, based on our Rapid Communication, for $^{69}$Co and $^{68}$Co from Ref. [67], $Q = 6.52(20)$ MeV is also much lower than the value used in REACLIB V1.0 $Q = 7.29(50)$ MeV [93]. As a result, the photodissociation rate is much higher than before (see Fig. 5). If the isomeric-state mass had been used for $^{69}$Co as obtained in Ref. [25], the rate would be four times higher at 1.5 GK. This highlights the importance of precise knowledge of the masses.

In conclusion, we have performed the first precision mass measurements of $^{67}$Fe and $^{68}$Co. With novel ion-manipulation techniques, we were able to identify the measured states in $^{69,70}$Co and provide accurate mass data relevant for nuclear structure and astrophysics. The position of the $(1/2^{-})$ proton-intruder state in $^{69}$Co was determined for the first time, and the decreasing trend of the $1/2^{-}$ intruder states up to $N$ = 42
was confirmed, in agreement with the large-scale shell-model calculations predicting increased collectivity and close-lying spherical and deformed states for \(^{69}\text{Co}\). No strong calculations predicting increased collectivity and close-lying was confirmed, in agreement with the large-scale shell-model PRECISION MASS MEASUREMENTS OF \(^{67}\text{Fe}\) AND ... PHYSICAL REVIEW C 2020 Research and Innovation Programme Grant Agreement No. 654002 (ENSAR2). A.K. acknowledges support from the Academy of Finland under Grant No. 275389, and D.A.N. and L.C. acknowledge support under Grants No. 284516 and No. 312544. T.E. acknowledges support from the Academy of Finland under Grant No. 295207, and A.d.R. acknowledges support under Grant No. 306980. A.K. and L.C. acknowledge the funding from the European Union’s Horizon 2020 Research and Innovation Programme under Grant Agreement No. 771036 (ERC CoG MAIDEN). A.P. was supported by MICIU (Spain) Grants No. SEV-2016-0597 and No. PGC-2018-94583. We are grateful for the bilateral mobility Grants from the Institut Français in Finland, the Embassy of France in Finland, the French Ministry of Higher Education and Research, and the Finnish Society of Science and Letters. We are grateful for the mobility support from Projet International de Coopération Scientifique Manipulation of Ions in Traps and Ion sourCes for Atomic and Nuclear Spectroscopy (MITICANS). S.G. is grateful for the mobility Grant from the EDPSIME.


