Lifetime measurements in neutron-rich ^{63,65}Co isotopes using the AGATA demonstrator

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Lifetimes of the low-lying $(11/2^-)$ states in ^{63,65}Co have been measured employing the recoil distance doppler shift method (RDDS) with the AGATA γ-ray array and the PRISMA mass spectrometer. These nuclei were populated via a multinucleon transfer reaction by bombarding a ^{238}U target with a beam of ^{64}Ni. The experimental $B(E2)$ reduced transition probabilities for ^{63,65}Co are well reproduced by large-scale shell-model calculations that predict a constant trend of the $B(E2)$ values up to the $N = 40$ ^{67}Co isotope.

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I. INTRODUCTION

In recent years a substantial effort was devoted to the study of the evolution of shell structure in neutron-rich nuclei. These studies were possible thanks to improvements in experimental techniques as well as theoretical advances. Experimentally, the use of state-of-the-art detector arrays combined with high-intensity stable or radioactive beam facilities have boosted the knowledge of such neutron-rich systems. On the other hand, large-scale shell-model calculations have allowed one to describe more and more exotic systems using renormalized interactions from realistic *NN* potentials. The appearance and disappearance of shell closures have their origin in the nature of the nucleus and its study brings an insight into the nuclear force, such as the monopole evolution due to the *NNN* forces [1] and its tensor character [2]. In the last decades, experimental studies have clearly shown that well-established shell closures disappear [3], such as $N = 8$, $N = 20$, $N = 28$ and new ones appear such as $N = 16$ [4] and $N = 32$ [5]. In some cases, as the weak subshell closure at $N = 40$ [6], its effect is local and disappears as soon as a few nucleons are added to or removed from the ^{68}Ni core. In fact, as soon as one takes away two protons from $Z = 28$, i.e., Fe ($Z = 26$) or four protons, i.e., Cr ($Z = 24$) a region of deformation develops due to quadrupole correlations brought by excitations to the $g_{9/2}$ and $d_{5/2}$ [7–9] neutron orbitals. Neutron-rich cobalt isotopes lie in between the spherical shapes found in Ni isotopes, one proton above, and the deformed ones in Fe, one proton below.

While the occurrence of a low-lying $1/2^-$ state in ^{67}Co was interpreted as a manifestation of collectivity [10] with a proton occupying the Nilsson $\frac{1}{2}[321]$ level, the trend followed by the $9/2^-$ and $11/2^-$ states with respect to the 2^+ states in the Ni isotones agrees with a spherical behavior.

In recently works, Co isotopes near $N = 40$ have been thoroughly studied [10–12]. The excitation energy of the $9/2^-$ state on ^{63,65,67}Co follows the same trend of the 2^+ state energies in Ni, suggesting a configuration of a $(\pi f_{7/2})^{-1}$ proton hole coupled to the 2^+ state in Ni [10]. In contrast, the energy systematics of the $3/2^-$ level in odd-mass neutron-rich Co nuclei mimics the behavior of the 2^+ level in the Fe isotopes. Consequently, the $3/2^-$ state might be interpreted as a single $\pi f_{7/2}$ proton coupled to the 2^+ state in Fe [10,11].

Lifetimes for the $9/2^-$ and $3/2^-$ states in ^{63}Co and the $(9/2^-)$ state in ^{65}Co were recently reported [11]. Nevertheless, no obvious conclusions can be derived from the obtained transition probabilities. The $B(E2)$ values reported for the decay of the $9/2^-$ states were deduced from $9/2^- \rightarrow 7/2^-$ transitions, that can certainly entail $E2/M1$ mixing making them difficult to interpret. On the other hand, the measured $B(E2)$ values of the $3/2^- \rightarrow 7/2^-$ transition in Co are far from being correlated with those of the $2^+ \rightarrow 0^+$ in Fe [11].

In this work, the evolution of the collectivity in the nuclei ^{63}Co and ^{65}Co is studied by measuring the lifetimes of the $(11/2^-)$ excited states employing the recoil distance doppler Shift method (RDDS). The deduced $B(E2)$ values will be discussed in the framework of the shell model. The paper is organized as follows. In Sec. II the experimental setup is described. In Sec. III the results are presented, that will be discussed later on in Sec. IV. Conclusions are in Sec. V.

II. EXPERIMENT

The neutron-rich Co isotopes were populated as products of a multinucleon transfer process following the collision of a ^{64}Ni beam with a ^{238}U target. The ^{64}Ni beam, with an energy of 460 MeV, was delivered by the LNL tandem-ALPI accelerator complex. For lifetime measurements, the recoil distance doppler shift (RDDS) method [13] was employed, using a dedicated differential plunger, as described in Refs. [13,14]. The thickness of the uranium target was 1.35 mg/cm^2, evaporated on a 1.2-mg/cm^2 Ta support to accomplish the stretching of the target. A thick 4.13-mg/cm^2 natural Nb foil, used as an energy degrader of the recoiling ejectiles, was positioned after the target. The degrader material and thickness were chosen to decrease the velocity β of the recoiling nuclei by $\sim$18% and to minimize the γ counting rate due to the reactions in the degrader [15].

The plunger was tilted by 50° with respect to the beam axis. To measure lifetimes ranging from 1 to 5 ps, three target-to-degrader distances, 20 μm, 45 μm, and 150 μm were chosen. The effective distances along the optical axis resulted to be of 39 μm, 64 μm, and 171 μm, after accounting for the plunger tilt, the offset from the calibrated zero, and the degrader thickness. After passing through the Nb degrader, the projectilelike products were identified with the magnetic spectrometer PRISMA [16–18] placed at the grazing angle of 60°.

The γ rays were detected with the AGATA demonstrator, which consisted of four triple clusters [14,19] placed at 18 cm from the target, covering continuously the angles from 130° to 180° with respect to the optical axis. The data were processed using the algorithms implemented in the online and offline analysis, namely the grid search algorithm [19,20] for the pulse shape analysis (PSA) and the MGT code [19,20] for the tracking. Gamma rays were Doppler corrected on an event-by-event basis by using the velocity vector measured by PRISMA and the position of the first γ interaction in AGATA. The beam intensity was 1.5 pnA on average, giving 80 kHz in singles counting rate per crystal, which resulted to be sustainable by the AGATA detectors with no sizable influence on the energy resolution.

Lifetimes in the nuclei of interest were extracted by measuring the intensity of both the shifted and the un-shifted γ rays emitted before and after the degrader, respectively. The velocity of the isotopes recoiling after the degrader was measured directly by PRISMA, whereas the velocity before the degrader was deduced from the value measured after the degrader, the Doppler shift, and the average angle of γ-ray emission [21]. Typical velocities of $\beta = 0.10$ and $\beta = 0.08$ were measured before and after the degrader, respectively. A γ ray, depending on the lifetime of the state it de-excites, can be emitted before or after the degrader and consequently experiences two different Doppler shifts, originating two components in the γ spectrum, separated by $\sim$15 keV for 1-MeV γ rays. Examples of such spectra are given in Figs. 1 and 2 for the two nuclei ^{63}Co and ^{65}Co, respectively.

The decay curve for a γ transition de-exciting a state that only presents direct feeding in the reaction is obtained with the ratio $R(t)$, defined as

$$R(t) = \frac{I_{\rm after}}{I_{\rm after} + I_{\rm before}}, \quad (1)$$

where $I_{\rm after}$ and $I_{\rm before}$ are the intensities of the two components, as a function of the flight time from the target to the degrader. This flight time is derived from the velocity before the degrader, and the effective averaged distance, from the middle of the target to the end of the degrader. In this case, the lifetime is obtained directly as described in Ref. [22].

III. RESULTS

Based on expectations from systematics and on shell-model calculations, the lifetimes of the low-lying states in ^{63}Co and ^{65}Co were expected in the ps range. For this reason the three target-to-degrader distances, i.e., 39, 64, and 171 μm were chosen. The statistics accumulated in this experiment for the two nuclei of interest, for each distance, was sufficient to observe two separate components for γ rays depopulating the $11/2^-$ state in ^{63}Co and the $(11/2^-)$ and $(13/2^-)$ states in ^{65}Co (see Figs. 1 and 2). The resulting lifetimes will be presented in the following.

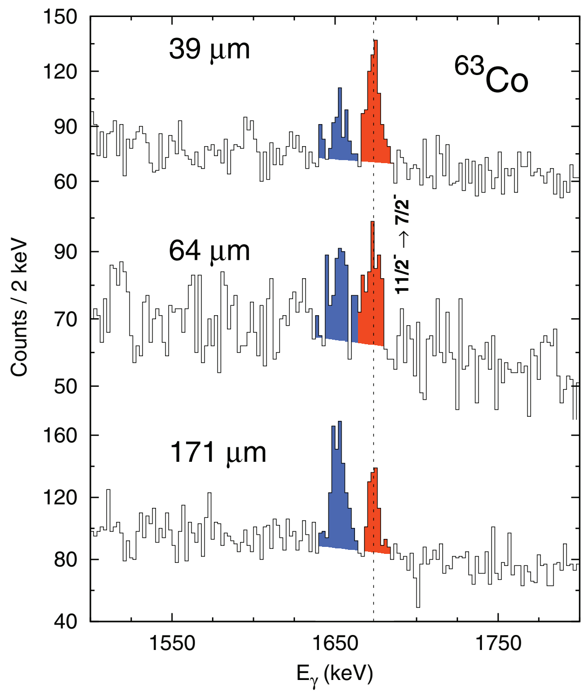

FIG. 1. (Color online) Doppler-corrected γ-ray spectra for ^{63}Co showing both before (blue) and after-degrader (red), background subtracted, components of the γ-ray transition $11/2^- \rightarrow 7/2^-$ at 1674 keV for different target to degrader distances. Peaks after degrader are indicated by a dashed line.

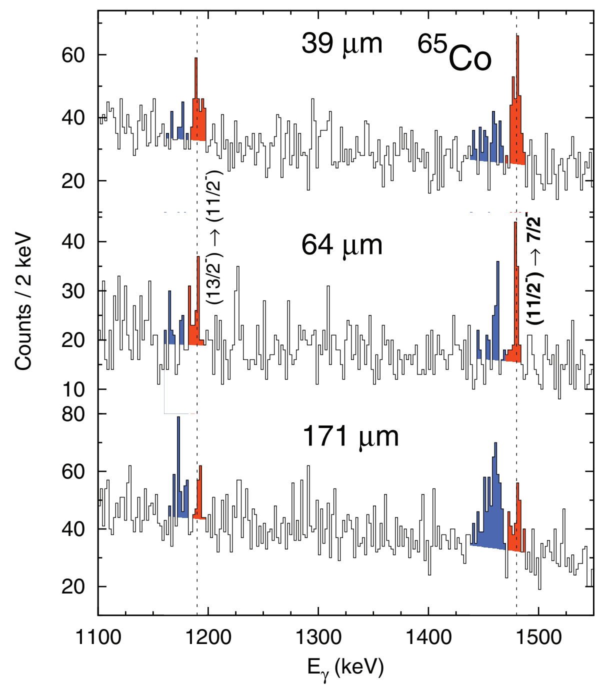

FIG. 2. (Color online) As Fig. 1, Doppler-corrected γ-ray spectra for ^{65}Co showing both before (blue) and after-degrader (red), background subtracted, components of the γ-ray transition $(11/2^-) \rightarrow 7/2^-$ at 1480 keV and $(13/2^-) \rightarrow (11/2^-)$ at 1190 keV for different target to degrader distances. Peaks after degrader for both transitions are indicated by dashed lines.

A. Lifetime of the $11/2^-$ state at 1674 keV in ^{63}Co

In a recent experiment, the first lifetimes of low-lying states in ^{63}Co were measured [11] by using a multinucleon transfer reaction in inverse kinematics and a plunger setup similar to the one used in this work. Lifetimes of 15.4(18) ps and 0.9(4) ps were reported for the $3/2^-$ at 995 keV and the $(9/2^-)$ state at 1383 keV, respectively [11]. The short lifetime for the 1383-keV state was extracted after defining a low- excitation-energy gate [total kinetic energy loss (TKEL) measured in the spectrometer], which preserved the direct feeding of this state while suppressing the feeding from above.

In the present experiment the lifetime of the $3/2^-$ at 995 keV could not be measured because we optimized the setup distances for lifetimes of ~1-ps range, whereas the lifetime of this state is around 15 ps. The lifetime of the $9/2^-$ state at 1383 keV was not measured either. This is due to the presence of a non-negligible feeding from states above, that was not possible to suppress in our case because of the low statistics, via a gate on the TKEL measured by PRISMA [23], as performed in Ref. [11].

On the contrary, the lifetime of the $11/2^-$ state at 1674 keV was measured. Figure 1 shows the Doppler-corrected γ-ray spectra for ^{63}Co for the three different plunger distances, showing the two components of the 1674-keV transition. To be sure that possible feeding from above does not influence the lifetime of the state, we have checked if the $R(t)$ values for the 1674-keV transition presents any dependence from cuts in excitation energy when gating on the TKEL measured by PRISMA. No difference is observed in the ratio $R(t)$, and therefore the feeding from excited states above is considered negligible. This conclusion is corroborated by the fact that the known transitions feeding the $11/2^-$ state at 1674 keV [24] are not present in the spectra. The full statistics (i.e., without cuts in TKEL) was used to fit the decay curve shown in Fig. 3(a). This decay curve was fitted to an exponential function plus a constant, which gives a half-live of $T_{1/2} = 0.7(2)$ ps for the $11/2^-$ state at 1674 keV that results in a $B(E2;11/2^- \rightarrow 7/2^-) = 53(13)\ e^2\text{fm}^4$, when taking the branching ratio for the transitions depopulating the $11/2^-$ state from Ref. [12]. The already known half-life of the first 2^+ state in ^{66}Ni ($T_{1/2} = 0.8(2)$ ps, reported in Ref. [25]) was used to validate this method. A value of $T_{1/2} = 0.78(13)$ ps is obtained in this work, which is in prefect agreement with the literature value. Table I reports the $T_{1/2}$ and $B(E2;11/2^- \rightarrow 7/2^-)$ values measured in this work.

B. Lifetimes of the $(11/2^-)$ and $(13/2^-)$ states at 1480 and 2670 keV in ^{65}Co

Also in ^{65}Co a lifetime measurement was performed recently with a reported upper limit of 17.3 ps for the $(11/2^-)$ state at 1480 keV [11]. The authors claim that the limit is from the presence of a long-lived state in the feeding path above it, which did not allow one to extract the true lifetime of the state. In a subsequent extensive work on Co nuclei populated in multinucleon transfer reactions [12], the spin assignment of the low-lying $(9/2^-)$ and $(11/2^-)$ states was reversed. Therefore,

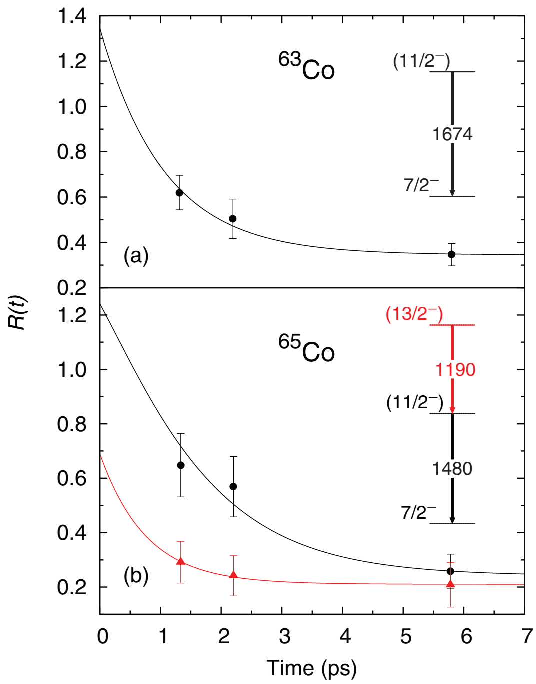

FIG. 3. (Color online) Experimental $R(t)$ values as a function of time and fitted decay curves for the $(11/2^-) \rightarrow 7/2^-$ transitions (in black circles) in both (a) ^{63}Co at 1674 keV and (b) ^{65}Co at 1480 keV. The decay curve for the 1480-keV transition is fitted taking into account the feeding from the excited state $(13/2^-)$ at 2670 keV, decaying with a γ-transition energy of 1190 keV (red curve).

the more recent spin assignment is adopted in this work, leading to a stretched $E2$ character for the 1480-keV transition depopulating the $(11/2^-)$ to the $7/2^-$ ground state. The two components (before and after the degrader) of the 1480-keV transition, whose intensities change as a function of the target-degrader distances are clearly seen in the spectra of Fig. 2. Also the 1190-keV line feeding the $(11/2^-)$ state is observed. This feeding from above, with its lifetime, influences the lifetime of the $(11/2^-)$ state and has to be taken into account. From the intensity of the two transitions (1190 and 1480 keV) such feeding results to be 45(3)% of the total population of the $(11/2^-)$ state. The decay curves of both transitions are shown in Fig. 3(b). The lifetimes of the two states $(11/2^-)$ and $(13/2^-)$ of interest are determined by fitting the ratios $R(t) = \frac{I_{\text{after}}}{(I_{\text{after}}+I_{\text{before}})_{1480}}$ as a function of the target-to-degrader distances, where the normalization factor $(I_{\text{after}} + I_{\text{before}})_{1480}$ corresponds to the total intensity of the $(11/2^-) \rightarrow 7/2^-$ transition. The data of the present experiment do not confirm the presence of a long-lived state as previously stated in Ref. [11].

For the stretched $E2$ 1480-keV transition a $B(E2)$ value of 90(40) $e^2\text{fm}^4$ was derived. On the other hand, the 1190-keV transition is most probably of $M1/E2$ character. Nevertheless, if an $E2$ character is assumed, then a $B(E2)$ of 150(20) $e^2\text{fm}^4$ is obtained. Table I reports the $T_{1/2}$ and $B(E2)$ values for the two excited states in ^{65}Co measured in this work.

TABLE I. List of states in ^{63,65}Co from which lifetimes were measured in this work, indicating the spin and parity I^π, energy of the γ-decay E_γ in keV, half-life $T_{1/2}$ in ps and deduced $B(E2,\downarrow)_{\text{exp}}$ in e^2 fm^4.

	I^π	E_γ (keV)	$T_{1/2}$ (ps)	$B(E2\downarrow)_{\text{exp}}$ (e^2 fm^4)
^{63}Co	$11/2^-$	1674	0.7(2)	53(13)[a]
^{65}Co	$(11/2^-)$	1480	0.9(4)	90(40)
	$(13/2^-)$	1190	0.6(4)	22(15)[b]

[a]Value adopting the branching ratio between the 1674- and 290-keV transitions from Ref. [12].
[b]Assuming the theoretical mixing-ratio $\delta^2_{E2/M1} = 0.0877$ obtained from shell-model calculations using the LNPS interaction and adopting the branching ratio between the 1190- and 190-keV γ transitions from Ref. [12].

IV. DISCUSSION

The interpretation of the excited states in Co isotopes and how their energies evolve towards $N = 40$ have been discussed in recent works [10–12]. The low-lying excited states in the odd-Co isotopes are explained as the coupling of the $f_{7/2}$ proton or hole with the first 2^+ excited state in the neighboring even Ni and Fe isotones, respectively. A similar behavior was observed in ^{69,71,73}Cu isotopes, where single-particle and collective states coexist at low excitation energy [30]. The configuration of the first excited $3/2^-$ state in ^{63,65}Co was proposed as a coupling of the $f_{7/2}$ proton to the deformed Fe core [11]. The excitation energy for the $3/2^-$ state decreases with the number of neutrons, following the same trend as the

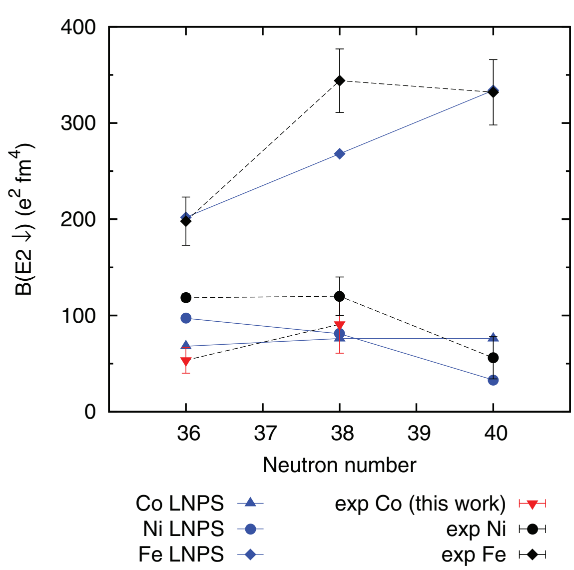

FIG. 4. (Color online) Experimental (dashed black lines) and theoretical (solid blue lines) $B(E2)$ values for the $11/2^- \rightarrow 7/2^-$ transitions in Co isotopes (triangles), $2^+ \rightarrow 0^+$ transitions in Fe (diamonds), and $2^+ \rightarrow 0^+$ transitions in Ni isotopes (circles). Results from this work are shown with red triangles. The effective charges used for the shell-model calculations with the LNPS interaction are 1.31 e, 0.46 e for protons and neutrons, respectively. The experimental values for the Ni and Fe isotopes are taken from Refs. [25–27] and [9,28,29], respectively.

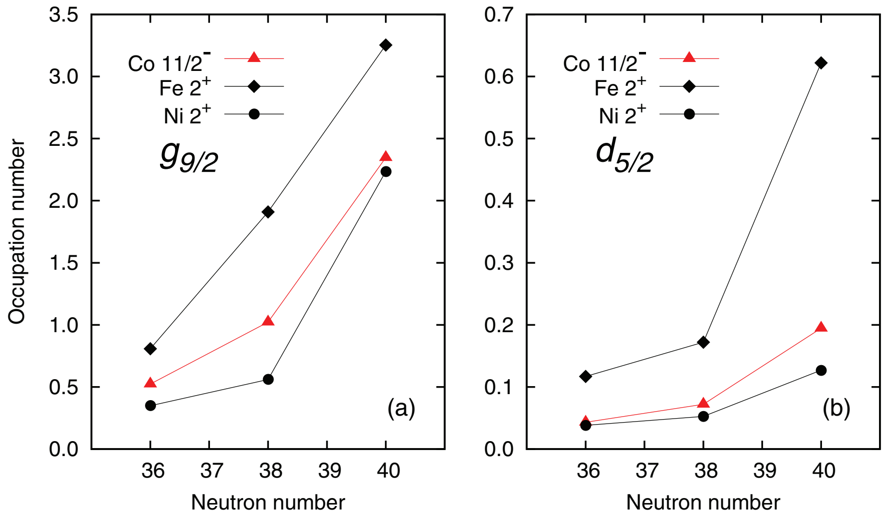

FIG. 5. (Color online) Neutron occupation numbers for the (a) $g_{9/2}$ and (b) $d_{5/2}$ orbitals for the $11/2^-$ states in Co isotopes, and the 2^+ states in Ni and Fe isotopes.

2^+ excitation energy of the Fe isotones and therefore pointing to its deformed character. Furthermore, the low-lying $(1/2^-)$ states in ^{65,67}Co, that arise from proton intruder configurations, present a lowering in the excitation energy when going towards $N = 40$, indicating the development of deformation [10]. On the other hand, the excitation energy of the $11/2^-$ state follows that of the 2^+ state in the even Ni isotopes, being interpreted as the result of $\pi(f_{7/2})^{-1} \otimes 2^+$Ni coupling [12].

Figure 4 shows the experimental $B(E2; (11/2^-) \to 7/2^-)$ deduced in this work for ^{63,65}Co (red triangles), together with the corresponding $B(E2; 2^+ \to 0^+)$ for the Ni and Fe isotones. One can notice that the $B(E2)$ values for the Ni $2^+ \to 0^+$ transitions have a minimum at $N = 40$, which is consistent with the presence of a subshell gap [25,26,31], while the systematics of the $B(E2)$ values for the Fe $2^+ \to 0^+$ transitions reveals an increasing collectivity towards $N = 40$. The Fe as well as the Cr neutron-rich isotopes lie in the so-called third island of inversion that was thoroughly discussed in Ref. [8]. The $B(E2)$ values deduced in this work for the $(11/2)^- \to 7/2^-$ transitions in the Co isotopes follow the same trend as their Ni isotones strengthening the interpretation of these states as a $\pi(f_{7/2})^{-1} \otimes 2^+$ Ni configuration. The theoretical $B(E2)$ values were calculated employing the shell-model code ANTOINE [32], and using the LNPS [8] interaction. The model space used was the pf shell for protons and the $0\,f_{5/2}$, $1\,p_{3/2}$, $1\,p_{1/2}$, $0\,g_{9/2}$, and $1\,d_{5/2}$ orbits for neutrons. It was already reported in Ref. [8] that the inclusion of the neutron $1\,d_{5/2}$ orbital is essential to reproduce the large quadrupole collectivity in this mass region. This can be understood in terms of the quasi-SU(3) approximate symmetry as was explained by Zuker *et al.* in Ref. [33]. The theoretical results for the reduced transition probabilities are also shown in Fig. 4. These values have been obtained using an effective charge of $e_\pi = 1.31\,e$ for protons and of $e_\nu = 0.46\,e$ for neutrons. Those effective charges are deduced theoretically in Ref. [34] and are able to reproduce simultaneously the transition probabilities in the fp as well as the sd shell.

Figure 4 shows that the large-scale shell-model calculations describe fairly well the development of collectivity in the Fe isotopes and at the same time the trend of the $B(E2)$ values for the spherical Ni isotopes. For the Fe $B(E2)$ values, a more comprehensive agreement among theory and experiment for masses ranging from $N = 32$ to $N = 42$ can be seen in Ref. [35], where the only discrepancy is found in ^{64}Fe ($N = 38$). This deserves further investigations. For the case of the Co isotopes, the $B(E2)$ transition probabilities for ^{63,65}Co are also well reproduced. Figure 5 shows the neutron occupation numbers of the $g_{9/2}$ and the $d_{5/2}$ orbitals for the $11/2^-$ excited states in ^{63,65}Co and 2^+ states in Ni and Fe, as they result from the above calculations. As discussed before, the inclusion of these orbitals into the valence space leads to an increase of the deformation in Fe isotopes. In fact, it is in those orbitals where the wave function between the spherical Ni and deformed Fe isotopes differ most. The quadrupole correlations together with the monopole shifts of the single-particle energies of these orbitals, give rise to the large $B(E2)$ values in Fe isotopes. In the Co isotopes, the trend of the occupation of both orbitals follows quite closely the Ni isotopes except for the case of $N = 40$, in which the relative increase in the $d_{5/2}$ occupation in ^{67}Co with respect to its isotone ^{68}Ni is reflected in a slightly larger $B(E2)$ value. While the $B(E2)$ values for Fe isotopes increase with N and those of Ni decrease at $N = 40$, the $B(E2)$ values for the Co isotopes show a presumably constant trend. The calculations predict a larger $B(E2)$ value in ^{67}Co than that of ^{68}Ni. Further experimental studies might confirm such theoretical predictions.

V. CONCLUSION

Lifetimes of the low-lying $(11/2^-)$ states in ^{63,65}Co have been measured for the first time. The deduced $B(E2; 11/2^- \to 7/2^-)$ values closely follow the strength value of the $2^+ \to 0^+$ transition in the Ni isotones, indicating that those $11/2^-$ states present a $\pi f_{7/2}^{-1} \otimes 2^+$ Ni configuration. Large-scale shell-model calculations predict accurately the $B(E2)$ strengths in Co isotopes as well as in Fe and Ni isotopes, showing a strong dependence of these values with the occupation of both the $g_{9/2}$ and the $d_{5/2}$ orbitals in the wave function. The $B(E2; 11/2^- \to 7/2^-)$ value predicted for $N = 40$ ^{67}Co is larger than the

$B(E2; 2^+ \rightarrow 0^+)$ of the ^{68}Ni isotone, which could be a first indication of the weakening of the $N = 40$ subshell gap, that already vanishes for the isotone ^{66}Fe. Nevertheless, no such conclusion can be drawn without further experimental data. A high efficiency γ-ray detector like AGATA could help to elucidate the persistence of the $N = 40$ subshell gap in Co isotopes and the evolution of the collectivity beyond.

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