Spectroscopy of neutron-rich Fe isotopes populated in the ^{64}Ni + ^{238}U reaction

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The neutron-rich Fe isotopes from $A = 61$ to 66 were studied through multinucleon transfer reactions by bombarding a ^{238}U target with a 400 MeV ^{64}Ni beam. Unambiguous identification of prompt γ rays belonging to each nucleus was achieved using coincidence relationships with the ions detected in a high-acceptance magnetic spectrometer. The new data extend our knowledge of the level structure of Fe isotopes, which is discussed in terms of the systematics of the region and compared with large-scale shell-model calculations.

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I. INTRODUCTION

Moderately neutron-rich nuclei can be populated, at relatively high-angular momentum, by means of binary reactions such as multinucleon transfer and deep-inelastic collisions using stable beams [1,2]. In recent years, the use of such reactions combined with modern γ arrays has increased substantially the amount of information available on the structure of previously inaccessible nuclei far from stability [3]. One of the first and best examples is the neutron-rich nucleus ^{68}Ni, whose study with the GASP array in a thick-target experiment has revealed its doubly magic character [4]. A large number of nuclei are populated in multinucleon transfer and deep-inelastic reactions and their identification, in thick-target experiments, is based on the cross-coincidence technique, i.e., a γ ray is assigned to a specific nucleus by gating on γ rays of the known complementary fragment. The limitations of this method (weak reactions channels, both binary fragments unknown) can be overcome by combining an efficient γ-ray array with a large-acceptance magnetic spectrometer for heavy-ion detection. This has been recently achieved at the Legnaro National Laboratories (LNL) by coupling the Clover detectors of Euroball (CLARA) [5] to the PRISMA magnetic spectrometer [6], which, with its high resolving power, gives the full identification of mass and Z for the reaction products. In particular, by bombarding ^{208}Pb or ^{238}U targets with the most neutron-rich projectiles available in nature it is possible to populate excited states of exotic neutron-rich nuclei allowing us to explore the evolution of the known shell closures for large N/Z ratios and to characterize new regions of nuclear deformation.

A neutron-rich region where new magic numbers may appear and the well-established ones may disappear is the one bounded by $N = 28$–50 and $Z = 20$–28. As a matter of fact, it was shown that a new subshell closure is present at $N = 32$ but only for $Z \sim 20$ [7]. When adding protons, this shell gap is quenched by the strong spin-orbit $1f_{7/2}$-$1f_{5/2}$ proton-neutron monopole interaction [8]. On the other hand it has been predicted that in the middle of this region nuclear deformation sets in and that the subshell closure at $N = 40$ disappears. Theoretical calculations [9] indicate that in nuclei where the proton $1f_{7/2}$ shell is not completely filled the neutrons excited to the sdg shell couple to the pf protons and deformation appears. These calculations predict that the removal of two or four protons from the spherical ^{68}Ni drives the $N = 40$ nuclei ^{66}Fe and ^{64}Cr into prolate shapes generating a new region of deformation [9].

So far, experimental evidence for deformation effects in this region has been drawn mainly from the systematics of the 2^+ states of even-even nuclei studied in β decay [10–12]. The magnitude and type of deformation can be established on a more solid basis with the observation of further members of the yrast structure in both even-even and odd-even nuclei. In even-even nuclei, the energy ratio $R = E_4/E_2$ can provide crucial additional evidence in this regard. Our recent study of the $N = 34$ nucleus ^{58}Cr [13] has shown, for example, that it is a transitional nucleus corresponding very closely to the $E(5)$ critical point phase transition symmetry proposed by Iachello [14]. On the other hand, odd-even nuclei with $N \sim 40$ below $Z = 28$ are poorly known, except for a series of isomers identified among the reaction products of a 60.3A MeV ^{86}Kr beam on a ^{nat}Ni target at GANIL [15]. These isomers involve the occupation of the neutron $g_{9/2}$ orbital and their interpretation [16] favors the existence of deformation in this neutron-rich region around $N = 40$. No excited states above the isomers are known in the literature: such states are accessible with the CLARA-PRISMA setup.

In this article we present our results on prompt γ rays belonging to neutron-rich Fe nuclei as obtained from an experiment performed at LNL by bombarding a ^{238}U target with a ^{64}Ni beam. This reaction had already been studied at LNL from the reaction mechanism point of view and the study showed that the channels we were interested in were populated with a considerable cross section [17]. In Sec. II the experimental data are discussed and level schemes for iron isotopes from $A = 61$ to $A = 66$ are proposed. The new data are then interpreted in Sec. III by comparison with neighboring nuclei and with state-of-the-art shell-model calculations.

II. EXPERIMENTS AND RESULTS

The neutron-rich Fe isotopes were populated as products of a multinucleon transfer process following the collision of a ^{64}Ni beam onto a ^{238}U target. The ^{64}Ni beam, with an energy of 400 MeV, was delivered by the LNL Tandem-ALPI accelerator complex. The thickness of the uranium target was 400 μg/cm^2. Projectile-like nuclei were detected with the PRISMA large acceptance (~80 msr) magnetic spectrometer [6], placed at 64° to the beam direction, covering a range of angles including the grazing angle of the reaction. The PRISMA spectrometer consists of a quadrupole singlet and a dipole magnet separated by 60 cm. The (x,y) coordinates of an ion entering the spectrometer are measured using a position-sensitive micro-channel plate (MCP) detector placed at 25 cm from the target [18]. After passing the magnetic elements, the coordinates of the trajectory are measured again in the focal plane of the spectrometer using a ten-element 100-cm-long multiwire parallel-plate avalanche counter (PPAC) [19]. Finally, the ion is stopped in a 10×4 element ionization chamber used for Z and energy determination. Therefore, for each ion detected in PRISMA, we determine the atomic number Z, the mass number A by means of trajectory reconstruction, and the ion charge state, thereby obtaining a very clean identification of all detected projectile-like isotopes. The mass spectrum obtained for the Fe isotopes is shown in Fig. 1. The most populated nuclei are ^{60}Fe and ^{61}Fe in the *-2p-2n* and *-2p-1n* transfer channels, respectively. Neutron-rich Fe isotopes up to ^{66}Fe are produced with sufficient yield to enable recoil-γ coincidence measurements. The γ rays following the deexcitation of the reaction products were detected with CLARA, an array of 25 Compton-suppressed Ge Clover detectors (22 detectors were used during the experiment), in coincidence with projectile-like fragments detected by PRISMA. CLARA was positioned in the hemisphere opposite to the PRISMA spectrometer, covering the azimuthal angles from 98 to 180°. Doppler correction of γ rays was performed on an event-by-event basis. The energy resolution of the γ-ray photopeaks following Doppler correction was typically around 0.6%.

The γ-ray spectra obtained in coincidence with the detection of even- and odd-mass Fe isotopes from $A = 61$ to $A = 66$ are shown in Figs. 2 and 3, respectively. This allows the assignment, in some cases for the first time, of γ rays to a specific nucleus. In a few cases, coincidence relationships

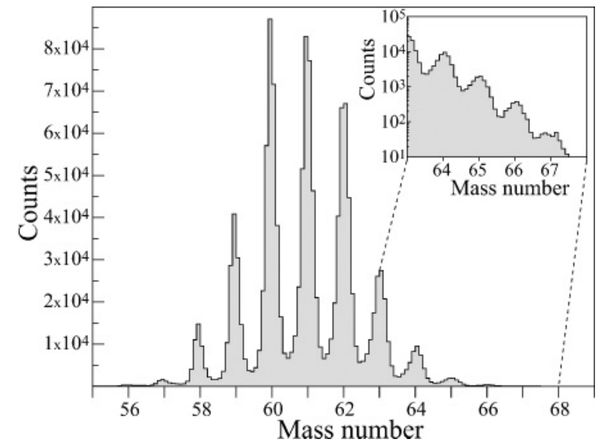

FIG. 1. Mass spectrum of iron isotopes detected at the focal plane of the PRISMA spectrometer following the ^{64}Ni+^{238}U reaction at 400 MeV. The inset shows the same spectrum, on a logarithmic scale, for masses above $A = 63$.

could be established from the γ-γ data of CLARA (see Fig. 4). These experimental results that, together with considerations from systematics, lead to the construction of the level schemes are discussed in the following subsections. Table I summarizes the γ-ray transitions assigned to the iron nuclei, their relative intensities, and the tentative spin assignment for the levels involved.

A. Even-mass Fe isotopes

The $N = 36$ nucleus ^{62}Fe was studied at GASP [20] and Gammasphere [21] in deep-inelastic thick-target reactions and its level scheme is known up to J ~ 8$\hbar$. We present our results on this nucleus to show which excited states are populated in the reaction: this will help to elucidate the more difficult cases

TABLE I. Energies (E_γ) and relative intensities (I_γ) of the γ transitions observed in coincidence with the Fe isotopes identified in this work. The relative intensities of the strongest transitions in each isotope (those with $I_\gamma = 100$ in column 3) are reported below the isotope label. The tentative spin assignment adopted for the levels involved (shown in Figs. 5 and 6) is also given; see text for details.

Isotope	E_γ (keV)	I_γ	$J_i^\pi \rightarrow J_f^\pi$
^{61}Fe	206.5(5)	68(6)	$5/2^- \rightarrow 3/2^-$
(1000)	752.4(4)	29(5)	$7/2^- \rightarrow 5/2^-$
	788.2(2)	100(7)	$13/2^+ \rightarrow 9/2^+$
	1341.0(5)	53(7)	$17/2^+ \rightarrow 13/2^+$
^{63}Fe	356.2(2)	45(9)	$3/2^- \rightarrow 5/2^-$
(251)	819.0(4)	100(15)	$13/2^+ \rightarrow 9/2^+$
	1404.1(5)	39(7)	$17/2^+ \rightarrow 13/2^+$
^{64}Fe	746.0(2)	100(8)	$2^+ \rightarrow 0^+$
(209)	781.3(4)	16(3)	$8^+ \rightarrow 6^+$
	1016.7(3)	79(9)	$4^+ \rightarrow 2^+$
	1077.5(4)	54(7)	$6^+ \rightarrow 4^+$
^{65}Fe	771.6(7)	100(20)	$13/2^+ \rightarrow 9/2^+$
(45)	1118.2(10)	48(15)	$17/2^+ \rightarrow 13/2^+$
^{66}Fe	574.7(10)	100(25)	$2^+ \rightarrow 0^+$
(8)			

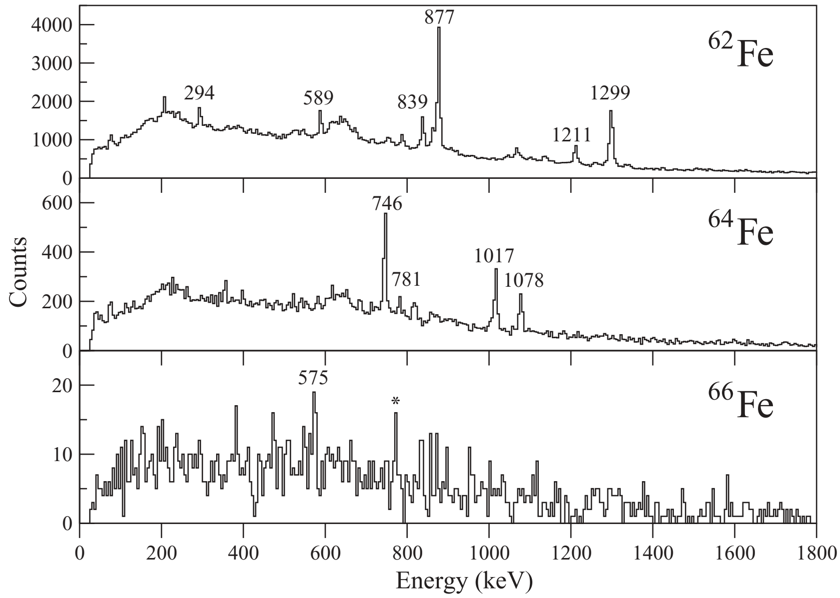

FIG. 2. γ-ray spectra in coincidence with the three even-mass Fe isotopes discussed in this work. Transitions assigned to each nucleus are labeled by their energies. The transition denoted by an asterisk in the spectrum in coincidence with ^{66}Fe belongs to ^{65}Fe, which is more strongly populated in the reaction (see Fig. 3).

(see below) where only γ rays in coincidence with PRISMA are available. Figure 2 shows the γ-ray spectrum from CLARA in coincidence with ^{62}Fe. We observe almost all the transitions assigned to the nucleus up to spin (8^+) [20,21], as can be seen in Fig. 5. This confirms that in this kind of reaction mainly yrast and near yrast states are populated [3]. The spin-parity assignments proposed in the two quoted works [20,21] for the higher spin states of ^{62}Fe are tentative and they are different for many levels. We adopt in Fig. 5 the spin-parity assignments of Ref. [20].

The first data on excited states in heavier ^{64,66}Fe come from β decay of ^{64,66}Mn produced in a spallation reaction [10] at Isolde-CERN. The 2^+ state has been located at 746 and 573 keV in ^{64}Fe and ^{66}Fe, respectively. In the case of ^{66}Fe, a second excited state has also been proposed at 1414 keV with a tentative spin and parity assignment of 4^+. The 746-keV transition in ^{64}Fe was also observed in the β decay of ^{64}Mn produced in a fragmentation reaction at GANIL [11]. Very recently, and in parallel with our studies, a level scheme of ^{64}Fe up to J $\sim 10\hbar$ has been published [22] as obtained with Gammasphere using the same reaction ^{64}Ni + ^{238}U.

The γ-ray spectrum in coincidence with ^{64}Fe from our data is shown in Fig. 2; the γ rays with energies of 746, 1017, and 1078 keV are clearly evident. From the γ-γ coincidences (see Fig. 4), we observed that the 746- and 1017-keV transitions are in coincidence. The statistics were, however, insufficient to prove coincidence relationships with the third 1078-keV transition. As mainly yrast states are populated in our reaction, we propose that the 1078-keV transition is the upper member of the $E2$ cascade belonging to the yrast ground-state band as shown in Fig. 5. This is consistent with the findings of the recent higher statistics γ-γ experiment at Gammasphere [22]. Furthermore, we observe also the 781-keV transition deexciting the (8^+) level of ^{64}Fe as proposed in Ref. [22].

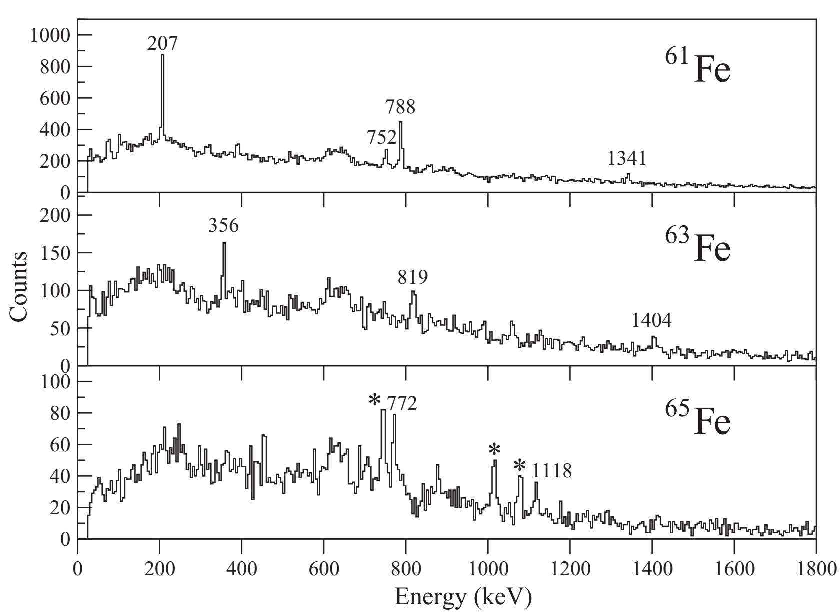

FIG. 3. γ-ray spectra in coincidence with the three odd-mass Fe isotopes discussed in this work. Transitions assigned to each nucleus are labeled by their energies. In the spectrum in coincidence with ^{65}Fe, transitions belonging to the much more strongly populated ^{64}Fe nucleus appear (see Fig. 2): they are labeled by an asterisk.

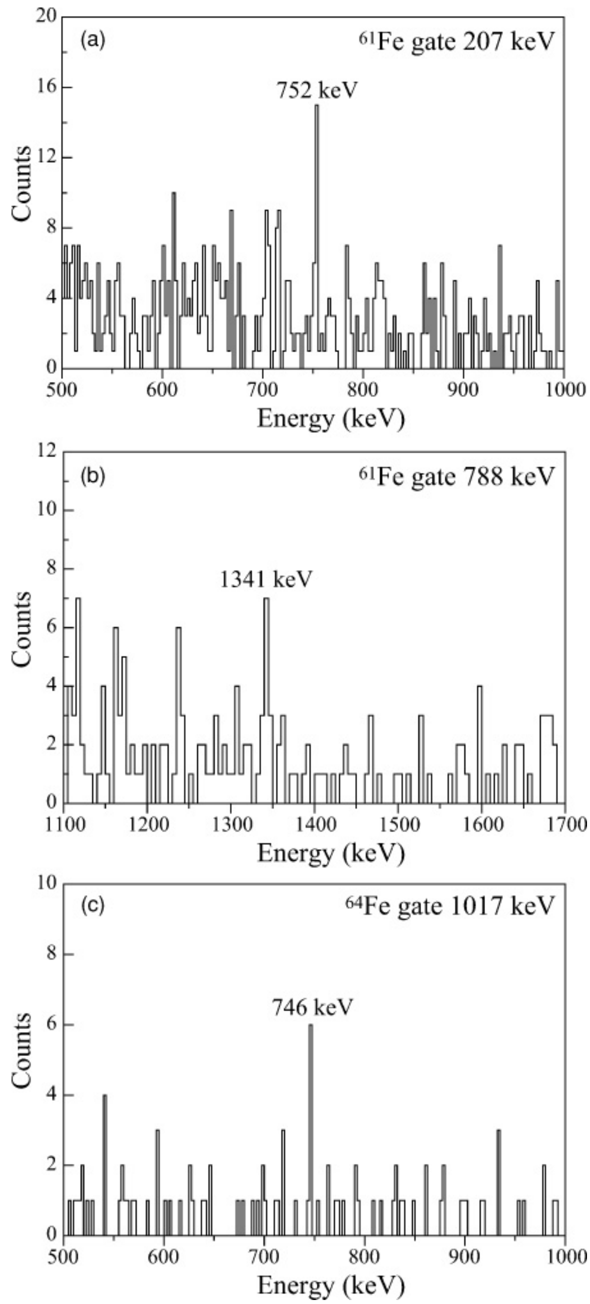

FIG. 4. Selected regions of γ-ray spectra in coincidence with ^{61}Fe (a, b) and ^{64}Fe (c) and with a γ-ray transition belonging to their respective decay scheme.

For the $N = 40$ nucleus ^{66}Fe our data (see Fig. 2) can only confirm the 2^+ state at 575 keV as seen in the β decay of ^{66}Mn [10]. This is the most exotic Fe isotope where meaningful recoil-γ coincidences could be observed in our experiment.

B. Odd-mass Fe isotopes

Figure 3 shows the γ-ray spectra in coincidence with the three odd-mass Fe nuclei studied in this work. On this basis, new γ-ray transitions have been assigned to each nucleus. The four transitions at 207, 752, 788, and 1341 keV are in coincidence with the ^{61}Fe isotope (see Fig. 3). In a previous experiment at the GASP spectrometer using the ^{64}Ni+^{130}Te reaction [23,24], a 0.22 μs isomer was located at 861 keV in ^{61}Fe and identified as the $9/2^+$ state decaying by a 654-keV $M2$ transition to the $5/2^-$ level at 207 keV. The same isomeric decay ($T_{1/2} = 0.25$ μs) was measured at GANIL in a fragmentation reaction [15]. Prompt-delayed coincidence relationships from the GASP experiment established also a 788-keV transition feeding the 0.22 μs isomer [20]. More recently, the g factor [25] and the quadrupole moment [26] of the isomer at 861 keV have been measured. Whereas the g factor is in very good agreement with the assigned $9/2^+$ spin-parity, the measured spectroscopic quadrupole moment points to a sizeable deformation of the isomer ($\beta_2 \sim 0.2$) leaving open the question of its oblate or prolate character [26]. In our data the 207- and 752-keV transitions are in mutual coincidence and the same is true for the 788- and 1341-keV transitions (see Fig. 4). This leads to the level scheme proposed in Fig. 6 where the spin and parity assignments are based on systematics. The coupling of the 2^+ and 4^+ states of the ^{60}Fe core with the $g_{9/2}$ neutron gives rise to the $13/2^+$ and $17/2^+$ states in ^{61}Fe. The observation of a such a decoupled band built on the $9/2^+$ isomer, with transition energies very close to those of the ^{60}Fe nucleus ($E_4/E_2 \sim 2.6$), is consistent with a prolate deformation of $\beta_2 \sim +0.24$ suggested for the isomer on the basis of the measured quadrupole moment and of the mean-field calculations of Ref. [26].

Three γ rays can be assigned with confidence to the ^{63}Fe nucleus, namely, those at 356, 819, and 1404 keV (see Fig. 3). Furthermore, two of them at 819 and 1404 keV are in coincidence. The 356-keV transition was earlier observed in the β decay of ^{63}Mn [27], a result later confirmed at GANIL [11]. From β-decay studies a spin-parity of $(5/2^-)$ was assigned to the ^{63}Fe ground state [28]. At variance with the neighboring odd-mass Fe isotopes, long-lived isomers ($T_{1/2} > 0.2$ μs) were not found in this nucleus [15]. Nevertheless, from ^{55}Fe up to ^{61}Fe the $9/2^+$ state is rapidly decreasing in energy, suggesting a low excitation energy above the $(5/2^-)$ ground state in ^{63}Fe. By analogy with the ^{61}Fe case we propose, in the level scheme of Fig. 5, the two transitions of 819 and 1404 keV as depopulating the states corresponding to the coupling of the $g_{9/2}$ neutron to the ^{62}Fe 2^+ and 4^+ states above a $9/2^+$ level of unknown excitation energy. In our interpretation the 356-keV transition, that was also seen in β decay [11,27], feeds the $(5/2^-)$ ground state from a $(3/2^-)$ level at 356 keV of $p_{3/2}$ character, although spin assignments here are only tentative. The analogous state is located 311 keV above the $5/2^-$ ground state in the isotone ^{65}Ni and it is strongly populated in a reaction similar to the one used in the present experiment [29].

In ^{65}Fe an isomer was identified at 364 keV with a half-life of 0.43 μs [15]. The interpretation for this isomer is similar to that of ^{61}Fe, i.e., it is due to an $M2$ transition between the $\nu g_{9/2}$ and the $\nu f_{5/2}^{-1}$ orbitals but in this case with a reversed order, because from systematics the state of $g_{9/2}$ character is expected below the $5/2^-$ state. A spin-parity of $5/2^-$ has therefore been suggested to the ^{65}Fe isomer as well as to the analogous isomer in ^{67}Fe [15] (further studies [16] concluded that the spin of the isomer in ^{67}Fe is $(1/2^-)$ and it decays through a 387-keV transition to a $(5/2^+)$ ground state). In our

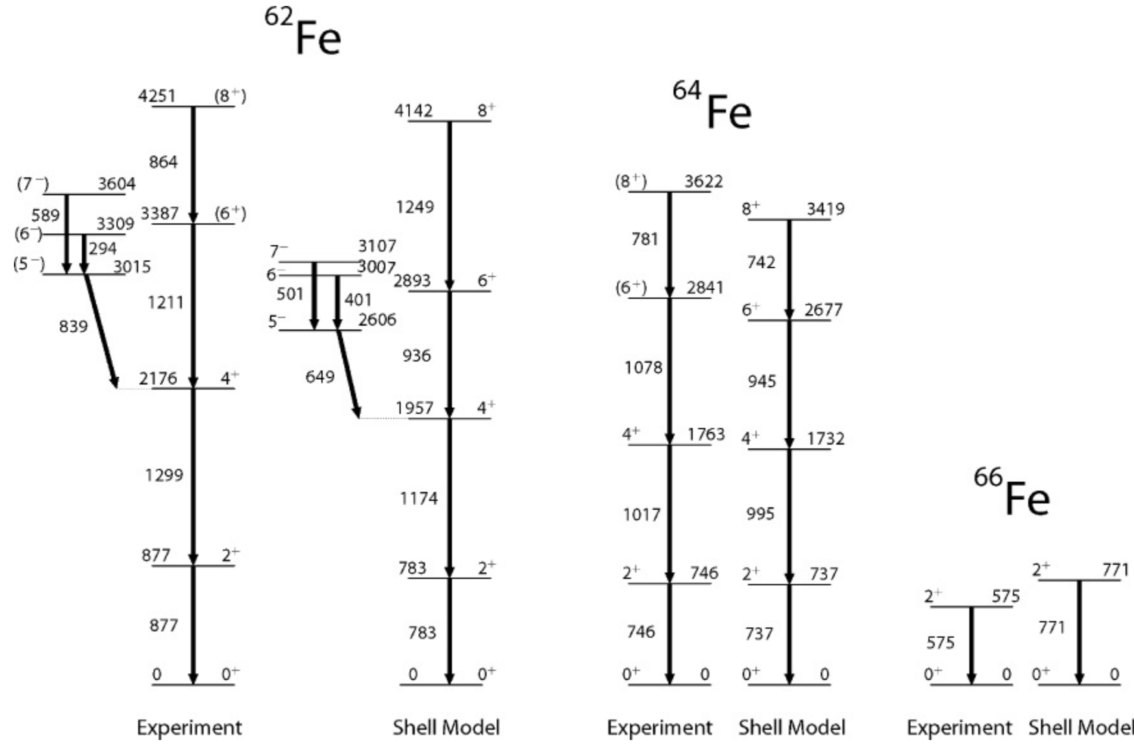

FIG. 5. Level schemes of ^{62}Fe, ^{64}Fe, and ^{66}Fe from the data of the present experiment and from Refs. [10,20,21] compared with the results of shell-model calculations described in the text.

experiment we could assign two γ rays to ^{65}Fe with energies of 772 and 1118 keV (see Fig. 3). The low statistics did not allow coincidence relationships between them to be measured. Anyway, the close resemblance of their energies with those of the $2^+ \rightarrow 0^+$ and $4^+ \rightarrow 2^+$ transitions in ^{64}Fe, and the fact that the same similarity with the respective core holds for the states above the $9/2^+$ isomer in ^{61}Fe, suggests, as in the case of ^{63}Fe, that the two transitions form the beginning of a structure built on the $(9/2^+)$ state that could be the ground state in ^{65}Fe. The relative position of the $9/2^+$ state and of the state fed by the isomeric 364-keV transition of Ref. [15] is not known, and it is also possible that they are the same state.

III. DISCUSSION

Iron isotopes evolve toward more collective structures when approaching $N = 40$. Inspection of Fig. 5 shows in fact that

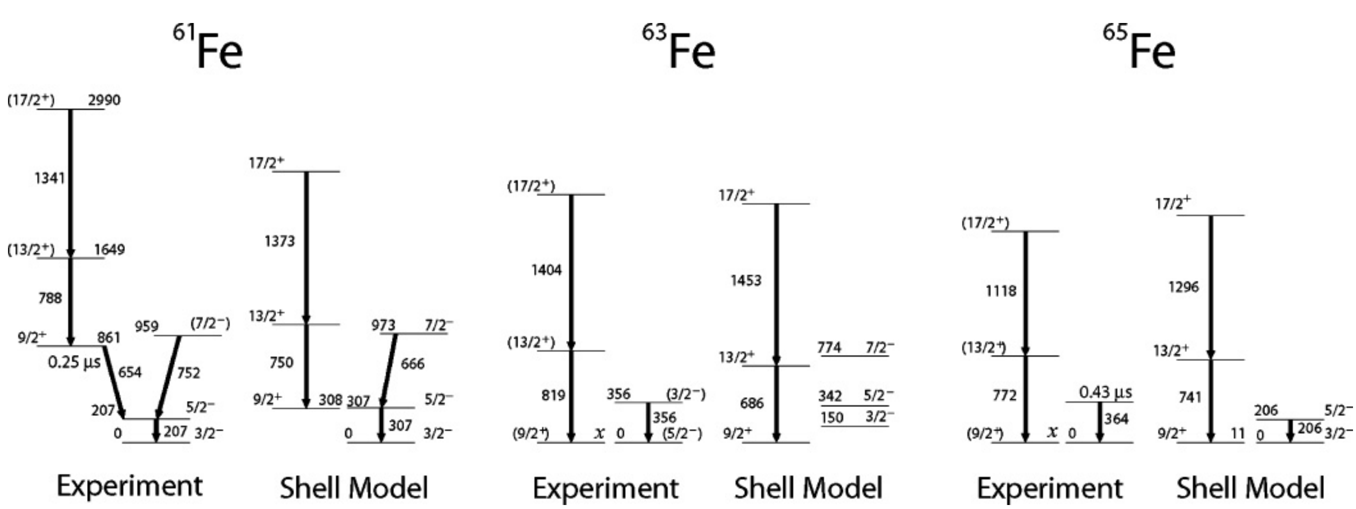

FIG. 6. Level schemes of ^{61}Fe, ^{63}Fe, and ^{65}Fe from the data of the present experiment and from Refs. [15,23]. For ^{63,65}Fe the excitation energy of the proposed $9/2^+$ states is not known experimentally and is denoted with an x. The half-lives of the isomeric states are from Ref. [15]. Shell-model calculations for each nucleus are also shown.

the excitation energy of the 2^+ state (usually considered a first fingerprint of nuclear collectivity) decreases with increasing neutron number in the even-A iron isotopes. In particular, at $N = 40$—that for nickel isotopes acts as a subshell closure [4]—the drop in the 2^+ excitation energy is large, which indicates increasing collectivity. This can be understood in terms of a decrease of the energy gap between the fp shell and the intruder $g_{9/2}$ orbital when the $1f_{7/2}$ proton shell is not completely filled and more neutrons are excited to the upper shell [9]. In fact, the removal of protons from the $f_{7/2}$ shell weakens the effect of the attractive spin-orbit monopole interaction with the neutrons in the $f_{5/2}$ orbital. In addition, excitations of protons to the $f_{5/2}$ orbital lower the neutron $g_{9/2}$ single-particle orbital due to the proton-neutron monopole tensor interaction. The effect is proportional to the occupation number and therefore increases with increasing neutron number.

To give a quantitative interpretation of the experimental findings we performed large-scale shell-model calculations. The effective interaction used is called fpg and is described in Ref. [30]. An inert core of ^{48}Ca is considered and the valence space chosen is the whole fp shell for the protons and the $p_{3/2}$, $f_{5/2}$, $p_{1/2}$, and $g_{9/2}$ orbitals for the neutrons. Nevertheless, the dimensions of the matrices are very large, and suitable truncations are mandatory. For consistency, we used the same truncation for all the studied isotopes as follows: a maximum of x protons was allowed to be excited from the $f_{7/2}$ to the rest of the fp shell and $(n - x)$ neutrons were allowed to jump from the three fp orbitals to the $g_{9/2}$ orbital, where $n = 5$.

The results of our calculations are compared with the data in Figs. 5 and 6 for the even- and odd-mass iron isotopes, respectively. In ^{61}Fe, the negative-parity levels are well reproduced, while the excitation energy of the $J^\pi = 9/2^+$ state is predicted too low, at 308 keV, compared to the experimental value of 861 keV. This is in part related to the uncertainty in the single-particle energy of the $g_{9/2}$ orbit in the shell-model calculations. The calculated positive-parity band above the $9/2^+$ bandhead state is similar to that observed experimentally in terms of relative energies, as can be seen by comparing the transition energies marked in Fig. 6. The shell-model calculations predict a spectroscopic quadrupole moment for the $9/2^+$ state that is consistent with a prolate deformation. As mentioned already in Sec. II B, the decoupled band structure built on the $9/2^+$ state agrees well with this interpretation. Continuing with the odd-mass isotopes, in ^{63}Fe, calculations predict a $J^\pi = 9/2^+$ ground state with a first excited $J^\pi = 3/2^-$ state at 150 keV, to be compared with a $(5/2^-)$ assignment [28] for the ground state and the nonobservation of an isomeric state in this nucleus. The new positive-parity levels that we propose above the $J^\pi = 9/2^+$ state are, as in the case of ^{61}Fe, satisfactorily reproduced by the calculations. The heaviest odd-mass isotope observed in this experiment is ^{65}Fe with $N = 39$ where the two γ transitions associated with the positive-parity band built on the $9/2^+$ state agree well with the calculations. Here, the ground state is predicted to be a $I^\pi = 3/2^-$ state, separated from the $J^\pi = 9/2^+$ state by only 11 keV. The isomer observed in Ref. [15] is not accounted for by the calculations and this again could indicate some problems with the relative position of the $g_{9/2}$ orbital. The occupation of the $g_{9/2}$ orbital is nonzero in all cases, both for positive- and negative-parity states. This means that this orbital influences considerably the structure of Fe isotopes in a wide mass range. The relative excitation of the $3/2^-$ and the $5/2^-$ is also affected by the position of the $g_{9/2}$ orbital. In addition to the position of the $g_{9/2}$ orbital, the truncation imposed to the calculations as well as possible deficiencies of the effective interaction may also contribute to this failure. These experimental data can therefore be very useful to tune effective interactions that include the $g_{9/2}$ orbital.

The theoretical description of the even-A isotopes ^{62,64}Fe (Fig. 5) is quite satisfactory, although the calculated level schemes are more compressed than the experimental ones. On the other hand, in the case of ^{66}Fe, the excitation energy of the 2^+ state is predicted too high. This could indicate that the considered valence space is not large enough to account for the increase of collectivity at $N = 40$, as suggested in Ref. [9] where also the $d_{5/2}$ orbital was included in the calculations. The 4^+ state is predicted at 1720 keV, also in disagreement with the proposed [10] energy of 1414 keV.

If we now consider the 4^+ to 2^+ energy ratio (E_4/E_2) for the iron isotopes of Fig. 5 (taking into account also the 4^+ state proposed in Ref. [10]), we note that its value of $\sim$2.5 is typical of a γ-soft rotor. The nucleus ^{58}Cr, whose excited states have been recently studied [13,31], was proposed as a good candidate [13] for the $E(5)$ critical point phase-shape transition [14] that is realized when going from a spherical vibrator to a γ-soft rotor [$O(6)$ symmetry in the Interacting Boson Model framework]. The fact that the neutron-rich even-A iron nuclei seem to be close to the γ-soft regime is consistent with the interpretation given for ^{58}Cr. However, as we are dealing with relatively light systems, where "good rotors" like ^{48}Cr [32] present values for the (E_4/E_2) ratio of $\sim$2.5, the development of axial quadrupole deformation with increasing neutron number cannot be disregarded in Fe isotopes on the basis of the present experimental data. More information on both excited states and lifetimes is essential to establish a clearer scenario.

IV. SUMMARY

In the present work the neutron-rich iron nuclei from $A = 61$ to $A = 66$ were populated via multinucleon transfer reactions. The PRISMA magnetic spectrometer in conjunction with the CLARA Ge array at the INFN Legnaro National Laboratory was used to identify the isotopes and to assign new γ-ray transitions to them. Level schemes have been proposed for all nuclei, based on experimental data and using, in some cases, arguments of systematics. In particular, the structures built on the $(9/2^+)$ state in ^{63,65}Fe are assigned on the basis of the strong similarity with the analogous states in ^{61}Fe. The systematic trend of the iron isotopes studied in this work indicates an increase of collectivity with increasing neutron number. Large-scale shell-model calculations have been performed, by allowing neutrons to occupy the $g_{9/2}$ orbital, that reproduce quite satisfactorily the experimental data and therefore also the collective aspects up to $N = 38$–39.

Further data on excited states of even more neutron-rich nuclei and on lifetimes are necessary to better understand the evolution of nuclear shapes at and beyond $N \sim 40$. To properly describe the various phenomena (spherical and deformed structures, phase-shape transition) in the framework of the shell model, a step forward has to be made both on enlarging the valence space and on better tuning the effective interactions.

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