SPECTROSCOPY OF NEUTRON-RICH Fe ISOTOPES POPULATED IN THE ^{70}Zn + ^{238}U REACTION*

J. Benito[a,b], S.M. Lenzi[a], F. Recchia[a], M. Axiotis[c], S. Aydin[d]
D. Bazzacco[a], G. Benzoni[e], P.G. Bizzeti[f], A.M. Bizzeti-Sona[f]
A. Bracco[e], R. Broda[g], D. Bucurescu[h], E. Caurier[i], L. Corradi[j]
G. de Angelis[j], F. Della Vedova[j], E. Farnea[a], B. Fornal[g]
E. Fioretto[j], A. Gadea[k], A. Gottardo[j], M. Ionescu-Bujor[h]
A. Iordachescu[h], S. Leoni[e], S. Lunardi[a], N. Mărginean[h]
R. Mărginean[h], P. Mason[a], R. Menegazzo[a], D. Mengoni[a]
B. Million[e], G. Montagnoli[a], D.R. Napoli[j], F. Nowacki[i]
R. Orlandi[l], G. Pollarolo[m], A. Poves[n], E. Sahin[o]
F. Scarlassara[a], R.P. Singh[p], A.M. Stefanini[j], S. Szilner[q]
C.A. Ur[h], J.J. Valiente-Dobón[j], O. Wieland[e]

[a]Dipartimento di Fisica and INFN, Sezione di Padova, Padova, Italy
[b]Grupo de Física Nuclear & IPARCOS, Univ. Complutense de Madrid, Madrid, Spain
[c]Demokritos, Institute of Nuclear & Particle Physics, Athens, Greece
[d]Department of Physics, University of Aksaray, Aksaray, Turkey
[e]Dipartimento di Fisica and INFN, Sezione di Milano, Milano, Italy
[f]Dipartimento di Fisica and INFN, Sezione di Firenze, Firenze, Italy
[g]Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland
[h]"Horia Hulubei" National Institute of Physics and Nuclear Engineering Bucharest, Romania
[i]IPHC, IN2P3-CNRS et Université de Strasbourg, Strasbourg, France
[j]INFN, Laboratori Nazionali di Legnaro, Legnaro, Italy
[k]IFIC, CSIC-University of Valencia, Spain
[l]Advanced Science Research Center, Japan Atomic Energy Agency, Tokai, Japan
[m]Dipartimento di Fisica and INFN, Sezione di Torino, Torino, Italy
[n]Departamento de Fisica Teorica and IFT-UAM/CSIC, Madrid, Spain
[o]University of Oslo, Department of Physics, Oslo, Norway
[p]Inter-University Accelerator Centre, Aruna Asaf Ali Marg, New Delhi, India
[q]Ruđer Bošković Institute, Zagreb, Croatia

Received 10 November 2023, accepted 12 January 2024, published online 24 April 2024

The excited states of neutron-rich Fe isotopes have been studied through a multinucleon transfer reaction of a ^{70}Zn beam on a ^{238}U target. Unambiguous identification of prompt γ rays belonging to each nucleus was performed by coincidence detection of the ions in a high-acceptance magnetic spectrometer. The observed spectra are compared with large-scale shell-model calculations in the *fpgd* model space.

DOI:10.5506/APhysPolBSupp.17.3-A4

* Presented at the XXXVII Mazurian Lakes Conference on Physics, Piaski, Poland, 3–9 September, 2023.

1. Introduction

The existence of a sub-shell closure at $N = 40$ is a topic that has attracted a substantial amount of experimental and theoretical effort. ^{68}Ni is considered to show rather good properties of a doubly magic nucleus having a high excitation energy for the first 2^+ state of more than 2 MeV [1] and a low collective $B(\mathrm{E2}; 2^+ \rightarrow 0^+)$ transition rate [2]. On the other hand, mass measurements show a weak harmonic oscillator gap for $N = 40$ [3]. Besides, the presence of low-lying 0^+ states indicates the presence of shape coexistence in the region [4].

At this point, it is clear that the pseudo-magic number $N = 40$ is not a very strong shell closure. There is evidence indicating its disappearance once two or more protons are removed. This can be deduced from the low-excitation energies measured for the 2^+ states in the iron [5, 6] and chromium [7, 8] isotopes when approaching $N = 40$. Moreover, enhanced $B(\mathrm{E2}; 2^+ \rightarrow 0^+)$ transition rates have been measured in these isotopes [9–11], confirming the region of deformation below ^{68}Ni.

The onset of deformation in this region is understood to be caused by the enhanced quadrupole collectivity generated when neutrons are excited into the quadrupole-partner orbitals $\nu g_{9/2}$ and $\nu d_{5/2}$ across the $N = 40$ sub-shell gap. Large-scale shell model calculations employing the Lenzi–Nowacki–Poves–Sieja (LNPS) interaction [12] have successfully explained the spectra and transition rates measured so far in this region.

Experimental information on iron isotopes proceeds mostly from β-decay studies [5, 13–19], and from transfer [6] and charge-exchange reactions [20]. Information on high-spin states in this isotopic chain has been extracted mostly in the Multi-Nucleon Transfer (MNT) experiments, employing the ^{64}Ni+^{238}U reaction [9, 21, 22]. The purpose of this work is to extend these studies to heavier isotopes populated with the ^{70}Zn+^{238}U reaction, and to interpret the structure within state-of-the-art shell-model calculations with the LNPS interaction.

2. Experimental details

The neutron-rich iron isotopes were generated as products of a multinucleon transfer (MNT) process following the collision of a ^{70}Zn beam onto a ^{238}U target. The ^{70}Zn beam, with an energy of 460 MeV, was delivered by the Laboratori Nazionali di Legnaro (LNL) Tandem-ALPI accelerator complex, in a 7-day long measurement. A target with a thickness of 1 mg/cm^2 was employed. The CLARA–PRISMA setup was used to identify the projectile-like nuclei in coincidence with the prompt γ rays emitted from their excited states. The PRISMA large-acceptance magnetic spectrometer was positioned at 61°, close to the grazing angle. The γ rays following the de-excitation of the reaction products were detected with the CLARA array, in a configuration with 22 Compton-suppressed Ge clover detectors. CLARA was positioned in the hemisphere opposite to the PRISMA spectrometer, covering polar angles from 98° to 180°. Doppler correction of γ rays was performed on an event-by-event basis. The detection efficiency of the CLARA spectrometer was 2.5%. More details on the CLARA–PRISMA setup and data analysis used for the present experiment can be found in Refs. [22–24].

Neutron-rich iron isotopes have been studied previously in a similar experiment at LNL, using the same setup, but employing a ^{64}Ni beam [22]. In comparison with this previous study, the use of a ^{70}Zn beam offered the possibility of populating states in more neutron-rich isotopes. The mass spectra for the different isotopic chains produced in this experiment are shown in Fig. 1. Among the iron isotopes, the maximum production was observed for ^{62}Fe, which corresponds to the $(-4p\text{–}4n)$ transfer channel. This contrasts with the mass spectrum obtained in the case of the reaction with a ^{64}Ni beam, whose maximum was located at ^{60}Fe [22]. Thanks to the enhanced production of more neutron-rich isotopes, in this experiment, it was possible to perform γ-ray coincidences for neutron-rich iron isotopes up to ^{68}Fe.

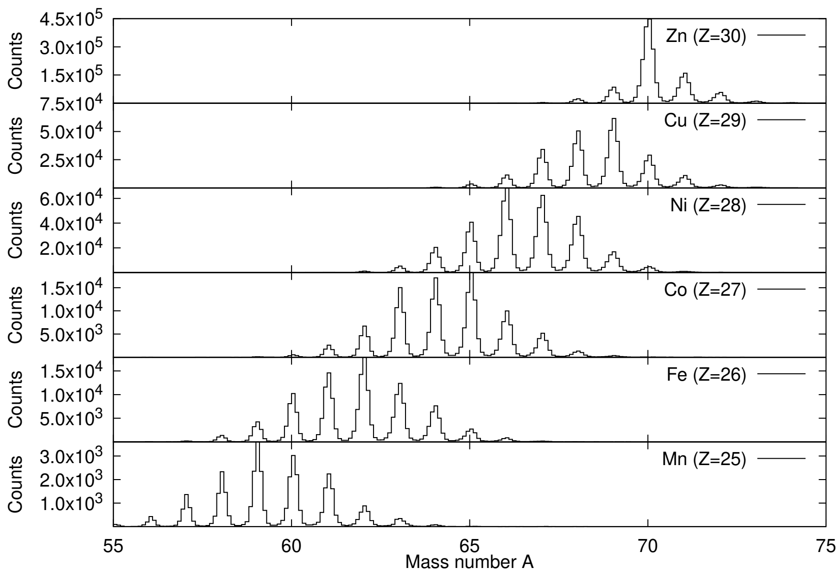

Fig. 1. Mass spectrum for the different isotopic chains detected at the focal plane of the PRISMA spectrometer following the ^{70}Zn+^{238}U reaction.

3. Results and discussion

The γ-ray spectra measured in coincidence with the detection of the iron isotopes in PRISMA from $A = 64$ to $A = 68$ are shown in Fig. 2.

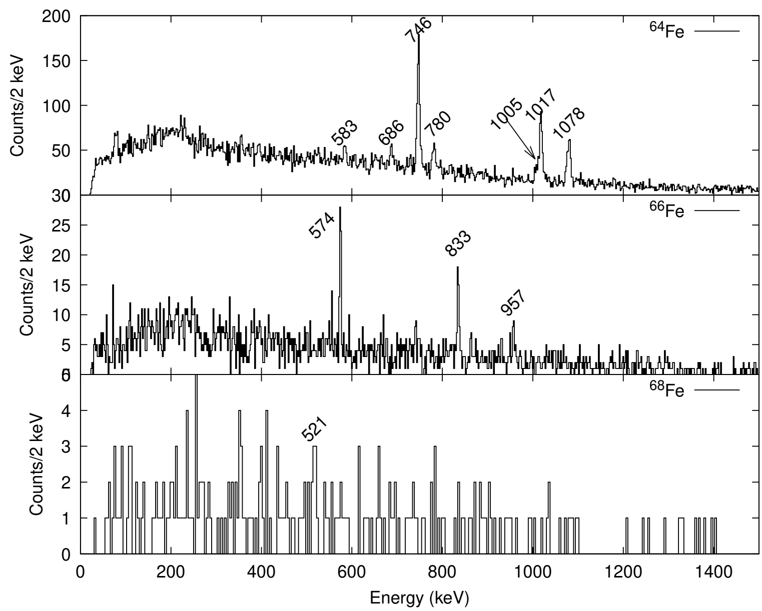

Fig. 2. Doppler-corrected γ-ray spectra registered in CLARA in coincidence with the iron isotopes in PRISMA. Transitions assigned to each nucleus are labelled with their energies.

The level scheme of ^{64}Fe has been established from β-decay experiments [5, 15] and multinucleon transfer in the ^{64}Ni+^{238}U reaction [21, 22], where the population of the positive-parity band was observed up to $J = 10\,\hbar$. Figure 2 presents the γ-ray spectra observed in coincidence with the ^{64}Fe ions detected in PRISMA. The three strongest peaks (1078, 1017, and 747 keV) are identified with the $6^+ \rightarrow 4^+ \rightarrow 2^+ \rightarrow 0^+$ transitions, respectively. Besides these transitions, three small peaks can be also observed at 583, 686, and 1078 keV, corresponding to the population of positive-parity states. In this work, we assumed the spin and parity assignments proposed in Ref. [21], which are in agreement with our shell-model calculations.

The excited levels of ^{66}Fe have been studied in detail in β-decay experiments [14, 18, 19], which provided information about the low-spin structure. Yrast states up to 4^+ are known from the MNT reaction experiment [22] and β-decay studies [16]. Two possible candidates for a 6^+ state were suggested in the proton knockout experiments [6]. In the γ-ray spectra observed in our experiment, see Fig. 2, three γ rays can be clearly observed. These three transitions are compatible with the de-excitation of the yrast states suggested in Ref. [6], supporting the identification of the 2364 keV state as the 6^+ state. The production of ^{68}Fe in our experiment was low, but still it was possible to clearly identify a peak at 521 keV, which corresponds to the decay of the first 2^+ state [14, 16, 20].

We have performed large-scale shell model calculations in order to give a quantitative interpretation of the experimental spectra. The LNPS interaction was employed, with an inert core of ^{48}Ca. The chosen valence space corresponds to the whole fp shells for protons and the $p_{3/2}$, $f_{5/2}$, $p_{1/2}$, $g_{9/2}$, and $d_{5/2}$ orbitals for neutrons. The results of our calculations are compared with the data obtained for the even iron isotopes in Fig. 3. The theoretical description is quite satisfactory. It is worth to compare it with the results of previous calculations including only the fpg shell space for ^{66}Fe [22], where the excitation energy of the 2^+ state was found to be 771 keV, 200 keV higher than the experimental value. The inclusion of the $d_{5/2}$ orbital in the calculations allows to reproduce the large quadrupole collectivity required to obtain a satisfactory agreement with the experimental data.

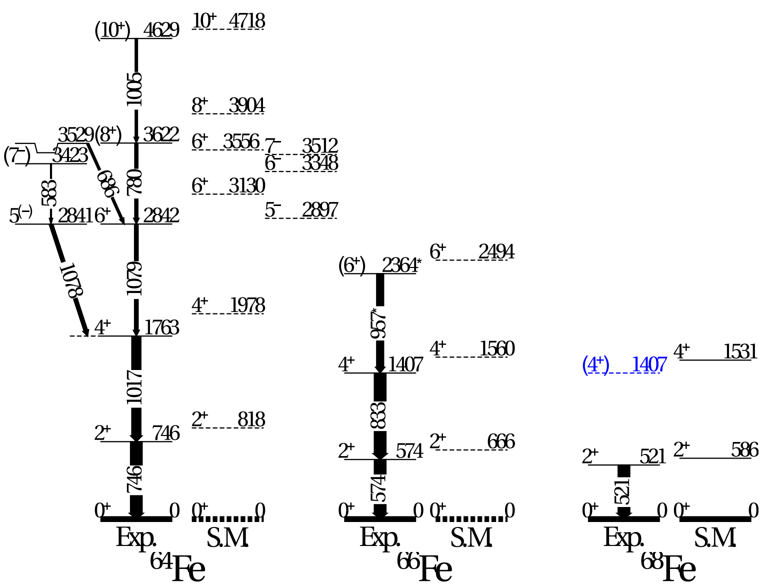

Fig. 3. (Colour on-line) Level schemes observed in our experiment for the of the ^{64,66,68}Fe isotopes. The experimental spectra are compared with the results of our shell-model calculations. The (4^+) state in ^{68}Fe (blue/grey) was not observed in this experiment, but the excitation energy of this state was determined in Refs. [16, 20]. This state was included for comparison with the theoretical calculations.

4. Summary

In this work, we presented the level schemes for the neutron-rich Fe isotopes from $A = 64$ to $A = 68$, populated in the multinucleon transfer reaction of a ^{70}Zn beam on a ^{238}U target. The experiment was performed at the INFN Legnaro National Laboratory, where the CLARA Ge array was coupled to the PRISMA magnetic spectrometer in order to unambiguously assign the γ rays emitted to the corresponding isotopes. New levels and transitions have been proposed in the even nuclei, based on arguments of systematics and a comparison with shell-model predictions. Analysis for the odd-mass isotopes is currently ongoing and it will be published elsewhere. Large-scale shell-model calculations have been performed in the $fpgd$ valence space using the LNPS interaction. The inclusion of the $d_{5/2}$ orbital allowed to reproduce quite successfully the experimental data and collective aspects up to $N = 42$.

The authors are grateful to the staff of the Tandem-ALPI accelerator of LNL for the excellent technical support received. J.B. also acknowledges the support from the Margarita Salas Fellowship, CT31/21, at the Complutense University of Madrid funded by the Spanish MIU and European Union — NextGenerationUE funds.

REFERENCES

[1] R. Broda *et al.*, *Phys. Rev. Lett.* **74**, 868 (1995).
[2] O. Sorlin *et al.*, *Phys. Rev. Lett.* **88**, 092501 (2002).
[3] C. Guénaut *et al.*, *Phys. Rev. C* **75**, 044303 (2007).
[4] F. Flavigny *et al.*, *Phys. Rev. C* **91**, 034310 (2015).
[5] M. Hannawald *et al.*, *Phys. Rev. Lett.* **82**, 1391 (1999).
[6] P. Adrich *et al.*, *Phys. Rev. C* **77**, 054306 (2008).
[7] O. Sorlin *et al.*, *Eur. Phys. J. A* **16**, 55 (2003).
[8] A. Gade *et al.*, *Phys. Rev. C* **81**, 051304 (2010).
[9] J. Ljungvall *et al.*, *Phys. Rev. C* **81**, 061301 (2010).
[10] W. Rother *et al.*, *Phys. Rev. Lett.* **106**, 022502 (2011).
[11] H.L. Crawford *et al.*, *Phys. Rev. Lett.* **110**, 242701 (2013).
[12] S.M. Lenzi *et al.*, *Phys. Rev. C* **82**, 054301 (2010).
[13] J.M. Daugas *et al.*, *Phys. Rev. C* **83**, 054312 (2011).
[14] S.N. Liddick *et al.*, *Phys. Rev. C* **87**, 014325 (2013).
[15] B. Olaizola *et al.*, *Phys. Rev. C* **88**, 044306 (2013).
[16] G. Benzoni *et al.*, *Phys. Lett. B* **751**, 107 (2015).

[17] B. Olaizola *et al.*, *JPS Conf. Proc.* **6**, 030006 (2015).
[18] B. Olaizola *et al.*, *J. Phys. G: Nucl. Part. Phys.* **44**, 125103 (2017).
[19] M. Stryjczyk *et al.*, *Phys. Rev. C* **98**, 064326 (2018).
[20] A. Gade *et al.*, *Phys. Rev. C* **104**, 024313 (2021).
[21] N. Hoteling *et al.*, *Phys. Rev. C* **74**, 064313 (2006).
[22] S. Lunardi *et al.*, *Phys. Rev. C* **76**, 034303 (2007).
[23] S. Szilner *et al.*, *Phys. Rev. C* **76**, 024604 (2007).
[24] D. Montanari *et al.*, *Eur. Phys. J. A* **47**, 4 (2011).