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Isomeric decay of ^{67}Fe —Evidence for deformation

M. Sawicka[1,a], J.M. Daugas[2], H. Grawe[3], S. Čwiok[4], D.L. Balabanski[5,6,7], R. Béraud[8], C. Bingham[6], C. Borcea[9], M. La Commara[10], G. de France[2], G. Georgiev[5,7], M. Górska[3,5], R. Grzywacz[1,6], M. Hass[11], M. Hellström[3], Z. Janas[1], M. Lewitowicz[2], H. Mach[12], I. Matea[2], G. Neyens[5], C.O' Leary[13], F. de Oliveira Santos[2], R.D. Page[13], M. Pfützner[1], Zs. Podolyák[14], K. Rykaczewski[1,15], M. Stanoiu[2], and J. Żylicz[1]

[1] Institute of Experimental Physics, Warsaw University, PL-00681 Warsaw, Hoża 69, Poland
[2] GANIL BP 5027, 14076 Caen Cedex 5, France
[3] Gesellschaft für Schwerionenforschung mbH, Darmstadt, D-64291 Darmstadt, Germany
[4] Faculty of Physics, Warsaw University of Technology, PL-00662 Warsaw, Koszykowa 75, Poland
[5] University of Leuven, IKS, Celestijnenlaan 200 D, B-3001 Leuven, Belgium
[6] University of Tennessee, Knoxville, TN 37996, USA
[7] St. Kilment Ohridski University of Sofia, BG-1164 Sofia, Bulgaria
[8] IPN Lyon, 69622 Villeurbane Cedex, France
[9] IAP Bucharest-Marguele P.O. Box MG6, Romania
[10] Department of Physics, University of Naples "Federico II", I-80126 Naples, Italy
[11] Department of Particle Physics, The Weizmann Institute of Science, 76100 Rehovot, Israel
[12] Department of Radiation Sciences, Uppsala University, S-61182, Nyköping, Sweden
[13] Oliver Lodge Laboratory, Department of Physics, University of Liverpool, L69 7ZE, UK
[14] Department of Physics, University of Surrey, Guildford, GU2 7XH, UK
[15] ORNL, Physics Division, Oak Ridge, TN 37830, USA

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Abstract. Decay-spectroscopy study of the ^{67m}Fe isomer has been performed at GANIL. This isomer is found to have an energy of 387 keV and a half-life of 75(21) μs. An intermediate excited state is introduced at 367 keV. The results are interpreted in terms of various nuclear models, and a deformed shape is inferred for ^{67}Fe.

PACS. 25.70.Mn Projectile and target fragmentation – 21.10.Tg Lifetimes – 27.50.+e $59 \geq A \geq 89$ – 21.60.Cs Shell model

An extension of nuclear spectroscopy studies to nuclei with a large neutron excess is both interesting and challenging. It is interesting since there are theoretical predictions for drastic changes of nuclear structure with increasing neutron number N —see recent review articles [1,2] and earlier references therein. The experimental verification of these predictions is challenging, as the yield of any nuclear reaction, like fission or high-energy fragmentation employed for production of neutron-rich nuclei, drops down very fast with increasing distance from the line of β-stability.

One has to develop experimental methods of very high sensitivity. In this context, the in-flight identification of reaction products in a fragment separator, combined with the decay study of isomers, has proven to be especially successful [3].

During the past five years a number of new experimental results on the isomeric properties like half-life and level schemes has been obtained in neutron-rich nuclei between ^{48}Ca and ^{78}Ni. Isomers within a half-life range from about 20 ns to over 800 μs have been observed. The experiment we presently report is a continuation of the studies performed with the 60 MeV/u ^{86}Kr beam on a ^{nat}Ni target in which several new isomers around the $Z = 28$ and $N = 40$ shell closure were observed [4,5]. Among these an isomer in ^{67}Fe was reported to decay via a 367 keV γ-transition with a half-life of 43(30) μs. This half-life suggested the $M2$ character of the transition.

In our present experiment, isomers were produced through fragmentation of a 61.6 MeV/nucleon ^{76}Ge beam. The primary beam of charge state $q = 30^+$ and mean in-

[a] e-mail: sawicka@ganil.fr and sawicka@zsjlin.igf.fuw.edu.pl

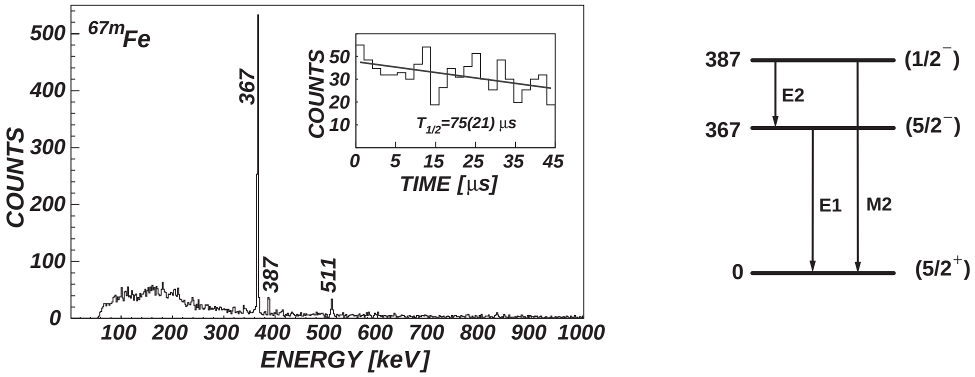

Fig. 1. Left: the γ-ray spectrum of $^{67\mathrm{m}}$Fe. In the insert, the decay pattern of the isomeric activity is shown. A weak 511 keV line is consistent with the presence of large background of long-lived β^+ emitters implanted at LISE final focus during previous experiments, and does not belong to the $^{67\mathrm{m}}$Fe decay. Right: tentative decay scheme of the 387 keV isomeric state. Position of the 367 keV level is not drawn to scale.

tensity 330 enA impinged on a rotating 500 μm thick ^{9}Be target. After separation in the LISE3 spectrometer [6], fragments were stopped in a telescope, consisting of three silicon detectors placed at the final focus. The first of them was 300 μm thick and acted as an energy loss (ΔE) detector. The two other detectors, each 500 μm thick, were used to provide redundant energy loss measurements and to obtain the total kinetic energy E. Determination of ΔE, E, the magnetic rigidity $B\rho$, and the time of flight was sufficient to identify mass A, atomic number Z and charge q of individual fragments. Three high-purity Ge detectors, two four-crystal clover and one low-energy photon spectrometer were packed in a close geometry around the telescope and were used to measure γ-radiation of the isomeric activities. The sensivity range for the detection of γ-rays was set between 40 keV and 3 MeV. The full-energy peak efficiency was found to be 12% at 200 keV. The time elapsing between the heavy-ions implantation signal and the isomeric decay was measured up to 45 μs and was recorded using standard time-to-amplitude converter (TAC) modules.

The present paper focuses selectively on the new evidence for the isomeric decay of ^{67}Fe, and on the interpretation of the results in terms of nuclear models.

The γ-ray spectrum of $^{67\mathrm{m}}$Fe is presented in fig. 1 (left). In addition to the known 367 keV line it shows a new line at 387 keV.

The intensity ratio of these lines is $I_\gamma(387)/I_\gamma(367) = 0.12(2)$. Within the experimental uncertainty, this ratio does not change with time. Our exponential χ^2 fit to the decay curve, see the insert to fig. 1 (left), yields the half-life of the isomer to be 75(21) μs. This half-life is somewhat longer than the one estimated in ref. [4] but overlapping with it within uncertainties.

It is suggested that the energy of the isomer is equal to 387 keV, and the 367 keV transition is in cascade with an unobserved highly converted 20 keV transition. In the data evaluation, the internal conversion is taken into account for the 20 keV transition, while it is negligible (at the level of 1% or less) for the 387 keV and 367 keV transitions.

The partial half-life of the 387 keV transition is 0.70(31) ms. If this transition has multipolarity $M2$, it is retarded with respect to the Weisskopf estimate by a factor of $F(M2) = 3.2(14) \times 10^3$ ($F = T_{1/2}^{\mathrm{exp}}/T_{1/2}^{\mathrm{Weisskopf}}$). If it is $E3$, the retardation factor is $F(E3) = 0.20(13)$. Other multipolarities may be disregarded. A comparison of experimental half-lives to the Weisskopf estimates for the $M2$ and $E3$ γ-transitions in neighbouring nuclei [7] gives the following intervals for the observed retardation factors: $1 \le F(M2) < 50$ and $1 \le F(E3) < 700$.

Our estimates are beyond these limits. The $E3$ enhancement by a factor of 5 could be understood only if strong octupole correlations were present. There is no structural reason to expect such correlation in ^{67}Fe. Hence, in the following we restrict our considerations to $M2$ multipolarity, and discuss the unusual retardation of the 387 keV $M2$ transition.

For the γ-ray cascade, the partial half-life is 84(25) μs. If the 20 keV transition is to precede that of 367 keV, the partial half-life indicates its multipolarity to be $E2$, the retardation factor to be $F(E2) = 1.5(4)$. Other multipolarities may be excluded. If the 367 keV transition is first, multipolarities other than $M2$ and $E3$ may be ruled out. Even for these two cases the retardation factors, $F(M2) = 3.0(9) \times 10^2$ or $F(E3) = 0.017(5)$, are outside the limits mentioned above. The choice would be $M2$, as for the 387 keV transition. This means that the spins of the isomer and the ground state differ by two units, and these two states have opposite parity. Thus, two possibilities for the cascade are considered: i) the 20 keV $E2$ transition followed by the 367 keV $E1$ transition, see fig. 1 (right), and ii) the 367 keV $M2$ transition followed by the 20 keV transition of multipolarity $M1$ (or $E2$, which would mean that the 20 keV level is another isomeric state). In the latter case, to maintain isomerism two stretched $M2$ transitions are required, one to the ground state and one to an excited state at 20 keV. As a consequence there would be a close-lying doublet of states having identical spin and parity, which in view of the single-particle structure is rather unlikely. Therefore, the following discussion in terms of nuclear models considers only the possibility i) as shown in fig. 1 (right).

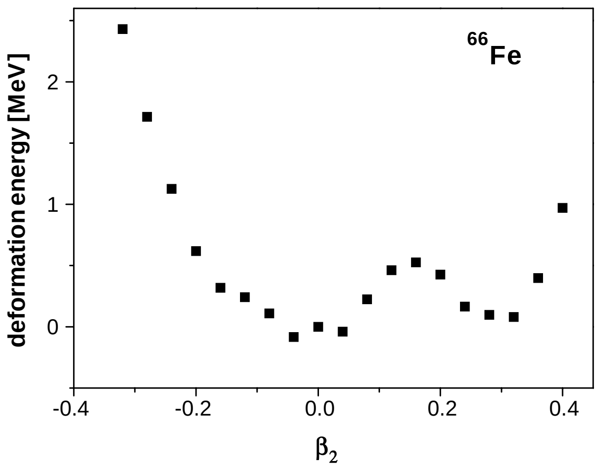

Fig. 2. Quadrupole-deformation dependence of the potential energy calculated for the nucleus ^{66}Fe.

The low energy of the 2^+ level in ^{66}Fe corresponds to a deformation $\beta_2 \approx 0.26$ [8]. In a first attempt to interpret the results, we assumed the same deformation for ^{67}Fe. The standard Nilsson model and the BCS approach (with the neutron energy gap parameter from [9]) was applied. Among the calculated quasiparticle levels, the $5/2^+$ [422] state is the lowest. Next are the $5/2^-$ [303] and $1/2^-$ [301] levels. This leads to the spin-parity assignment to the ground, intermediate and isomeric levels of ^{67}Fe in fig. 1, which would explain the transition multipolarities proposed. Qualitatively, the $M2$ hindrance is due to the fact that the $5/2^+$[422] and the $1/2^-$[301] levels originate from the spherical $0g_{9/2}$ and $1p_{1/2}$ orbitals, respectively, which cannot be connected by an $M2$ transition. A reliable estimate for the hindrance therefore requires a precise knowledge of the Nilsson wave functions to account for subtle interference effects. A crude half-life estimate of the 387 keV $M2$ transition has been obtained from the Nilsson model. Using the wave function of ref. [10], given in a spherical basis for deformation $\beta = 0.2$, which reproduces best the observed sequence of the $5/2^+$[422], $5/2^-$[303] and $1/2^-$[301] levels, a hindrance of $F = 33$ is calculated for a free nucleon $M2$ operator. To determine an effective $M2$ operator, the experimentally known $g_{9/2} \to f_{5/2}$ $M2$ transitions in ^{63,65,67}Ni were calculated in a large-scale shell model approach [11] yielding an effective g-factor of $g_s = 0.35 g_s^{\rm free}$. This single-particle transition contributes the major admixture to the forbidden transition. Including the effective operator a hindrance of $F = 270$ is calculated. In view of the assumptions made for the Nilsson wave function this agrees reasonably with the observed $M2$ retaradation.

Experimentally two other cases of highly retarded $M2$ transitions are known, which show a striking similarity to the situation we encounter in ^{67}Fe. These are the transitions $1/2^- \to 5/2^+$ in ^{101}Tc hindered by $F = 154$ [12] and $7/2^- \to 3/2^+$ in ^{127}Ba with $F = 12050$ [13]. Both nuclei are deformed with $\beta_2 = 0.18$ and 0.24, respectively. The assigned Nilsson configurations are $1/2^-$[301] and $5/2^+$[422] in the odd-proton nucleus ^{101}Tc [14], and

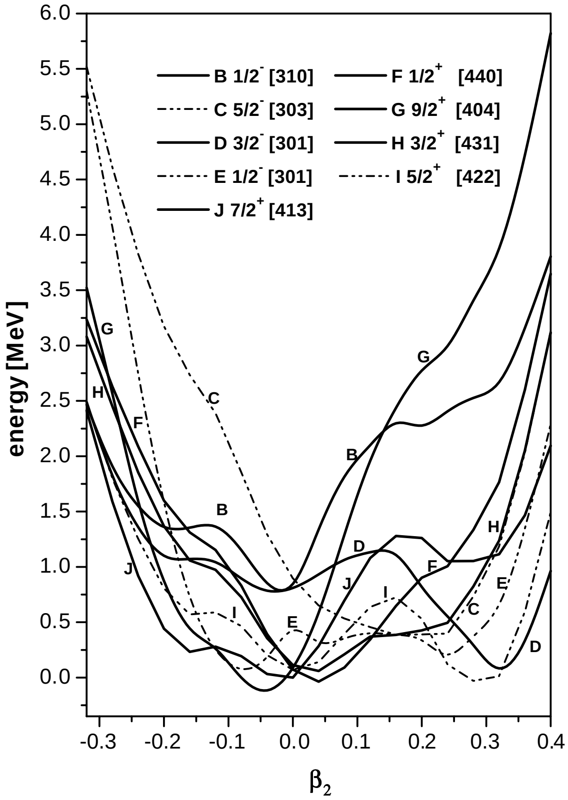

Fig. 3. Relative energies of the one-quasiparticle states calculated for the nucleus ^{67}Fe.

$1/2^+$[411] for the $3/2^+$ band member and $7/2^-$[523] in the odd-neutron case ^{127}Ba [15]. The latter configurations originate from the spherical $1d_{3/2}$ and $0h_{11/2}$ orbitals, one major shell higher than the aforementioned $1p_{1/2}$ and $g_{9/2}$ orbitals. From the striking analogy of these three cases of highly retarded $M2$ transitions, we infer deformation for ^{67}Fe and high confidence for the decay scheme i) (see fig. 1) and the tentative spin-parity assignments. Theoretical calculation yielded for the ^{66}Fe deformation either $\beta_2 = 0.27$ [16], which is compatible with [8], or $\beta_2 = 0.0$ [17]. To have an independent theoretical estimate for the deformation, we used the code MINQP5 [18] to carry out calculations based on the Strutinsky shell-correction method [19]. The macroscopic part of the total energy was assumed to be given by the Yukawa-plus exponential mass formula [20]. The shell correction was calculated using the axially deformed single-particle Woods-Saxon Hamiltonian with the "universal" parameters [21]. The nuclear surface is defined by means of standard β_λ axial-deformation parameters

$$R(\Omega) = c(\beta) R_0 \left[1 + \sum_{\lambda=2}^{6} \beta_\lambda Y_{\lambda 0}(\Omega) \right], \qquad (1)$$

with $c(\beta)$ being determined from the volume conservation condition and $R_0 = r_0 A^{1/3}$. The shell correction was calculated according to the prescription given in [22]. The energy minima have been obtained at the spherical shape $\beta_2 \approx 0.0$, and at a prolate deformation, $\beta_2 \approx 0.3$, see fig. 2. In the next step, level energies were calculated for the 41-st neutron in ^{67}Fe, for the deformation interval $-0.4 \le \beta_2 \le 0.4$, in the way described in ref. [23]. The calculations were performed for those single-particle levels in the Woods-Saxon potential which originate from the $g_{9/2}$, $p_{1/2}$ and $f_{5/2}$ orbitals, and thus are close to the Fermi level. The residual interaction was assumed to be of the monopole pairing type. The Lipkin-Nogami method was applied with account for blocking effect. The results are shown in fig. 3, where the individual levels are labelled with the Nilsson-model quantum numbers $[N, n_3, \Lambda]$. The minimum at $\beta_2 = 0.0$ is slightly deeper than that at $\beta_2 = 0.3$. However, the assumption of the spherical shape does not allow for a straightforward interpretation of our results. We focus our attention, therefore, on the deformed minimum. The $5/2^+$ [422] level is likely to be the ground state. For the isomer one has then a unique assignment of $1/2^-$ [301], and the intermediate state must be $5/2^-$ [303]. The fact that the latter two states appear in fig. 3 to be inverted means perhaps that the energy distance between the $p_{1/2}$ and $f_{5/2}$ shell model states is somewhat different than calculated. This more advanced calculation leads to the same conclusions as the original simple BCS approach. While the model considerations provide a qualitative interpretation of the isomerism observed in ^{67}Fe, more advanced theoretical studies are obviously needed to explain the unusual retardation of the 387 keV $M2$ transition quantitatively. One should presumably account for a mixing of single-particle and collective degrees of freedom. There may be also an effect of different deformation in the ground and isomeric state. In conclusion, the inferred decay scheme and tentative spin-parity assignments for the ^{67}Fe isomer provide convincing evidence for the existence of deformation in this neutron-rich region of the fpg shell, near $N = 40$.

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References

1. H. Grawe *et al.*, AIP Conf. Proc. **561**, 287 (2001).
2. H. Grawe, M. Lewitowicz, Nucl. Phys. A **693**, 116 (2001).
3. R. Grzywacz *et al.*, Phys. Lett. B **355**, 437 (1995).
4. R. Grzywacz *et al.*, Phys. Rev. Lett. **81**, 766 (1998).
5. J. M.Daugas *et al.*, Phys. Lett. B **476**, 213 (2000).
6. R. Anne *et al.*, Nucl. Instrum. Methods A **257**, 215 (1987).
7. R.B. Firestone, *Table of Isotopes*, 8th ed. (John Wiley & Sons Inc., New York, 1986).
8. M. Hannawald *et al.*, Phys. Rev. Lett. **82**, 1391 (1999).
9. A.S. Jensen, P.G. Hansen, B. Jonson, Nucl. Phys. A **431**, 393 (1984).
10. J.P. Davidson, *Collective Models of the Nucleus* (Academic Press, New York, 1968).
11. H. Grawe *et al.*, Nucl. Phys. A **704**, 211 (2002).
12. H. Bartsch *et al.*, Z. Phys. A **285**, 273 (1978).
13. C.F. Liang *et al.*, Z. Phys. A **299**, 185 (1981).
14. H. Dejbakhsh *et al.*, Phys. Rev. C **44**, 119 (1991).
15. D. Ward *et al.*, Nucl. Phys. A **539**, 547 (1992).
16. Y. Aboussir *et al.*, At. Data Nucl. Data Tables **61**, 127 (1995).
17. S. Goriely *et al.*, At. Data Nucl. Data Tables **77**, 311 (2001).
18. S. Ćwiok *et al.*, Comput. Phys. Commun. A **573**, 379 (1987).
19. V.M. Strutinsky, Nucl. Phys. A **95**, 420 (1967).
20. P. Möller, J.R. Nix, Nucl. Phys. A **361**, 117 (1981).
21. J. Dudek, Z. Szymański, T. Werner, Phys. Rev. C **23**, 920 (1981).
22. M. Brack *et al.*, Rev. Mod. Phys. **44**, 320 (1972).
23. S. Ćwiok *et al.*, Nucl. Phys. A **573**, 356 (1994).