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Hindered E4 decay of the 12^+ yrast trap in ^{52}Fe

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Abstract

The γ decay of the 12^+ yrast trap in ^{52}Fe has been measured for the first time. The two E4 γ-branches to the 8^+ states are hindered with respect to other $B(\mathrm{E4})$ reduced transition probabilities measured in the $f_{7/2}$ shell. The interpretation of the data is given in the full pf shell model framework, comparing the results obtained with different residual interactions. It is shown that measurements of hexadecapole transition probabilities constitute a powerful tool in discriminating the correct configuration of the involved wavefunctions.

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High multipole moments in nuclei are considered to be a vital source of information in nuclear structure studies connected with shape phenomena [1]. In particular electric hexadecapole moments and transition strengths are experimentally accessible and provide information on features that are independent of the quadrupole structure of the nucleus and therefore contribute to test the theoretical models and, in particular, to reduce the degrees of freedom in the effective nuclear interaction.

As pointed out in Refs. [1,2], the calculation of E4 transition strength seems to be more sensitive to model details than the E2 transitions and therefore it has a higher discrimination power when identifying individual components in the nuclear wave function. In particular, in the sd shell, the $B(\mathrm{E2})$ values for the transition to the ground state in even–even nuclei do not change very much from nucleus to nucleus while the $B(\mathrm{E4})$ values show drastic changes. Interestingly, the investigation of E4 transitions has allowed to determine a significant hexadecapole collectivity of 4^+ states in closed shell nuclei ($A \sim 132$, $A \sim 208$) (see Ref. [3] for a systematic survey).

Electric hexadecapole moments in stable $N = Z$ nuclei were studied in the past in sd-shell nuclei by inelastic scattering with several probes (electrons, protons, α-particles) [2,4]. Such experiments cannot be done for heavier $N = Z$ nuclei without resorting to radioactive beam facilities. With the recent developments in detection techniques, information of transition strengths can be directly obtained by γ-ray spectroscopy. Whenever γ-transition probabilities are compatible with the detection sensitivity, these measurements give more complete information than that deduced by using scattering techniques. Moreover, γ-ray spectroscopy allows to measure hexadecapole transitions from high spin states.

In the past few years, considerable effort has been put into the study of high spin states in $f_{7/2}$-shell nuclei. It has been shown that near the middle of the shell (^{48}Cr) nuclei present strong deformation [5–8]. Heavier nuclei, like ^{52}Fe, are less deformed due to their proximity to the $N, Z = 28$ shell closure. In such cases one often encounters isomeric states and even inversion of states in the yrast line creating spin traps that decay by high multipolarity transitions.

Recently, Ur et al. [9] have studied the high spin structure of ^{52}Fe with the γ-ray detector array GASP [10]. The level scheme of ^{52}Fe has been extended up to the 10^+ state at 7.4 MeV excitation energy, lying above the yrast 12^+ isomer, thereby confirming the predicted inversion [11,12] of the yrast 10^+ and 12^+ states. From a β^+-decay end-point measurement the excitation of the 12^+ state was determined with an accuracy of the order of hundred keV, and the half-life of the isomer was measured to be 45.9(6) s [12]. The 12^+ isomer mainly decays (99.98%), by Gamow–Teller transitions, into excited states of the daughter nucleus ^{52}Mn.

In this Letter we report on the measurement of the E4 γ-decay of the 12^+ yrast trap in ^{52}Fe to the two known 8^+ states. The experiment was performed at the GSI on-line mass separator, where a 2.5 mg/cm^2 thick $^{\mathrm{nat}}$Si target was bombarded by a 170 MeV ^{36}Ar beam delivered by the UNILAC accelerator. The estimate of the cross section, performed with HIVAP [13], for this reaction, gives a population of ≈ 13 mb for ^{52}Fe, above the 12^+ isomer.

The recoiling reaction products were stopped in the graphite catcher of a FEBIAD-E type ion source [14]. After ionisation and extraction from the ion source, the mass separated $A = 52$ beam was implanted in a tape which moved every 80 s, taking away the undesirable long-lived activity.

The implantation position was surrounded by a plastic scintillator, with a β-detection efficiency of $\sim 85\%$ (measured with a ^{24}Na source), two composite germanium (Ge) detectors of the Cluster [15] and large Clover [16] type, and a 60% single Ge crystal. The setup included a second single crystal low-energy Ge detector, as shown in Fig. 1, but was not relevant for the present analysis. The photopeak efficiency of the Ge setup was 3.9% for a γ-ray energy of 1.33 MeV, which improved the detection sensitivity limit by a factor of 100 compared to that achieved in the previous study [12]. The large segmentation of the detection system (12 independent large volume Ge crystals) was essential to keep the summing losses within a reasonable limit, i.e., below 10% for large multiplicity cascades. By using a complete Monte Carlo simulation of the setup performed with the GEANT3 library [17], the summing perturbation to all measured quantities was estimated to be far below the respective experimental uncertainties.

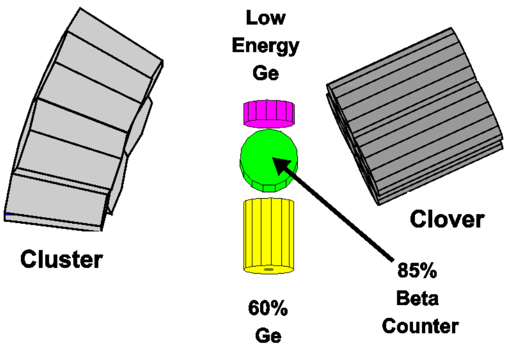

Fig. 1. Sketch of the β–γ detection setup at the GSI on-line mass separator. The $A = 52$ beam is implanted into a tape which is not shown. The implantation position is in the center of the β-detector. Collimation system, tape and β-detector are mounted in a vacuum chamber, while the Ge detectors are positioned around the chamber.

The total measurement time amounted to 32 hours with a production rate of $\approx 4.5 \times 10^4$ atoms/s. β–γ–γ and γ–γ coincidence events were recorded and afterwards sorted into 3D-cubes and 2D-matrices. The analysis of the γ–γ coincidences, including the "add-back" of the composite detectors and a veto condition derived from the β counter allowed us for the first time to observe the γ de-excitation of the 12^+ isomer to the 8_1^+ and 8_2^+ at 6360 and 6493 keV states via E4 transitions of 597 and 465 keV, respectively. The anti-coincidence with the β counter served to reduce the background contribution from β-delayed γ-rays. The resulting spectrum is shown in Fig. 2.

The new transitions fix the excitation energy of the 12^+ isomer at 6957.5(4) keV (see Fig. 3). This value is significantly more accurate than the previous result deduced from β-decay measurements [12].

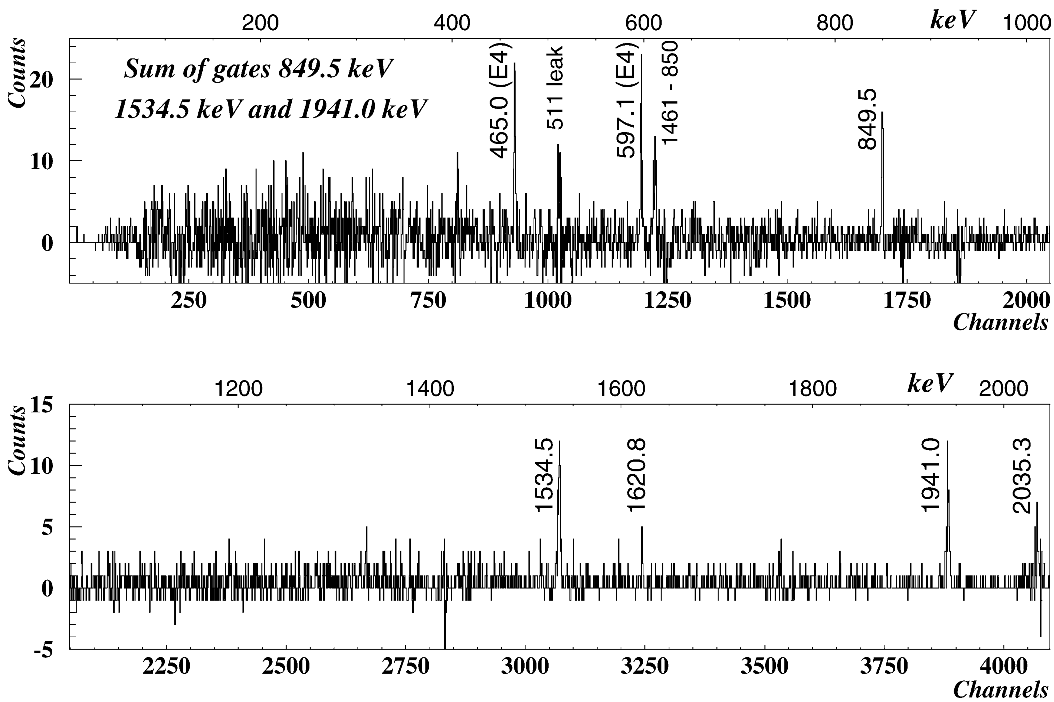

Fig. 2. Spectrum obtained in coincidence with strong transitions in ^{52}Fe and in anti-coincidence with the β-counter. In the spectrum there is a small "leak" of the large β^+ annihilation peak, due to the background subtraction procedure, and a peak coming from the Compton back-scattering of the 1461 keV background transition (1461–850 keV). The gamma transitions belonging to ^{52}Fe are marked by their energies in keV.

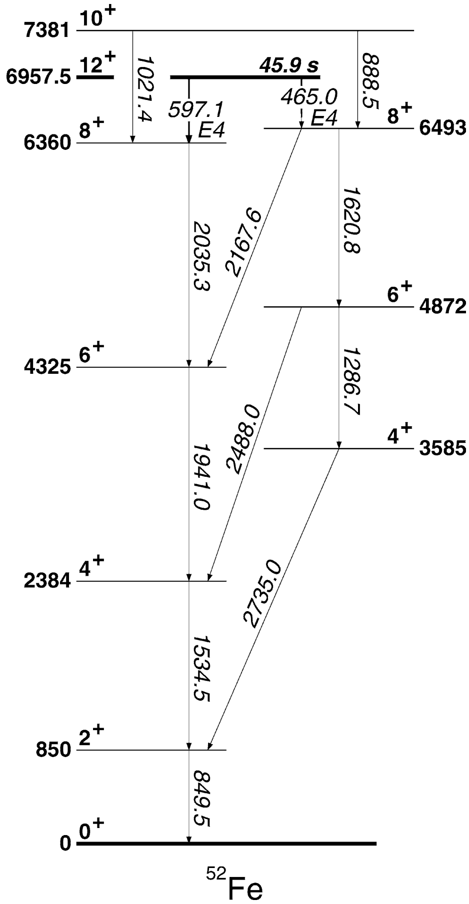

Fig. 3. Level scheme of the ^{52}Fe 12^+ isomer decay. Transitions from the higher lying 10^+ state at 7381 keV observed in a in-beam study [9] are shown.

From the spectrum shown in Fig. 2 it is evident that the 465 and 597 keV transitions have similar intensities. Their E4 transition probabilities, however, are strikingly different due to the strong dependence on the latter quantities upon the transition energy. The transition intensities per isomer decay have been estimated to be $1.2(4) \times 10^{-4}$ for the 597 keV ($12^+ \rightarrow 8_1^+$) transition and $0.9(3) \times 10^{-4}$ for the 465 keV ($12^+ \rightarrow 8_2^+$) transition. These results are based on the combined information of γ–γ coincidence matrices with and without β-detector veto. Two methods have been used to determine the intensities. The first one consisted on determining the absolute intensity of the 850 keV $2^+ \rightarrow 0^+$ transition in ^{52}Fe starting from the γ-ray spectrum in anti-coincidence with the β-detector. The intensity of the β-decay branch has been obtained from the total spectrum without any condition. All the intensity populating the 2^+ in ^{52}Fe is expected to go through the two E4 transitions, and since the relative intensities of these two transitions are easily obtained from the γ–γ coincidence matrix, it is possible to evaluate the intensity of each transition compared to the total isomer decay rate. The second method to determine the intensities is based exclusively on the γ–γ coincidences. Considering a 100% intensity for the E2 850 keV transition to the ground state and the measured absolute efficiencies of the setup for this and the observed E4 transition, the determination of the intensity of the latter is straightforward. Also in this case the β-decay branch intensity is determined from the total spectrum. Both methods gave the same values.

The evaluated intensities reflect very low E4 transition probabilities: 1.1(4) e^2 fm^8 ($4.6(17) \times 10^{-4}$ W.u.) and 8(3) e^2 fm^8 ($3.5(13) \times 10^{-3}$ W.u.) for the 597 keV and 465 keV transitions, respectively. If one compares the ^{52}Fe data with the B(E4) observed in other $f_{7/2}$-shell nuclei (see Table 1), to obtain the lowest value, corresponding to ^{52}Mn (0.138 W.u.), partial deexcitation branches that are ~ 300 and ~ 40 times higher than those observed for the 597.1 keV and 465.0 keV transitions, respectively, would be needed. This explains why these transitions where not observed in previous studies [12].

To interpret these results we have performed calculations in the shell model framework with the code ANTOINE [18] in the full pf model space. Three different residual interactions have been used, namely the FPD6 [19], the KB3G [20], and the recently introduced GXPF1 [21] interactions. The effective charges used to calculate the B(E4) reduced transition probabilities are the same as those used to obtain the B(E2) values, i.e., $e_p = 1.5$ and $e_n = 0.5$ [9]. A recent measurement of the $2_1^+ \rightarrow 0^+$ B(E2) value in ^{52}Fe, using Coulomb excitation techniques [22], is in excellent agreement with the calculation performed in Ref. [9].

The calculated energies and reduced transition probabilities of the two E4 transitions in ^{52}Fe are confronted with the experimental data in Table 2. All calculations overestimate the experimental values. The best description is achieved by the FPD6 interaction while both the KB3G and GXPF1 calculations fail in reproducing even the order of magnitude of the B(E4)

Table 1
Experimental E4 systematics for $f_{7/2}$-shell nuclei

	E_γ (keV)	$J_i \to J_f$	$T_{1/2}$	γ branch	B(E4) (W.u.)
^{44}Sc	271	$6^+ \to 2^+$	58.61 h	0.988	1.42
^{46}Ti	2010	$4^+ \to 0^+$	1.62 ps		1.6[a]
^{52}Mn	378	$2^+ \to 6^+$	21.1 min	0.0175	0.138
^{52}Fe	597	$12^+ \to 8^+_1$	45.9 s	$1.2(4) \times 10^{-4}$	$4.6(17) \times 10^{-4}$
^{52}Fe	465	$12^+ \to 8^+_2$	45.9 s	$9(3) \times 10^{-5}$	$3.5(13) \times 10^{-3}$
^{53}Fe	701	$19/2^- \to 11/2^-$	2.52 min	0.9866	0.256
^{54}Fe	3578	$10^+ \to 6^+$	364 ns	0.019	0.79

[a] The experimental B(E4) value for the $4^+ \to 0^+$ in ^{46}Ti obtained from the γ-intensity measurements reported in Ref. [23] (B(E4) = 400(300) W.u.) is inconsistent with the values expected in the region. This discrepancy is not understood. However, agreement with the expectations is obtained by using the B(E4) value extracted from the hexadecapole deformation measured in Ref. [24] (B(E4) ≈ 1.6 W.u.).

Table 2
Experimental and calculated energies and reduced transition probabilities of the two E4 transitions in ^{52}Fe and previously known E4 transitions in $f_{7/2}$-shell nuclei

	$J_i \to J_f$	E_γ (keV)				B(E4) (W.u.)			
		Exp	FPD6	KB3G	GXPF1	Exp	FPD6	KB3G	GXPF1
^{52}Fe	$12^+ \to 8^+_1$	597	1227	907	888	$4.6(17) \times 10^{-4}$	2.4×10^{-3}	3.3×10^{-1}	6.5×10^{-2}
^{52}Fe	$12^+ \to 8^+_2$	465	519	700	756	$3.5(13) \times 10^{-3}$	4.7×10^{-3}	2.6×10^{-2}	2.3×10^{-2}
^{44}Sc	$6^+ \to 2^+$	271	674	373	281	1.42	1.96	1.79	1.65
^{46}Ti	$4^+ \to 0^+$	2010	1966	1819	2000	1.6	10.7	7.9	7.39
^{52}Mn	$2^+ \to 6^+$	378	205	91	213	0.138	0.272	0.422	0.728
^{53}Fe	$\frac{19}{2}^- \to \frac{11}{2}^-$	701	990	883	776	0.256	0.151	1.23	0.84
^{54}Fe	$10^+ \to 6^+$	3578	3660	3838	3306	0.79	1.80	0.98	1.25

values. Both interactions yield a higher value for the B(E4) $12^+ \to 8^+_1$ transition, in contrast with the experimental findings.

It is interesting to see how these interactions reproduce the other B(E4) values known in the $f_{7/2}$ shell. The results obtained with the three interactions are listed in Table 2 together with the corresponding experimental data. A full pf calculation has been performed for ^{44}Sc, ^{46}Ti and ^{52}Mn, whereas for ^{53}Fe nine of the thirteen valence particles have been allowed to be excited to orbitals above the $f_{7/2}$ one, and for ^{54}Fe a truncation to eight of the fourteen valence particles has been made. As shown in Table 2, all interactions reproduce with the same good accuracy the experimental B(E4) data of these nuclei.

In Fig. 4, the ratios between the experimental and theoretical reduced transition probabilities are shown for all the measured E4 transitions in the $f_{7/2}$-shell nuclei. It is evident that both the KB3G and GXPF1 interactions fail in the case of ^{52}Fe. A possible ori-

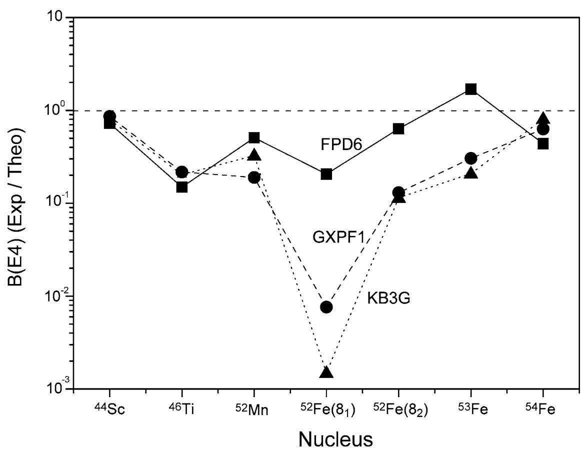

Fig. 4. Ratio between experimental and theoretical B(E4) values for nuclei in the $f_{7/2}$ shell. Results obtained by using the FPD6, GXPF1 and KB3G interactions are shown by squares (full line), full circles (dashed-line) and triangles (dotted-line), respectively. See Table 2 for details.

Table 3
Proton (or neutron) occupation numbers for the states of interest in ^{52}Fe

	$f_{7/2}$	$p_{3/2}$	$f_{5/2}$	$p_{1/2}$
FPD6				
8_1^+	4.64	0.50	0.71	0.15
8_2^+	5.27	0.35	0.32	0.06
12_1^+	5.43	0.26	0.26	0.05
KB3G				
8_1^+	5.70	0.15	0.21	0.04
8_2^+	5.02	0.30	0.57	0.10
12_1^+	5.63	0.14	0.19	0.03
GXPF1				
8_1^+	5.20	0.30	0.41	0.08
8_2^+	5.37	0.30	0.26	0.06
12_1^+	5.67	0.19	0.12	0.02

gin of this failure could arise from the fact that both 8^+ states in ^{52}Fe are very close in excitation energy (see Table 2), and therefore these calculations could mix the configurations of the two levels or invert their order. A possible way to check the quality of the interactions in describing the two 8^+ states is to calculate the quadrupole transition probabilities $B(\mathrm{E2})$ for their decay to the 6_1^+ state and compare the predictions with the measured values [9]. Unfortunately, all the reduced transition probabilities are of the same order and the experimental uncertainties do not allow a discrimination.

To get a better understanding of the wave functions, we report in Table 3 the occupation numbers (protons and neutrons are equivalent in an $N = Z$ nucleus) of the different orbits for the states involved in the E4 decay. While the 12^+ states have similar occupations with any of the interactions, the 8^+ states are different. The 8_1^+ level obtained with FPD6 is the most collective one, followed by the 8_2^+ state obtained with KB3G.

To elucidate these discrepancies, we have computed the wave function overlaps between the 8^+ states and between the 12^+ states calculated by using different interactions. As expected, the overlap between the yrast 12^+ wave functions obtained with any of the interactions are $\geqslant 0.96$, which implies that the 12^+ states described by all the Hamiltonians almost coincide. When comparing the 8^+ states calculated with the FPD6 and KB3G interactions, vanishing overlaps are obtained between the yrast 8_1^+ state and between the yrare 8_2^+ state. On the contrary, an overlap of ~ 0.93 is obtained between the 8_1^+ FPD6 state and the 8_2^+ KB3G state, and vice versa between the 8_2^+ FPD6 state and the 8_1^+ KB3G state. This inversion of the 8^+ states could explain the fact that the $B(\mathrm{E4})$ values obtained with the KB3G interaction, when compared with experiment, are inverted in strength. In the case of the GXPF1 interaction, the two 8^+ states are similar, which translates in similar overlaps (~ 0.60–0.70) with the 8_1^+ and 8_2^+ states of FPD6 and KB3G wave functions.

As mentioned above, the $B(\mathrm{E4})$ values have been obtained with the effective charges used to reproduce the quadrupole transition probabilities in ^{52}Fe and neighboring nuclei. As for $N = Z$ nuclei, the $B(\mathrm{E4})$ transition probability is proportional to $(e_p + e_n)^2$, it is the square of the *sum* of the effective charges which enters as a multiplicative factor. In a very recent work [25], the polarization charges have been deduced from $B(\mathrm{E2})$ values measured for the mirror pair $A = 51$, obtaining $e_p = 1.15$ and $e_n = 0.8$. The use of these effective charges would not change the present results for the $B(\mathrm{E4})$ values in ^{52}Fe. The need of using very large or even negative polarization charges to reproduce the systematics of the $B(\mathrm{E4})$ values in this mass region has been discussed by Yokoyama [26]. In the latter work, however, shell model calculations were performed in strongly truncated spaces ($f_{7/2}^n$ or $f_{7/2}^n + f_{7/2}^{n-1}(p_{3/2}, p_{1/2}, f_{5/2})^1$). Even if it is out of the scope of the present study to fit the polarization charges, it is interesting to note that enlarging the model space has allowed us to reproduce on the same footing all the hexadecapole transition probabilities known for $f_{7/2}$-shell nuclei by using the same polarization charges.

Finally, the origin of the hindrance of the $B(\mathrm{E4})$ values in ^{52}Fe, can be understood from the hexadecapole strength distribution. Using the different residual interactions, we have calculated the E4 strength from the 12^+ isomer to all the $I^\pi = 8^+$ states in the pf shell model space. As expected, the results indicate that most of the E4 strength is located at excitation energies higher than the 12^+ state. In fact, only up to few per cent (10% for KB3G, 2% for GXPF1 and 0.2% for FPD6) of the E4 strength is predicted to feed the first and second experimentally observed 8^+ states.

In conclusion, the combination of in-beam and off-beam (ISOL) experiments has allowed us for the first time to observe the γ-decay of the ^{52}Fe 12^+ yrast trap and to establish its excitation energy. Two γ-rays of 597 keV and 465 keV have been assigned to be the E4 transitions feeding the 8_1^+ and 8_2^+ states, respectively. These two transitions are strongly hindered compared to any other E4 transition in the region. From large scale shell model calculations performed in the full pf space it has been shown that the hexadecapole transitions can give vital information to distinguish the more realistic wave function from those predicted by different interactions, which might be indistinguishable on the basis of $B(\mathrm{E2})$ measurements.

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