Possible Shape Transition in the Yrast Band of ^{56}Fe

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Spin and parity assignments and lifetime measurements on high-spin states of ^{56}Fe have been made by γ-ray spectroscopy in various reactions. The results show that the first 6^+ and 8^+ states are not members of the ground-state rotational band with prolate deformation, indicating a sudden change in nuclear shape at $J > 4$ along the yrast band of ^{56}Fe.

According to the recent shell-model approach to nuclear collective motion,[1,2] a typical rotational spectrum appears in a nucleus which has active protons and neutrons moving in different shell orbits. The nucleus ^{56}Fe, having two proton holes in the $f_{7/2}$ orbital and two neutrons in the $p_{3/2}$, $f_{5/2}$, and $p_{1/2}$ orbitals inside and outside the ^{56}Ni core, respectively, therefore provides one of the simplest among systems that are expected to show a rotational structure. In fact, the shell-model calculation of Horie and Ogawa[2] based on the above configuration predicts rotationlike levels up to 10^+. On the other hand, ^{56}Fe stands close to the spherical region of nickel isotopes, and could qualify for shape coexistence or shape transition which is known in various soft or transitional nuclei.[3] Experimentally, the first 2^+ (847 keV) and 4^+ (2085 keV) states of ^{56}Fe are known to be members of the ground-state quasirotational band (gsb) with prolate deformation.[4] The third member of the gsb often cited in the literature[5] is the 3388-keV state with proposed J^π assignment of 6^+.[6,7] Another candidate for the 6^+ state belonging to the gsb is the 3755-keV state, to which conflicting J^π assignments have been given, i.e., $J^\pi = 6^+$ (Ref. 6) and $J = 5$ (Ref. 7). In this note we present J^π assignments and lifetimes for several high-spin states of ^{56}Fe, which confirm the existence of the two 6^+ states and give evidence for marked deviation of the gsb from the yrast states. We then compare the results with the shell-model calculation,[2] and try to show a possible change in nuclear shape along the yrast band of ^{56}Fe.

^{56}Fe was studied by in-beam γ-ray spectroscopy in three reactions, ^{50}Cr(^{12}C, $\alpha 2p$), ^{54}Fe(α, $2p$), and ^{56}Fe(α, α), using the FN tandem accelerator of Saclay. All targets used were isotopically enriched to more than 95%. γ rays were detected with two 80-cm^3 Ge(Li) counters. The present experiment consists of (i) excitation functions measured in 2-MeV steps, from 26 to 58 MeV with the ^{12}C beam and from 12 to 24 MeV with α particles; (ii) γ-γ coincidence spectra taken in the ^{50}Cr + ^{12}C (48 MeV) and ^{56}Fe + α (24 MeV) reactions; (iii) γ-ray angular distributions measured in all reactions at various energies; and (iv) lifetime measurements using the ^{54}Fe + α reaction at 20 and 24 MeV.

Figure 1 shows the γ-ray decay scheme established in this work together with calculated levels of Horie and Ogawa.[2] Our level scheme is simi-

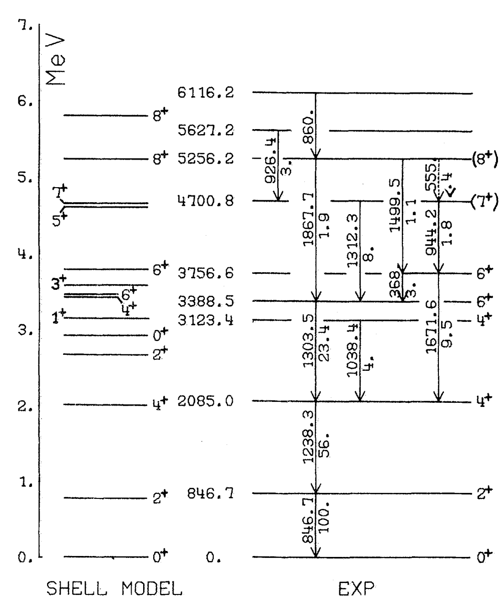

FIG. 1. Right: Experimental decay scheme of ^{56}Fe established in this work. Given relative intensities are those obtained in the reaction ^{54}Fe(α, $2p$) for a thick target at 24 MeV (the 860-keV γ ray was not observed in this reaction, but confirmed in the ^{50}Cr + ^{12}C reaction). Energies are given in keV. Left: Calculated levels of ^{56}Fe, taken from Ref. 2.

lar, for the location of levels, to that of Poletti *et al.*,[7] but contains several new transitions between high-spin states. The J^π assignments shown in Fig. 1 were mainly based on γ-ray angular distributions and correlations, where the γ-γ coincidence data taken at 0° and 90° were used for the analysis of directional correlation from oriented nuclei.[8] In addition, results of lifetime measurements were often helpful to limit possible γ-ray multipolarities. Figure 2(a) shows angular distributions of 1303.5- and 1671.6-keV γ rays (see also Fig. 1), from which we conclude that the relevant 3388.5- and 3756.6-keV states have either $J=6$ or $J=4$ (the mixing ratio $\delta \approx 1$). The $J=4$ assignment to the 3388.5-keV state is, however, quite improbable when we consider the relatively high population to this state (note that the 3123.4-keV level of $J^\pi = 4^+$ is very weakly populated). Consequently, the 3756.6-keV state must have $J=6$ becuase the 368-keV transition is too strong to be a pure quadrupole transition. Positive parities were attributed to these states from their lifetimes described later.

The lifetime measurements were performed

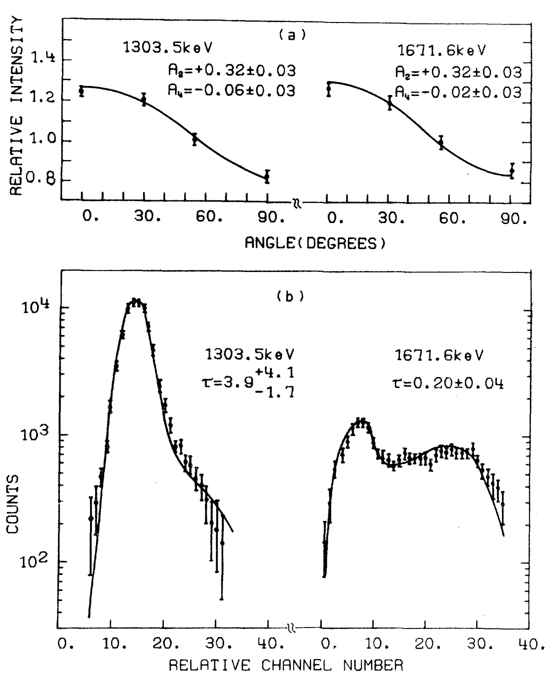

FIG. 2. (a) Angular distributions of the 1303.5- and 1671.6-keV γ rays measured in the $^{54}Fe+\alpha$ (24 MeV) reaction using a thick target. Solid curves show best fits with $W(\theta) \propto 1 + A_2P_2(\cos\theta) + A_4P_4(\cos\theta)$. (b) Line shapes of the same γ rays observed at 30°. Solid curves show best fits obtained without considering the side-feeding effect.

with the Doppler-shift attenuation method in the reaction $^{54}Fe(\alpha, 2p)$ under two different conditions: (i) with a thick (more than 100 mg/cm^2) target bombarded at 24 MeV and (ii) with a relatively thin (around 1.5 mg/cm^2) self-supporting target at 20 MeV. Line shapes of the single γ rays measured at various angles between 0° and 90° were analyzed with the code SHAPE6.[9] As examples, we show, in Fig. 2(b), experimental line shapes of the 1303.5- and 1671.6-keV γ rays. The recoil velocity was calculated, in a manner similar to that of Urbon, Sarantites, and Rutledge,[10] under the assumption that the above reaction proceeds via the formation of a compound nucleus. Since the present analysis is based on the single-γ-ray spectra, it is essential to take the feeding time of levels properly into account. Lifetimes of all observed transitions populating relevant states were therefore included in our analysis. As for the unobserved feeding fraction which is often called "side feeding," we first performed the analysis without considering its effect. The shortest mean life thus obtained turned out to be around 0.15 psec for the 4700.8-keV state, indicating very short lifetimes for unobserved transitions. Then we repeated the analysis by assuming a 0.1-psec lifetime for the side feeding in each state (this value appears reasonable from the results of Ref. 10), and adopted the average between two values obtained in different treatments. It should be noted, however, that lifetimes which resulted from both treatments agree well within experimental errors except for the 3123.4- and 4700.8-keV states, for which we increased errors by a factor two so that they cover each value well. The results are summarized in Table I together with branching and mixing ratios and $B(E2)$ values for some transitions.

The striking and new feature that comes out of this work is the surprisingly low $B(E2{:}6_1^+ \to 4_1^+)$ value and the collective character of the 2_1^+, 4_1^+, and 6_2^+ states (see Table I). In order to see this fact more quantitatively, we calculated $B(E2)$ using the symmetric-rigid-rotor model with $\beta = 0.22$, where β is the conventional deformation parameter; the adopted value of β is consistent with the static quadrupole moment of the 2_1^+ state measured by Lesser *et al.*[4] The results given in Table I clearly support the rotational-model description for the 2_1^+, 4_1^+, and 6_2^+ states, but not for the 6_1^+ state. The 5256.2-keV state with the most probable J^π assignment of 8^+ does not show the collective enhancement in a transition either to the 6_1^+ state or to the 6_2^+ state. This indicates

TABLE I. Properties of γ-ray transitions of ^{56}Fe deduced in this work.

$J_i \to J_f$	E_γ (keV)	Branching ratio[a]	Mixing ratio[a] (E2/M1)	Meanlife of J_i (psec)			$B(E2)$ (e^2fm^4)		
				Present	Previous	Adopted	Experiment	Rotor model[b]	Shell model[c]
$2_1^+ \to 0_g^+$	846.7	1			$9.7\pm.3$[d]	$9.7\pm.3$	193±6	181	179
$4_1^+ \to 2_1^+$	1238.3	1		$.95^{+.35}_{-.20}$	$1.0^{+.6}_{-.3}$[e]	$.95^{+.35}_{-.20}$	295±79	258	234
$4_2^+ \to 4_1^+$	1038.4	1	$-.16\pm.11$ $1.26\pm.26$	$.19\pm.08$	$.065^{+.07}_{-.04}$[e]	$.11^{+.06}_{-.04}$			
$6_1^+ \to 4_1^+$	1303.5	1		$3.9^{+4.1}_{-1.7}$		$3.9^{+4.1}_{-1.7}$	56^{+43}_{-29}	285	53
$6_2^+ \to 4_1^+$	1671.6	.76±.05		$.20\pm.04$	$.18\pm.03$[f]	$.19\pm.03$	250±43	285	152
$\to 6_1^+$	368.0	.24±.05	.00±.05						
$(7^+) \to 6_1^+$	1312.3	.82±.03	.08±.08	$.12\pm.04$		$.12\pm.04$			
$\to 6_2^+$	944.2	.18±.03							
$(8^+) \to 6_1^+$	1867.7	.73±.04		$.45^{+.17}_{-.09}$	$.49\pm.05$[f]	$.48\pm.05$	55±7	297	45
$\to 6_2^+$	1499.5	.27±.04					60±11	297	29

[a] Average values obtained in the three reactions described in text.
[b] Calculated from the rigid-rotor model with $\beta = 0.22$ and $R_0 = 1.2A^{1/3}$ fm by assuming that every transition belongs to the gsb.
[c] Taken from Ref. 2, where effective charges for proton and neutron are assumed to be $2e$ and e, respectively.
[d] From Ref. 11.
[e] From Ref. 12.
[f] From Ref. 10.

that the gsb deviates, also at $J^\pi = 8^+$, from the yrast line of ^{56}Fe. The 8^+ state belonging to the gsb was not observed in this work although it is expected to lie at around 5.9 MeV from the $I(I+1)$ law and the shell-model calculation.[2]

In view of the present J^π assignments, we realized that the calculation of Horie and Ogawa[2] was one of the most accurate descriptions of ^{56}Fe. In cases where the comparison is possible, their calculated levels agree remarkably well with experiment as shown in Fig. 1. The last column of Table I shows their calculated $B(E2)$ values, which also reproduce well the general trend of the experimental $B(E2)$ although their absolute values depend on effective charges used. It is therefore quite meaningful to examine their wave functions for the understanding of the nature of the observed two 6^+ states. According to their calculations, the 6_1^+ state is mainly composed of the simple seniority-two state where two proton holes are coupled to $j = 6$ and two neutrons are coupled to $j = 0$. On the contrary, the wave function of the 6_2^+ state is much more complex. There is no dominant configuration in its wave function which mainly consists of various seniority-four states. Complex configurations of this kind also appear in the ground, 2_1^+, and 4_1^+ states. The similar features as mentioned above in the wave functions of the 6_1^+ and 6_2^+ states have also been pointed out by Paar.[13] The static quadrupole moment of the 6_2^+ state calculated in Ref. 2 is $-110e$ fm^2, and is consistent with prolate deformation suggested from our experiment. In contrast with this, the 6_1^+ state has a large positive quadrupole moment ($+350e$ fm^2) as easily expected from its main configuration.

To summarize, the experimental and theoretical results mentioned above suggest that a transition from prolate rotational states to oblate (but not very collective) states takes place at around 3.4 MeV in the yrast band of ^{56}Fe. This is consistent with the Hartree-Fock calculation of Parikh,[14] who predicted that a prolate shape is energetically favored in ^{56}Fe, and an oblate shape will appear at about 3 MeV. Whether or not collective states with permanent deformation will appear again as yrast levels at higher excitation energies is an interesting problem open to future study. Another important point to be noted in this work is that electric transitions between levels of different shape such as the $6_1^+ \rightarrow 4_1^+$ transition are not extremely hindered. This gives a practical support for a treatment of Jaffrin[15] in the aligned-coupling-scheme calculation, where the mixing of prolate and oblate components is allowed.

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Time Evolution of Heavy-Ion–Induced Fission Studied by Crystal Blocking

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The shapes of crystal-blocking angular distributions have been used to study the fission decay of excited compound nuclei produced by bombardment of tungsten with ^{16}O ions. The results show that while most of the fission decays (~ 80%) occur with lifetimes too short to be measured by the blocking technique ($\tau \lesssim 10^{-18}$ sec), a large fraction (~ 20%) corresponds to lifetimes $\tau \gtrsim 10^{-16}$ sec. This indicates a significant contribution from fission after evaporation of several neutrons.

Applied to the measurement of very short nuclear lifetimes, ~10^{-15}–10^{-18} sec, the crystal-blocking technique is basically a recoil-distance method where the characteristic recoil distance $v\tau$ ranges from ~10^{-8} to 10^{-9} cm.[1,2] Extraction of a unique lifetime from the measured blocking dip requires that the compound-nucleus decay can be approximated as a simple exponential, corresponding to a well-defined lifetime. In reactions where many different levels of the compound nucleus may be formed, this requirement is not always fulfilled. We report here on a new application of the crystal-blocking technique to study the time evolution of compound nuclei which