Decay scheme and magnetic moment of a new isomeric state in ^{86}Y

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A new isomeric state has been identified at 302.2 keV excitation in ^{86}Y populated by the ^{86}Sr(p,n), ^{86}Sr$(d,2n)$, and ^{85}Rb$(^3$He$,2n)$ reactions at the energies $E_p = 14$ MeV, $E_d = 13.5$ MeV, and $E_{^3\mathrm{He}} = 30$ MeV. The decay scheme was investigated by pulsed-beam γ-ray spectroscopy. Its g factor was measured by the time-differential perturbed angular distribution method in external magnetic field. The isomer properties $T_{1/2} = 125$ ns, $J^\pi = 7^-$, and $g = -0.083(3)$ were determined. The transition strength and the g factor indicate a superposition of single-particle and collective contributions. The g factor $g = +0.542(9)$ has been determined for the $5/2^-$ 266.3 keV 178 ns isomeric state in ^{85}Y.

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I. INTRODUCTION

During the last decade the Y nuclei ($Z = 39$) have been the subject of experimental and theoretical investigations which revealed an evolution of the nuclear structure along the chain, from spherical shapes near the shell closure at $N = 50$ towards large deformations when the neutron number is approaching the middle of the *f-p-d* shell. The high-spin level sequences observed in the odd-mass ^{89}Y ($N = 50$) [1] and ^{87}Y ($N = 48$) [2] were successfully described by spherical shell-model calculations in the model space $\pi(2p_{3/2},1f_{5/2},2p_{1/2},1g_{9/2})\nu(2p_{1/2},1g_{9/2})$, enlarged in the case of the semimagic ^{89}Y by the inclusion of the $2d_{5/2}$ neutron orbital. A weakly deformed shape with $\beta \approx 0.15 - 0.20$ has been established for ^{85}Y [3], while large quadrupole deformations of $\beta \approx 0.25 - 0.35$ have been determined for the rotational bands in ^{83}Y [4] and ^{81}Y [5] based on highly enhanced transition strengths of $B(E2) \approx 70 - 130$ Weisskopf units (W.u.). Regular rotational bands have been also identified in the odd-odd ^{80}Y [6], ^{82}Y [7–11], and ^{84}Y [12], and the corresponding shapes at high spin were found rather similar to those in the neighboring odd-mass nuclei. On the other hand, at low energies complex level structures often involving isomeric states are resulting by the coupling of the odd proton with the odd neutron. In order to elucidate the connection between the high-spin structures and the low-lying states a better knowledge of the isomer properties is necessary. Detailed studies of the low-lying isomers in ^{80}Y [13] and ^{82}Y [7,9,10] were recently reported.

The structure of the $N = 47$ odd-odd ^{86}Y nucleus situated at the border between the spherical region and the deformed one is much less known. A few low-lying states are known from the decay of ^{86}Zr [14], while several states of the yrast band have been reported from in-beam γ-ray spectroscopy studies [15,16]. Detailed investigations were recently undertaken in this laboratory to elucidate the structure of ^{86}Y at both low and high excitations. By applying the pulsed-beam technique in light-particle induced reactions a new isomeric state has been identified. In this work we report on a detailed study of the isomer properties including the magnetic moment. The study of the high-spin structures using fusion-evaporation reactions induced by heavy ions is in progress and the results will be reported later.

II. EXPERIMENTAL PROCEDURE AND RESULTS

The experiments have been carried out at the U-120 cyclotron in Bucharest. The excited ^{86}Y nuclei were populated by the ^{86}Sr(p,n), ^{86}Sr$(d,2n)$, and ^{85}Rb$(^3$He$,2n)$ reactions with pulsed beams of protons ($E_p = 14$ MeV), deuterons ($E_d = 13.5$ MeV), and ^{3}He ($E_{^3\mathrm{He}} = 30$ MeV). The pulsed beam characteristics were pulse width of 4 ns and repetition period of 4 μs. Thick targets of isotopically enriched compounds of ^{86}SrCO$_3$ (97.6% ^{86}Sr) and ^{85}RbCl (99.7% ^{85}Rb) were used. The deexciting γ rays were detected by large volume HPGe and planar Ge detectors and NaI(Tl) crystals of 6 mm thickness. Energy spectra corresponding to various time intervals with respect to the beam pulse, as well as time spectra gated by selected energies were registered.

A. Decay scheme of the new isomeric state

The lowest-lying states known in ^{86}Y are a 5^- level at 208.1 keV and two isomeric states, a 8^+ state at 218.3 keV and a 2^- state at 242.8 keV, with half-lives of 43 min and 28.5 ns, respectively [14]. The 208.1 and 242.8 keV levels deexcite by direct transitions to the 4^- ground state, while the 218.3 keV isomer deexcites by a 10.2 keV $E3$ transition to the 5^- 208.1 keV level.

In our pulsed-beam measurements performed by irradiating the ^{86}SrCO$_3$ target with protons and deuterons, prompt γ-ray spectra coincident with the beam pulses, as well as delayed γ-ray spectra corresponding to various time intervals inbetween the beam pulses were registered with HPGe and planar Ge detectors. Figure 1 illustrates a delayed spectrum registered in the time interval 50–170 ns after the beam pulse with a planar Ge detector. From such spectra the presence of a new isomeric decay in ^{86}Y, which involves the 83.9, 94.1, and 208.1 keV γ rays, has been inferred. As seen in the decay curves presented in Fig. 2, these γ rays have similar time behaviors corresponding to an average half-life of $T_{1/2} = 125(6)$ ns. Based on the known level scheme of ^{86}Y the isomer has been placed at 302.2 keV excitation energy, the 83.9 and 94.1 keV isomeric transitions populating the 218.3 and 208.1 keV states, respectively. The multipolarity of the 94.1 keV transition has been established based on its total conversion coefficient deduced from the experimental intensity ratio of the delayed 94.1 and 208.1 keV cascade

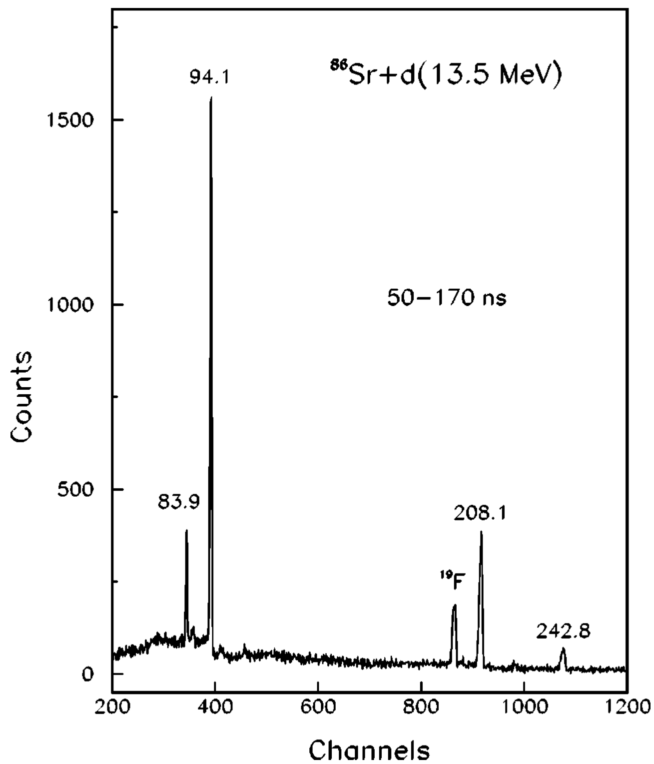

FIG. 1. Delayed spectrum corresponding to the 50–170 ns time interval. Transitions assigned to ^{86}Y are labeled by energies. The 242.8 keV γ-ray deexcites the 2^- 28.5 ns isomer in ^{86}Y [14].

transitions according to the relation $I(94.1\ \text{keV})/I(208.1\ \text{keV}) = [1+\alpha_{\text{tot}}(208.1\ \text{keV})]/[1+\alpha_{\text{tot}}(94.1\ \text{keV})]$. A value of 0.441(46) for this intensity ratio was determined from the delayed spectra corresponding to the 200–400 ns time range where the γ-ray angular distributions are isotropic (see next section). The 208.1 keV is known to have a mixed $M1$ $+E2$ multipolarity with $|\delta(E2/M1)| = 1.07(22)$ [17]. By using $\alpha_{\text{tot}}(208.1\ \text{keV}) = 0.052(5)$ [14,17] a value $\alpha_{\text{tot}}(94.1\ \text{keV}) = 1.38(10)$ was deduced which, compared with the theoretical values 0.13 ($E1$), 0.21 ($M1$), and 1.33 ($E2$) (Ref. [18]), allowed to assign a $E2$ multipolarity to the 94.1 keV transition. The spin-parity $J^\pi = 7^-$ was therefore assigned to the isomeric level at $E_x = 302.2$ keV and an $E1$ character resulted for the 83.9 keV transition to the 8^+ isomeric state. From the delayed intensity ratio 0.176(6) of the 83.9 and 94.1 keV transitions, the branching ratios 8.2(3)% and 91.8(3)%, respectively, were deduced. The established level scheme for the new isomeric state in ^{86}Y is presented in Fig. 3.

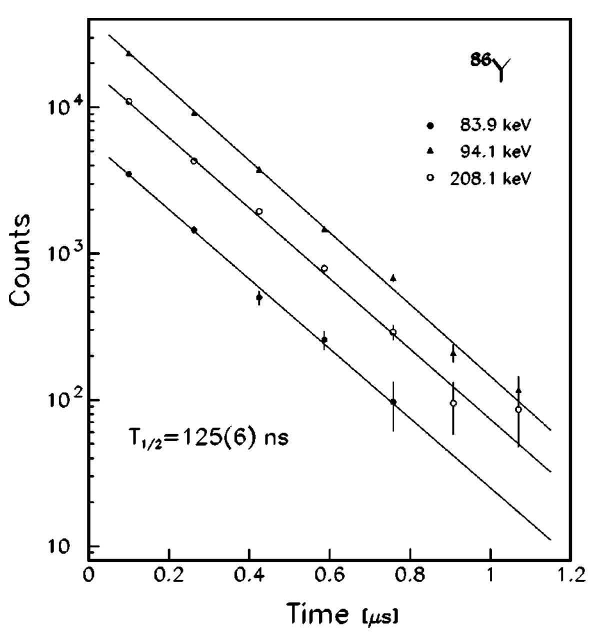

FIG. 2. Decay curves obtained from time gated energy spectra registered with the planar Ge detector.

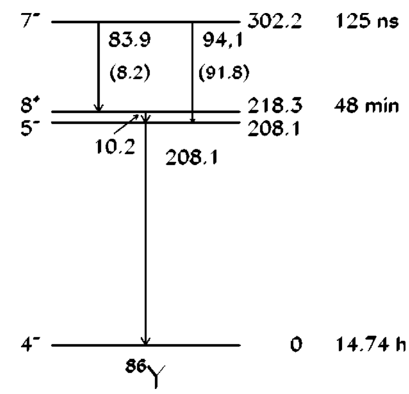

FIG. 3. Decay scheme of the 125 ns isomeric state in ^{86}Y. The data concerning the 5^- and 8^+ levels where taken from Ref. [14].

In a previous study of ^{86}Y through the ^{85}Rb(α,3n) reaction using techniques of in-beam γ ray spectroscopy a level at 302.3 keV depopulated by a 94.2 keV γ ray in coincidence with the 208.1 keV γ ray, has been placed [19]. In that work a spin (6) was tentatively assigned to the 302.3 keV level based on a large negative angular distribution coefficient A_2 for the 94.2 keV transition. Most likely the 302.3 keV level observed in the ^{85}Rb(α,3n) reaction is the same with the presently observed isomeric level, however the level spin assigned in Ref. [19] is not confirmed by the present work.

B. *g* factor of the 7^- isomeric state

For the g-factor determination the time-differential perturbed angular distribution (TDPAD) method has been applied. The deexciting γ-rays were detected with thin NaI(Tl) crystals. Two independent TDPAD experiments were performed. In the first experiment the isomer was populated in the ^{85}Rb(^{3}He,2n) reaction using as target the chemical compound of ^{85}RbCl with cubic crystalline structure and the detectors were placed at $\theta = \pm 135°$ with respect to the beam direction. In the second experiment the target of ^{86}SrCO$_3$ in the powder form was irradiated with protons and the detectors were placed at $\theta = 0°$ and 90°. The target was placed in an external magnetic field applied perpendicular to the beam-detection plane. The measurements have been performed at room temperature and different strengths of the external magnetic field.

The time spectra $I(\theta,t)$ gated by the 94.1 and 208.1 keV delayed γ rays, background corrected and normalized, were

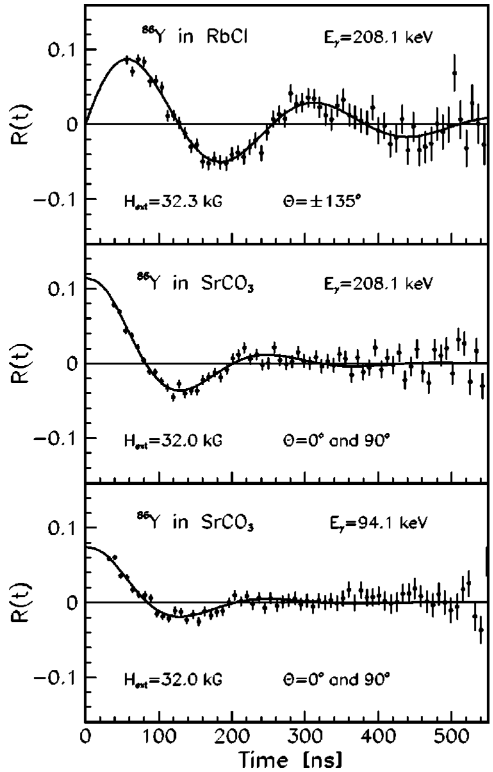

FIG. 4. TDPAD spectra of the 94.1 and 208.1 keV γ rays deexciting the 125 ns isomeric state in ^{86}Y.

used to construct the experimental ratio

$$R_{\mathrm{exp}}(t)=\frac{I(\theta,t)-I(\theta+90°,t)}{I(\theta,t)+I(\theta+90°,t)}. \quad (1)$$

Illustrative $R_{\mathrm{exp}}(t)$ ratios obtained at the highest magnetic field strength of 32 kG are shown in Fig. 4. They were least-squares fitted to the expression

$$R_{\mathrm{theo}}(t)=b_2\, e^{-t/\tau_{\mathrm{rel}}}\cos 2(\phi-\omega_L t), \quad (2)$$

in which the amplitude b_2 related to the effective angular distribution coefficients A_2, the relaxation time τ_{rel}, the Larmor precession frequency ω_L, and the phase ϕ depending on the detector position angle and the beam-bending in the magnetic field were free parameters. On the basis of the Larmor frequencies obtained from the above presented procedure in the (p,n) and (^{3}He,2n) experiments consistent g-factor values were determined which led to an average g factor

$$g_{\mathrm{exp}}(7^-,{}^{86}\mathrm{Y})=-0.083(3)$$

corresponding to the magnetic moment

$$\mu(7^-,{}^{86}\mathrm{Y})=-0.581(21)\ \ \mathrm{nm}.$$

The effective angular distribution coefficients derived from both experiments were $A_2=+0.103(11)$ and $A_2=+0.159(7)$ for 94.1 and 208.1 keV transitions, respectively, the positive sign being established from the measurements with the detectors placed at 0° and 90° (see Fig. 4). The A_2 determined for the 94.1 keV γ ray supports the $E2$-multipolarity assignment (previous subsection). The larger value of the A_2 in the case of the 208.1 keV γ ray is in accordance with its mixed $M1+E2$ character [14,17] and its positive sign allowed to fix the sign for the mixing coefficient $\delta(E2/M1)=+1.07(22)$. As seen in Fig. 4, in both experiments the amplitude of the Larmor oscillations was found to decrease in time. The effect was more pronounced in the case of the $SrCO_3$ target, where after $\approx$200 ns the angular distribution became isotropic. The observed reduction of the initial anisotropy indicate perturbing interactions at the Y nuclei sites in the chemical compounds used as targets.

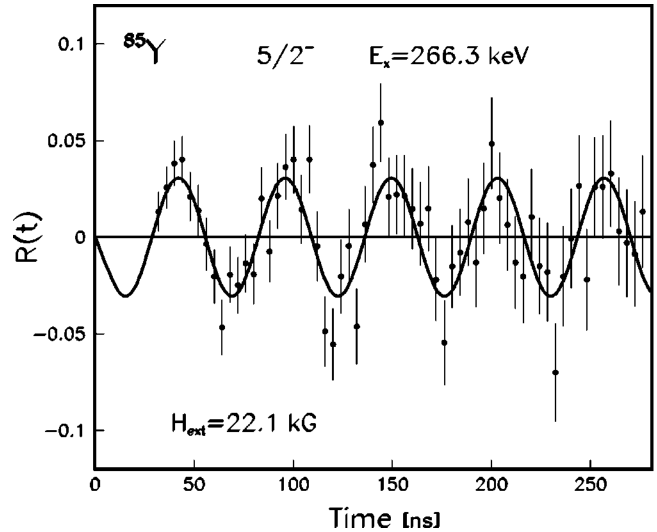

FIG. 5. TDPAD spectrum of the 266.3 keV γ ray deexciting the 178 ns isomeric state in ^{85}Y.

A by-product of the present experimental work is the determination of the magnetic moment for the $5/2^-$ 266.3 keV 178 ns isomeric state in ^{85}Y [20]. This state was populated by the ^{85}Rb(^{3}He,3n) reaction in the experiment performed with the ^{3}He beam on the RbCl target. The TDPAD spectrum of the 266.3 keV γ ray corresponding to the $5/2^-\rightarrow 1/2^-$ transition is presented in Fig. 5 together with the corresponding fit. From these data a value

$$g_{\mathrm{exp}}(5/2^-,{}^{85}\mathrm{Y})=+0.542(9)$$

has been obtained for the g factor of the $5/2^-$ isomeric state in ^{85}Y, corresponding to the magnetic moment

$$\mu(5/2^-,{}^{85}\mathrm{Y})=+1.355(22)\ \ \mathrm{nm},$$

in very good agreement with the value $\mu=+1.33(8)$ reported in Ref. [21].

III. DISCUSSION

The ^{86}Y nucleus has one proton above the spherical subshell closure at $Z=38$ and three neutron holes in the $1g_{9/2}$ orbital below the $N=50$ shell closure. The structure of the low-lying levels can be interpreted by the coupling of $2p_{1/2}$, $2p_{3/2}$, $1f_{5/2}$, and $1g_{9/2}$ proton orbitals with the $2p_{1/2}$ and $1g_{9/2}$ neutron orbitals. The 4^- ground state and the 5^- state

TABLE I. Transition strengths in ^{85,86}Y.

Nucleus	E_x (keV)	$T_{1/2}^{\mathrm{exp}}$	E_γ (keV)	$J_i^\pi \rightarrow J_f^\pi$	$\sigma\lambda$	Branching ratio (%)	$B(\sigma\lambda)$ (W.u.)
^{85}Y	266.3	178(6) ns	266.3	$5/2^- \rightarrow 1/2^-$	$E2$	100	0.107(4)[a]
^{86}Y	218.3	43(1) min	10.2	$8^+ \rightarrow 5^-$	$E3$	100	0.035(3)[b]
	242.8	28.5(21) ns	242.8	$2^- \rightarrow 4^-$	$E2$	100	1.00(8)[b]
	302.2	125(6) ns	83.9	$7^- \rightarrow 8^+$	$E1$	8.2(3)	$3.2(2)\times10^{-7}$[c]
			94.1	$7^- \rightarrow 5^-$	$E2$	91.8(3)	10.6(5)[c]

[a]From Ref. [20].
[b]From Ref. [14].
[c]Present work.

at 208.1 keV were interpreted as the two members of the $\pi 2p_{1/2}\otimes \nu 1g_{9/2}$ multiplet [22], while the 8^+ isomeric state was described by the $\pi 1g_{9/2}\otimes \nu 1g_{9/2}$ configuration [23,24]. In the proton-neutron coupling scheme the 2^- and 7^- isomers could be the lowest and highest spin members, respectively, of the $\pi 1f_{5/2}\otimes \nu 1g_{9/2}$ multiplet. To check this assignment we compared the experimental g factor of the 7^- isomer with the g factor calculated using the additivity relation and empirical values for the odd-particle g factors. The presently determined value $g(5/2^-, {}^{85}\mathrm{Y}) = +0.542(9)$ and the value $g(9/2^+, {}^{85}\mathrm{Sr}) = -0.222(1)$ [25] were used for the g factor of $1f_{5/2}$ proton and $1g_{9/2}$ neutron states, respectively. The calculated g factor $g_{\mathrm{emp}}([\pi 1f_{5/2}\otimes \nu 1g_{9/2}]7^-) = +0.051(5)$ is, however, rather different from the experimental g factor $g_{\mathrm{exp}} = -0.083(3)$, what could indicate some other contributions in the wave function of the 7^- state. Further insight into the isomer structure was obtained from its decay properties. If the 7^- state has the $\pi 1f_{5/2}\otimes \nu 1g_{9/2}$ configuration, the transition to the 5^- state with the $\pi 2p_{1/2}\otimes \nu 1g_{9/2}$ configuration has to be compared with the $1f_{5/2}\rightarrow 2p_{1/2}$ proton transition in the neighboring ^{85}Y. The reduced transition strengths of isomeric transitions in ^{85,86}Y are collected in Table I. The strength $B(E2) = 0.107(4)$ W.u. for the 266.3 keV transition in ^{85}Y indicates a single-particle character. On the other hand, the enhanced transition strength $B(E2) = 10.6(5)$ W.u. for the 94.1 keV transition points to collective contributions. Assuming the coupling of the $[\pi 2p_{1/2}\otimes \nu 1g_{9/2}]5^-$ configuration with a 2^+ phonon, an estimate of the g-factor was performed by using the value $g(1/2^-, {}^{89}\mathrm{Y}) = -0.275(1)$ for the $2p_{1/2}$ proton state and $g(2^+, {}^{86}\mathrm{Sr}) = +0.275(50)$ [25]. The derived value $g_{\mathrm{emp}}([\pi 2p_{1/2}\otimes \nu 1g_{9/2}]5^-\otimes 2^+) = -0.084(27)$ is in excellent agreement with the experimental g factor.

Similar conclusions concerning collective contributions are also inferred for the 2^- isomeric state in ^{86}Y. As seen in Table I, it decays through an $E2$ transition enhanced by an order of magnitude compared with the proton transition in ^{85}Y. Moreover the g factor of this state $g_{\mathrm{exp}}(2^-, {}^{86}\mathrm{Y}) = -0.53(3)$ [25] differs considerably from the empirical value $g_{\mathrm{emp}}([\pi 1f_{5/2}\otimes \nu 1g_{9/2}]2^-) = -0.859(13)$. We calculated the g factor for the 2^- state described by coupling the $[\pi 2p_{1/2}\otimes \nu 1g_{9/2}]4^-$ configuration with a 2^+ phonon. The obtained value $g_{\mathrm{emp}}([\pi 2p_{1/2}\otimes \nu 1g_{9/2}]4^-\otimes 2^+) = -0.55(6)$ reproduces very well the experimental value.

The strength $B(E2) = 10.6(5)$ W.u. of the $7^- \rightarrow 5^-$ transition in ^{86}Y is comparable with transition strengths determined for low-lying states in the odd-odd nuclei ^{82,84}Y [11,12] what indicates similar contributions of single-particle and collective excitations. The $B(E1)$ value of the $7^- \rightarrow 8^+$ 83.9 keV transition (see Table I) is also comparable with the reduced strengths of $E1$ transitions in these nuclei [10,12]. On the other hand the evolution of the collectivity with spin was found different in the two nuclei. In ^{82}Y ($N = 43$) the $E2$ transition rates are increasing with spin up to a saturating value which is an order of magnitude larger compared to the $B(E2) \approx 7$ W.u. reported for the $6\rightarrow 4$ transitions in both positive and negative parity structures [11], while in ^{84}Y ($N = 45$) the $B(E2)$ remains rather constant with values of 20–30 W.u. over the spin range. The study of ^{86}Y at high spins will be of large importance for elucidating the behavior of high spin structures in odd-odd nuclei with neutron number approaching the shell closure.

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