New short-lived isomers in ^{84}Y

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(Received 26 July 2005; published 27 October 2005)

Low-lying short-lived isomeric states have been investigated in ^{84}Y by the ^{84}Sr(p,n) reaction at $E_p = 13.5$ MeV. The g factors were measured by applying the time-differential perturbed angular distribution method in an external magnetic field. The properties determined for the new isomers are $E_x = 112.4$ keV, $I^\pi = (4^+)$, $T_{1/2} = 79(2)$ ns, $g = +0.578(7)$; $E_x = 210.4$ keV, $I^\pi = (4^-)$, $T_{1/2} = 292(10)$ ns, $g = +0.234(6)$. On the basis of the measured g factor, the $\pi 1g_{9/2} \otimes \nu 1g_{9/2}$ configuration has been assigned to the 4^+ isomeric state. The low-lying states in ^{84}Y were discussed within the two-quasiparticles plus rotor model. The 4^- isomeric state has been interpreted by the pure $\pi[301]3/2 \otimes \nu[422]5/2$ configuration, which reproduces the experimental g factor at a prolate quadrupole deformation of $\varepsilon_2 \approx 0.16$.

DOI: 10.1103/PhysRevC.72.044313 PACS number(s): 21.10.Ky, 21.10.Tg, 23.20.Lv, 27.50.+e

I. INTRODUCTION

Information concerning the structure of the neutron-deficient odd-odd nuclei from the *pfg* shell has increased considerably in the past decade. These nuclei provide important details of the interplay between the collective and single-neutron and single-proton degrees of freedom. Moreover, they are useful systems to elucidate the neutron-proton (*np*) residual interaction, and in particular the *np* pairing in both isoscalar and isovector coupling. Evidence for isovector *np* pairing in $N = Z$ nuclei of this region has been reported from in-beam experiments for ^{70}Br [1] and ^{74}Rb [2,3] and from decay studies of ^{78}Y and ^{82}Nb [4,5]. These nuclei have $I^\pi = 0^+$ in their ground state and exhibit an unusual low-level density at energies below 1 MeV. In contrast, the neighbouring odd-odd nuclei with $N > Z$ have rather complex low-lying level schemes, involving also isomeric states. Collective high-spin bands have been observed in a variety of neutron-deficient odd-odd nuclei, such as $^{74-80}$Br [6–10], $^{76-82}$Rb [11–15], $^{80-84}$Y [16–25], and ^{84,86}Nb [26,27]. In this mass region the deformation depends strongly on the occupation of the proton and neutron high-j $1g_{9/2}$ subshells. For nuclei with N around 40, large quadrupole deformations of $\beta_2 \approx 0.35$ were inferred on the basis of transition strengths deduced from measured lifetimes in the rotational bands [7,13,14,19]. With increasing neutron number toward $N = 50$, this deformation-driving feature gradually diminishes. The high-spin level sequences observed in the odd-odd ^{86}Rb and ^{88}Y ($N = 49$) nuclei have been successfully described in the framework of the spherical shell model [28,29]. For the nuclei in between, competition of the polarizing effects of the $1g_{9/2}$ valence proton and neutron results in a transitional character, leading to a very fragile coexistence of excitation modes based on different deformations.

Investigation of low-lying isomeric states in neutron-deficient nuclei of the *pfg* shell offers the opportunity to elucidate nuclear phenomena such as shape coexistence in this region far from stability. The isomers are important for elucidating the complex level schemes of odd-odd nuclei and provide information about the competition between single-particle and collective structures. Detailed studies of isomeric states in odd-odd nuclei with $A \approx 80$ were reported recently based on various techniques applied in decay [16], fusion-evaporation reactions induced by heavy ions [20,23,30], or projectile fragmentation [31] processes.

The present work, part of a program devoted to detailed investigations of short-lived isomers in neutron-deficient nuclei with $A \approx 80$ populated in reactions induced by light particles [32–34], aims to bring new information concerning the low-lying level scheme of ^{84}Y. The level structure of this odd-odd nucleus has been the subject of several studies in the past; however, until recently it has been far from being elucidated. Early evidence was presented that it has very likely a 1^+ ground state with a half-life of 4.6 s and a higher lying (5^-) isomer with a half-life of 39.5 min at an energy of about 500 keV [35]. This structure was deduced from β^+/EC decay studies of ^{84}Y, and the excitation energy of the isomer was an estimate only [36–38]. A few γ rays have been observed in the β^+/EC decay of ^{84}Zr and assigned to ^{84}Y [39,40]; however, they were not placed into a level scheme. In a subsequent investigation performed using the ^{59}Co(^{28}Si,2pn)^{84}Y reaction, high-spin band structures of moderate deformation have been reported [24,25]. Based on theoretical arguments a spin parity of (6^+) has been assumed for the lowest observed energy level. Very recently, new information relevant for the level structure in ^{84}Y, based on a detailed study of the ^{84}Zr $\rightarrow ^{84}$Y $\rightarrow ^{84}$Sr decay chain, has been reported [41]. In that study it is proposed that the 39.5-min activity corresponds to a ground state with $I^\pi = (6^+)$, rather than (5^-) as assigned earlier, whereas the 1^+ 4.6-s isomer has an excitation energy of 67 keV. Three cascade γ rays of 112, 45, and 41 keV were included in the level scheme as de-exciting the states at 112 keV (4^+), 157 keV (3^+), and 198 keV (2^+), the last level de-exciting also by a 131-keV γ ray to the 1^+ 4.6-s isomer. In the quoted paper the presence of more than 40 new γ rays assigned to ^{84}Y is mentioned, without however giving any details concerning their energies and decay scheme.

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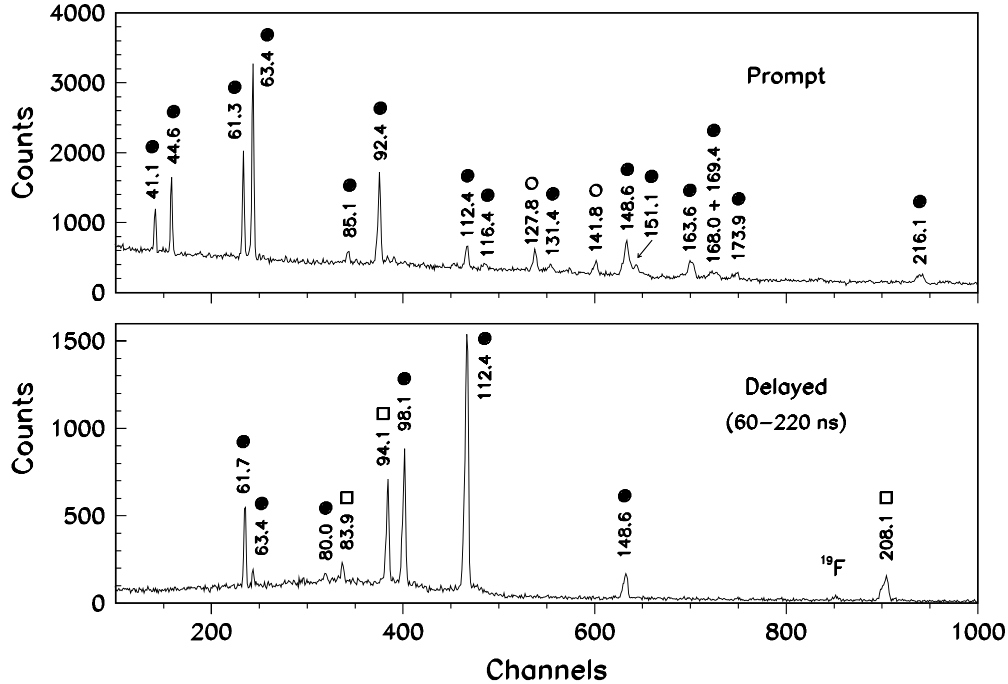

FIG. 1. Prompt and delayed γ-ray spectra registered with a planar HPGe detector of 7 mm thickness. The prompt spectrum was obtained with a time gate of 20 ns centered on the beam pulse. The delayed spectrum corresponds to the time interval 60–220 ns after the beam pulse. It was corrected for the background from long-lived activities by subtracting a spectrum registered in the time interval 3060–3220 ns. The transitions belonging to ^{84}Y (full circle), ^{86}Y (open square), and ^{88}Y (open circle) are labeled by energies.

In view of the present existing situation, a γ-ray spectroscopy investigation was undertaken to elucidate the level structure of ^{84}Y populated in the ^{84}Sr(p, n) reaction. γ-γ coincidence measurements, as well as pulsed-beam experiments to investigate short-lived isomers, have been performed. In this work we report on the detailed study of new low-lying isomeric states, including their g-factor determination. The investigation of the complete level scheme is presently ongoing and the results will be published elsewhere [42].

II. EXPERIMENTAL PROCEDURE AND RESULTS

The experiments have been carried out at the U-120 cyclotron and FN tandem accelerators in Bucharest. The ^{84}Y nucleus was populated in the ^{84}Sr(p, n) reaction at a proton beam energy of 13.5 MeV. The target was in the form of $SrCO_3$ with an isotopic composition of 61.0% ^{84}Sr, 8.8% ^{86}Sr, and 26.8% ^{88}Sr. The proton beam delivered by the cyclotron was pulsed with a pulse width of 4 ns at a repetition period of 4 μs. A suppression of unwanted cyclotron natural pulses greater than 10^6 was achieved by using two external electrostatic devices. This assured a low background, allowing the observation in the delayed spectra of weak low-energy transitions. The γ rays were detected by large-volume and planar HPGe detectors and NaI(Tl) crystals of 6 mm thickness. Energy spectra corresponding to various time intervals with respect to the beam pulse, and time spectra gated by selected energies were registered. To avoid the absorption of the low-energy γ rays between target and detectors, in spectroscopic studies a reaction chamber with mylar windows has been used. γ-γ coincidences in ^{84}Y have been investigated in an experiment performed at the FN tandem accelerator. Planar HPGe detectors of 15 mm thickness and large-volume HPGe detectors have been used. In the off-line analysis of the γ-γ coincidence data accumulated in list mode, a t-γ-γ tridimensional matrix has been sorted, from which γ-γ coincidence matrices were cut for different time gates. The absolute γ-ray efficiency calibration of the HPGe detectors has been made using standard sources of ^{241}Am, ^{133}Ba, and ^{152}Eu placed at the target position.

A. Short-lived isomeric states in ^{84}Y

The presence of two isomeric states in ^{84}Y has been inferred from the observation of delayed γ rays in spectra gated by various time intervals in between the beam pulses. Such a spectrum is shown in the lower part of Fig. 1 and evidences delayed transitions of 61.7, 63.4, 80.0, 98.1, 112.4, and 148.6 keV. Among these, only the 63.4- and 112.4-keV γ rays were observed in previous decay studies [39,40]. As seen in the decay curves presented in Fig. 2, the delayed γ rays have similar time behaviors, corresponding to an average half-life $T_{1/2} = 292(10)$ ns and indicating that they are involved in the same isomeric decay. Besides the 292-ns component, the 112.4-keV line presents an intense shorter lived component. A half-life of 79(2) ns has been derived from the time spectra gated by the 112.4-keV γ ray detected with a thin NaI(Tl) crystal (see the inset of Fig. 2).

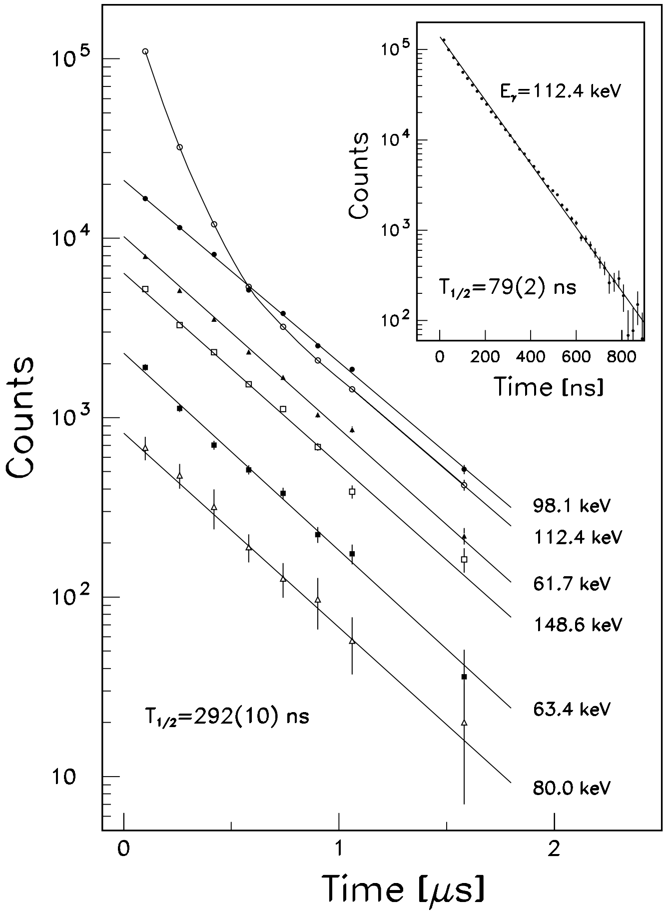

FIG. 2. Decay curves obtained from time-gated energy spectra registered with the planar HPGe detector. The inset shows the time spectrum of the 112.4-keV γ ray registered with a thin NaI(Tl) crystal.

The upper part of Fig. 1 illustrates a prompt spectrum registered with the planar HPGe detector during the beam pulses. The 41.1-, 44.6-, 61.3-, 63.4-, 112.4-, and 131.4-keV γ rays observed in this spectrum were previously assigned to ^{84}Y from decay studies [39,40]. The assignment of the other transitions to this nucleus is based on the study of coincidence relationships; the level scheme will be discussed in a future paper [42].

The coincidence relationship between the delayed transitions has been established from the γ-γ coincidence spectra obtained with a large time window to allow the observation of isomeric transitions. As illustrated in Fig. 3, the 98.1-keV transition is in coincidence with the 112.4-keV transition, whereas the 148.6-keV transition is coincident with the 61.7-keV transition. The sum of the γ-ray energies in these two-transition cascades is 210.5 and 210.3 keV, respectively, allowing us to establish a 210.4-keV excitation energy for the 292-ns isomer. The much weaker γ lines of 80.0 and 63.4 keV have also been put in a cascade feeding the 1^+ 4.6-s state assigned in Ref. [41] at 67 keV. The 98.1-, 61.7-, and 80.0-keV lines were not seen in the prompt spectra registered during the beam pulses (see the upper panel of Fig. 1), and therefore they were assigned as de-exciting the 292-ns isomer. The proposed decay scheme of this isomer,

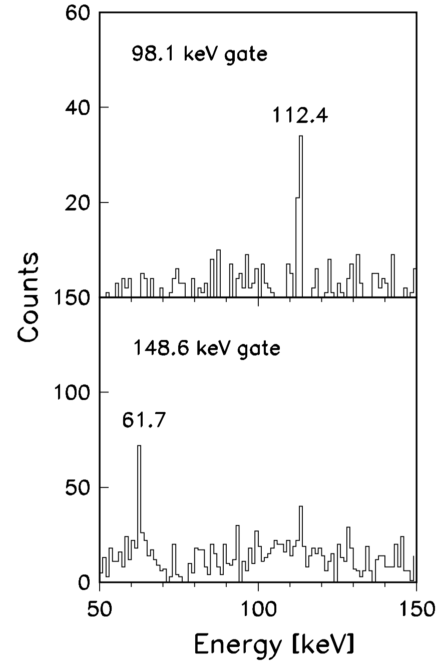

FIG. 3. Coincidence spectra for γ lines involved in the decay of the new isomeric states in ^{84}Y.

which feeds both the (6^+) ground state and the 4.6-s 1^+ 67-keV state in ^{84}Y, is shown in Fig. 4. Except for the 112.4-keV level already included in the level scheme proposed in Ref. [41], the other excited states are new. The spins and parities assigned to the levels are based on transition multipolarities and angular distribution coefficients, as well as on considerations concerning the transition strengths.

Information about the multipolarities was obtained from the analysis of the experimental γ-ray intensity ratios of the delayed cascade transitions. The energies and relative intensities of the delayed γ rays involved in the decay of the 292-ns isomer, and the energies of the depopulated levels are presented in Table I. The experimental γ-ray relative intensities of cascade transitions are compared in Fig. 5 with theoretical values calculated for different possible multipolarity combinations by assuming a mixing ratio

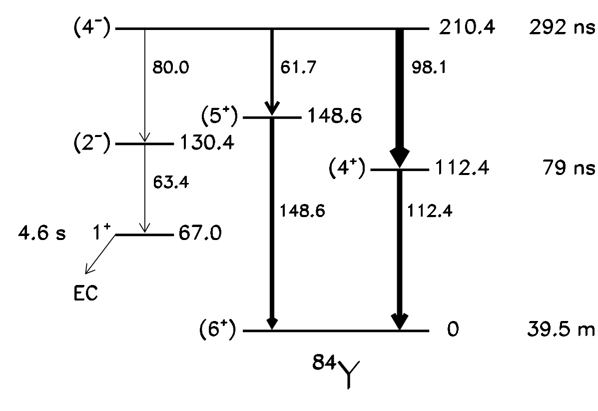

FIG. 4. Level scheme of the new short-lived isomeric states in ^{84}Y. The arrow widths are proportional to the γ intensity in the decay of the 210.4-keV level.

TABLE I. Energy and relative intensity for the delayed γ rays involved in the decay of the 292-ns isomer in ^{84}Y, and energy of de-excited levels. The intensity of the 112.4-keV γ ray has been deduced from a delayed spectrum created after 900 ns with respect to the beam pulse, when the 79-ns component is totally decayed, and is corrected for its own lifetime.

E_γ[a] (keV)	I_γ^{rel}	E_x[a] (keV)
61.7	421(37)	210.4
63.4	79(8)	130.4
80.0	40(6)	210.4
98.1	1000(94)	210.4
112.4	688(84)	112.4
148.6	575(56)	148.6

[a]The uncertainties on E_γ and E_x are ± 0.2 keV.

$\delta(E2/M1) = 0$ and using the theoretical conversion coefficients from Ref. [43]. As seen in the figure, based on the ratio $I_{112.4}/I_{98.1} = 0.69(11)$ an $E2$ multipolarity is firmly established for the 112.4-keV transition. This is in accordance with the $I^\pi = 4^+$ assignment for the 112.4-keV level in Ref. [41]. From this ratio the 98.1-keV transition could be an $E1$ or $M1$ dipole transition, and therefore the 210.4-keV level might have a spin value 3, 4, or 5. The ratio $I_{63.4}/I_{80.0} = 1.98(36)$ leads to assignments of $E2$ for the 80.0-keV transition and of $E1$ or $M1$ for the 63.4-keV transition. On the basis of these cascade transitions placed on the 1^+ state, the possible spin values of the 210.4-keV isomer range between 0 and 4. A dipole character is inferred for the 61.7-keV transition based on the ratio $I_{148.6}/I_{61.7} = 1.37(18)$. As for the 148.6-keV transition, whose multipolarity could not be derived from this intensity ratio, a dipole character was assigned based on a negative angular distribution coefficient A_2 (see next section). This cascade of two dipole transitions placed above the 6^+ ground state allows in principle for the isomer a spin between 4 and 8. From this analysis a spin $I = 4$ was assigned to the 210.4-keV isomeric level. Note that this assignment is supported by the positive angular distribution coefficient found for the 98.1-keV transition with $\Delta I = 0$ (see next subsection). To assign the level parity, arguments based on transition strengths were used. Assuming a positive parity for the isomeric state gives an $M1$ multipolarity for the 98.1-keV transition, corresponding to a transition probability of $B(M1,\ 98.1\ \mathrm{keV}) = 4 \times 10^{-5}$ W.u. This strength is, however, extremely small, very far from the usual values for $M1$ transitions in this mass region [44]. An $I^\pi = 4^-$ assignment for the 210.4-keV isomer appears much more plausible, corresponding to a transition probability $B(E1,\ 98.1\ \mathrm{keV}) = 0.72(9)\times 10^{-6}$ W.u., very similar to those reported for $E1$ transitions in this nuclear region. With a similar argument concerning the transition strength, an $E1$ multipolarity was assigned to the 61.7-keV transition, which gives a positive parity for the level at 148.6 keV. The reduced transitions strengths for the isomeric states in ^{84}Y are given in Table II.

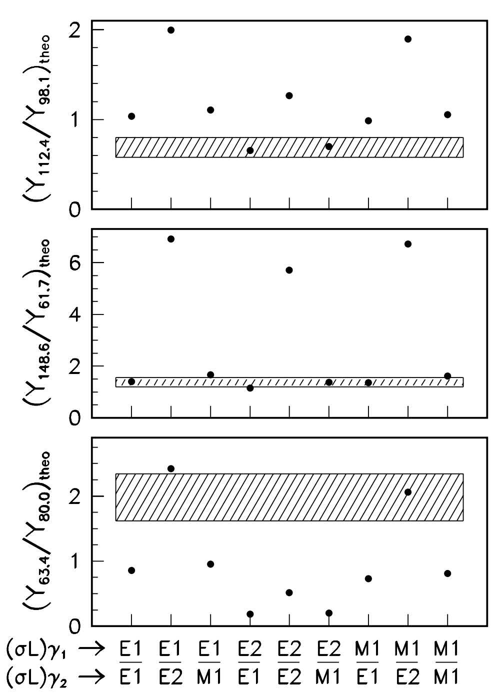

FIG. 5. Experimental γ-ray intensity ratios for cascade transitions in ^{84}Y values (shaded areas) compared with theoretical values as a function of their multipolarities.

B. *g*-factor measurements

For the *g*-factor determination the time-differential perturbed angular distribution (TDPAD) method has been used. The target was placed in an external magnetic field applied perpendicular to the beam-detection plane. The measurements have been performed at room temperature, at three strengths of the external magnetic field: 20.6(2), 22.2(2), and 32.0(2) kG. The γ rays were detected with thin NaI(Tl) crystals placed at $\theta = \pm 135^\circ$ and $\theta = 0^\circ$ and 90° with respect to the beam direction. For each angle time spectra gated by the 98.1-, 112.4-, and 148.6-keV delayed γ rays were registered. Following the standard procedure of the TDPAD method, the time spectra, background corrected and normalized, were used to create the experimental modulation ratio $R_{\mathrm{exp}}(t)$ defined as

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

In the present case two cascade decaying isomeric levels with comparable half-lives are simultaneously populated in the nuclear reaction. The modulation ratios corresponding to the γ rays that depopulate the upper 4^- isomeric state were least-squares fitted to the theoretical expression

$$R(t) = \tfrac{3}{4} A_2 \cos 2(\phi - \omega_L t), \tag{2}$$

where the effective angular distribution coefficient A_2, the Larmor frequency ω_L, and the phase ϕ depending on the detector angle and the beam-bending in the magnetic field were free parameters. Example of modulation ratios for the 98.1-keV γ ray are illustrated in Fig. 6. The sign of the angular distribution coefficient was established as positive for the 98.1-keV $\Delta I = 0$ transition and negative for the 148.6-keV transition assigned as a dipole. The modulated

TABLE II. Transition strengths for the isomeric states in ^{84}Y.

E_x (keV)	E_γ (keV)	α_{tot}	Branching ratio	$I_i^\pi \rightarrow I_f^\pi$	σL	$B(\sigma L)$ (W.u.)
112.4	112.4	0.700	1.00	$4^+ \rightarrow 6^+$	$E2$	10.7(2)
210.4	61.7	0.439	0.31(3)	$4^- \rightarrow 5^+$	$E1$	$1.10(11)\times10^{-6}$
	80.0	2.406	0.07(1)	$4^- \rightarrow 2^-$	$E2$	0.56(8)
	98.1	0.114	0.62(7)	$4^- \rightarrow 4^+$	$E1$	$0.72(9)\times10^{-6}$

intensity of the 112.4-keV γ ray de-exciting the lower lying 4^+ isomeric state is composed of two contributions: the cascade component coming from the 4^- state and the direct component from the side population during the short pulse irradiation. The calculated modulation ratio for the total intensity has a complicated form, as given in [45]. In the present experimental conditions the g factor has been derived from the observed Larmor oscillations of the strong side-feeding component. The cascade contribution from the 4^- isomeric decay manifested itself as an attenuation of the oscillation amplitude. The experimental ratio was least-squares fitted to the theoretical expression

$$R(t) = \frac{3}{4}\frac{A_2}{1 + A(t)}\cos 2(\phi - \omega_L t), \quad (3)$$

with a factor $A(t)$ related to the lifetimes and initial feedings of the isomeric states [45]. Figure 7 illustrates the experimental and least-squares-fitted modulation ratios for the 112.4-keV γ rays and two detection geometries. From the measurement performed with the detector placed at 0° and 90°, a positive A_2 was found, in accordance with the quadrupole character of the transition.

The modulation ratios, as shown in Figs. 6 and 7, have revealed very small effective anisotropies, of about 2%–4%. This has to be related to a rather low nuclear alignment of the states populated in the (p, n) reaction. Moreover, strong reduction of the alignment took place owing to perturbing interactions at the Y nuclei sites in the chemical compound used as target.

On the basis of the Larmor frequencies derived in measurements performed at different values of the external magnetic field, consistent g-factor values were obtained, leading to the average values $g(4^+, 112.4\ \text{keV}) = +0.578(7)$ and $g(4^-, 210.4\ \text{keV}) = +0.234(6)$.

III. DISCUSSION

The ^{84}Y nucleus with $Z = 39$ and $N = 45$ lies in the transitional region between the highly deformed nuclei with $N \leqslant 42$ and the spherical nuclei near the $N = 50$ shell closure. Microscopic calculations of Nazarewicz *et al.* [46] predicted for this region the coexistence at low energies of spherical, oblate, and prolate states. In the macroscopic-microscopic calculations of Möller *et al.* [47], performed by using a finite-range droplet model and the folded Yukawa single-particle model, ^{84}Y has been calculated to be almost spherical in its ground state, with a small quadrupole deformation of $\beta_2 = 0.053$. A spherical shape was also calculated recently for this nucleus by Goriely *et al.* [48] by applying the Hartree-Fock-BCS method.

In the spherical shell model, the low-lying levels of the odd-odd ^{84}Y nucleus are interpreted by coupling the valence proton occupying one of the $1f_{5/2}, 2p_{3/2}, 2p_{1/2}$, and $1g_{9/2}$ orbitals with the valence neutron in the $2p_{1/2}$ or $1g_{9/2}$ orbital.

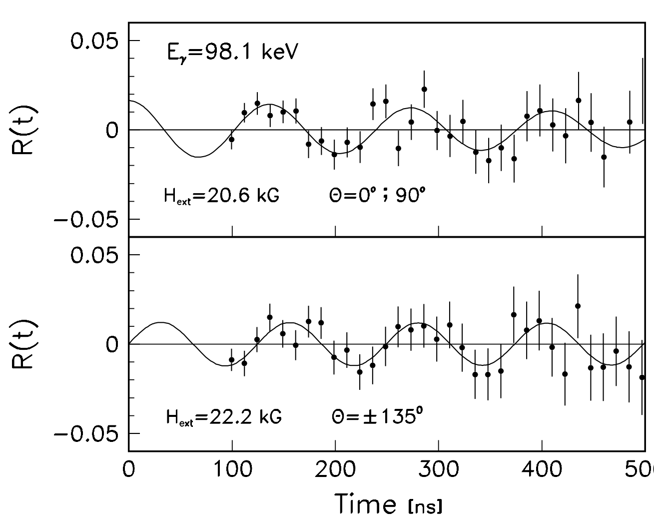

FIG. 6. Experimental and theoretical modulation spectra for the 98.1-keV γ ray for two values of the external magnetic field and two detection geometries.

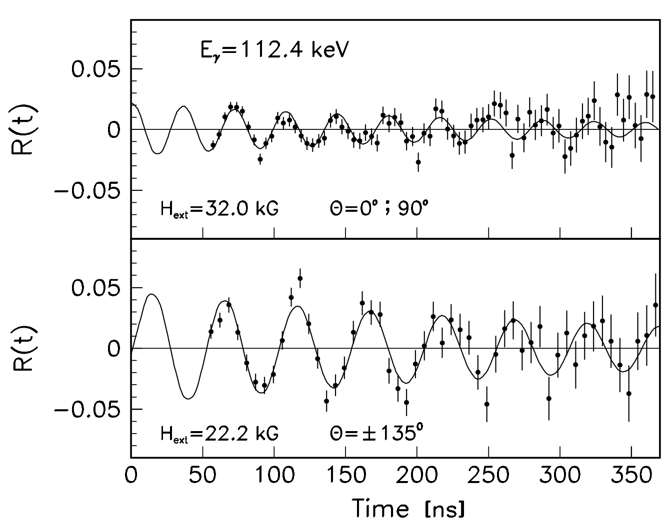

FIG. 7. Experimental and theoretical modulation spectra for the 112.4-keV γ ray for two values of the external magnetic field and two detection geometries.

TABLE III. Possible configurations for states with $I^\pi = 4^\pm$ and comparison of their empirical g factors with the present experimental values. In applying the additivity rule the following measured g factors in the neighboring odd-mass nuclei have been used: $g(1/2^-, {}^{89}\text{Y}) = -0.275(1)$, $g(3/2^-, {}^{81}\text{Rb}) = +1.373(1)$, $g(5/2^-, {}^{85}\text{Y}) = +0.542(7)$, and $g(9/2^+, {}^{85,87}\text{Y}) = +1.37(6)$, for proton states; $g(1/2^-, {}^{83}\text{Sr}) = +1.162(8)$, $g(9/2^+, {}^{85}\text{Sr}) = -0.222(1)$, and $g(7/2^+, {}^{83}\text{Sr}) = -0.248(1)$, for neutron states [49].

Proton state	Neutron state	I^π	g_{emp}	g_{exp}
$1g_{9/2}$	$1g_{9/2}$	4^+	+0.572(33)	+0.578(7)
$2p_{3/2}$	$(1g_{9/2})^3_{7/2}$	4^-	+0.076(1)	+0.234(6)
$2p_{3/2}$	$1g_{9/2}$	4^-	–0.262(1)	
$2p_{1/2}$	$1g_{9/2}$	4^-	–0.217(1)	
$1f_{5/2}$	$1g_{9/2}$	4^-	–0.146(5)	
$1g_{9/2}$	$2p_{1/2}$	4^-	+1.391(47)	

The 6^+ ground state could be described by the coupling of the proton and neutron in the $1g_{9/2}$ orbital, and the same configuration could be involved in the structure of the 4^+ state at 112.4-keV, which decays to the ground state by an $E2$ transition of a moderate strength of 10.2(7) W.u. (see Table II). Note that this is about a factor of 2 smaller than the $B(E2)$ strengths estimated from lifetime measurements in the positive-parity rotational band developed in this nucleus on a low-lying 8^+ state assigned to the same proton-neutron coupling [24,25]. A smaller collectivity for the low-lying states compared to the well-established deformation at high spins has been also reported for the neighboring ^{82}Y [20,22] and reflects the transitional character of these nuclei.

The g factors determined in the present work might provide support for a spherical description. We estimated empirical g factors, g_{emp}, for various configurations coupling to $I = 4$, by using the additivity relation and experimental g factors in the neighboring odd-mass nuclei. The comparison of these estimates with the presently measured g factors is given in Table III. As seen in the table, the g factor of the 4^+ state is in very good agreement with the calculated value for the $\pi 1g_{9/2} \otimes \nu 1g_{9/2}$ configuration using experimental g factors of the $9/2^+$ proton and neutron states. Based on measured magnetic moments, this proton-neutron coupling has been assigned to several positive-parity isomeric states in the neighboring odd-odd nuclei with N < 50, namely the 8^+ states in ^{90}Nb and ^{86,88}Y and the 6^+ states in ^{90}Nb and ^{80,82}Rb [49]. The 4^+ state in ^{84}Y is the lowest spin state with the same configuration, identified in this mass region on the basis of the g-factor measurement. However, within the spherical picture no pure configuration could account for the measured value $g = +0.234(6)$ of the 4^- state. All configurations involving a proton in a negative-parity orbital coupled with the neutron in the $1g_{9/2}$ orbital give a negative value for the g factor. By taking as neutron state the $7/2^+$ ground state of the ^{83}Sr nucleus, interpreted by the $(1g_{9/2})^3_{7/2}$ three-particle configuration, the calculated g factor is positive, but much smaller than the measured g factor. For the configuration involving the coupling of the $1g_{9/2}$ proton orbital with the $2p_{1/2}$ neutron orbital the estimated g factor has a too large value. The failure of the spherical approach to reproduce the g factor of the 4^- isomer suggests that a description in a deformed basis is required.

We have performed calculations using the two-quasiparticle-plus-rotor model (TQRM) [50] in which the two quasiparticles are treated explicitly in addition to the collective even-even core. This model, mainly used to describe observed features such as signature splitting and signature inversion in the collective bands [20, 51], has been recently applied to describe the low-lying states in several odd-odd nuclei of the $A \approx 80$ region [1,4,16]. The modified harmonic oscillator potential was used for the deformed mean field to calculate single-particle energies. The standard κ and μ parameters of Ref. [52] are adopted, but with the proton parameters for $N = 3,4$ used for both protons and neutrons. This adjustment has been used in recent calculations reported for ^{78}Y [4], ^{80}Y [16], and ^{82}Y [20]. The core moments of inertia were calculated in such a way that the experimental energy of 573 keV of the 2^+ state of the even-even ^{82}Sr core [53] was reproduced. Effective g_s factors for the odd proton and neutron were either taken equal with the free values or reduced by a factor of 0.7. The collective g factor g_R was taken as Z/A. The quadrupole deformation parameter ε_2 was varied in the range 0.06–0.20, and axial-symmetric oblate and prolate shapes of the core were assumed. Calculations were done either without considering the proton-neutron residual interaction or by using a residual interaction modeled as a zero-range delta force as described in [1]. No attenuation for the Coriolis matrix elements was taken into account.

Low-lying positive-parity states in ^{84}Y were calculated with both odd proton and odd neutron located in the $1g_{9/2}$ orbital. The results obtained in calculations performed without considering a residual proton-neutron interaction are shown in Fig. 8 for a comparison with experimental levels. At prolate deformation the calculated states are considerably depressed compared to experimental states and do not reproduce the observed sequence of spins, the 4^+ and 8^+ states being calculated below the 6^+ state. The inclusion of a repulsive residual interaction [1] does not give a better agreement, as the 6^+ state is pushed at higher energy. However, at oblate deformation the calculations reproduce the observed spin sequence, except for the 1^+ state. Note that the g factor of the 4^+ state is also better reproduced at oblate deformation. The inclusion of the residual proton-neutron interaction does not change the level ordering; its effect is a slight increase of the calculated energies for all excited states.

Positive-parity states in ^{84}Y could also arise by coupling the valence proton and neutron in deformed orbits of the *fp* shell. In the corresponding TQRM calculations states of low spin between 1^+ and 5^+ were predicted to occur at low energies, whereas the states with $I^\pi \geqslant 6^+$ were calculated at excitation energies higher than 1 MeV. Most probably the 1^+ long-lived isomeric state at 67 keV is described by the coupling of proton and neutron in the *fp* shell.

Two TQRM calculations were performed to describe the negative-parity states in ^{84}Y. In the first calculation it was assumed that the odd proton occupies states in the $1g_{9/2}$ subshell and the odd neutron is in Nilsson orbitals of the

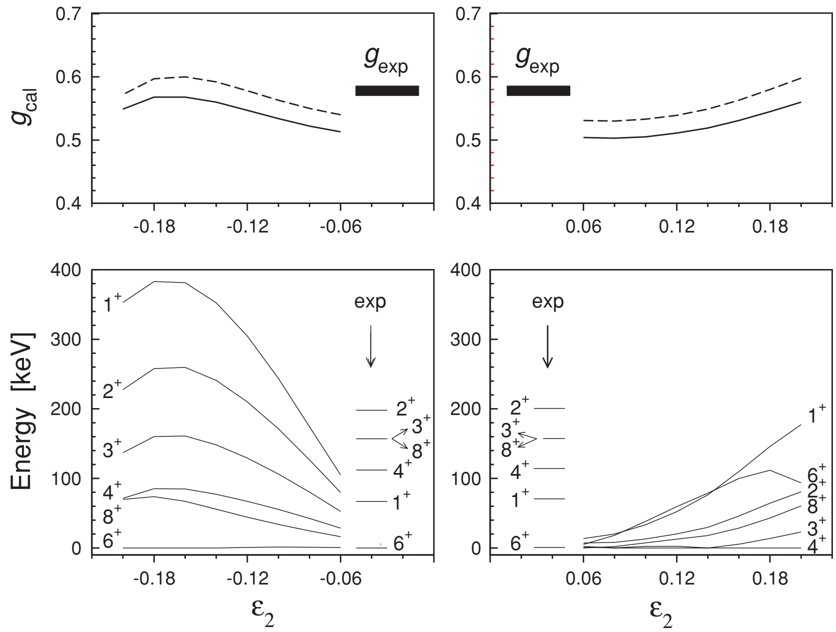

FIG. 8. Excitation energies of calculated low-lying positive-parity states for the odd proton and neutron in the same single $j = 1g_{9/2}$ orbit (lower panels) and calculated g factor of the 4^+ state (upper panels) as a function of the quadrupole deformation ε_2. The experimental states with I^π equal to 1^+ to 6^+ are those reported in [41] and the present work; the 8^+ state was identified in [25]. Two different g_s factors have been used: $g_s = g_s^{\rm free}$ and $g_s = 0.7 g_s^{\rm free}$, given by dashed and solid lines, respectively.

fp shell. In the second calculation the valence proton was located in the *fp* shell and the valence neutron was taken in the $1g_{9/2}$ subshell. The calculated configurations corresponding to these two distinct couplings compete in describing the structure of negative-parity states at low energies. The first calculation predicts that the lowest lying states have $I^\pi = 4^-$ and 5^- for all considered quadrupole deformations in the range $-0.2 \leqslant \varepsilon_2 \leqslant 0.2$, whereas the 2^- state is calculated at a higher energy. However, in the calculations performed with the proton located in the *fp* space and the neutron in the $1g_{9/2}$ orbital, for quadrupole deformations $|\varepsilon_2| > 0.10$ the 2^- state becomes the lowest lying state and the 4^- state is located higher, in accordance with the level order established in the present work (see Fig. 4). The main feature of these calculations is that very strongly mixed two-quasiparticle states for ^{84}Y are obtained. However, the measured g factor of the 4^- state could not be reproduced by any of the two TQRM calculations. It appears that the strong K mixing predicted by the TQRM calculations is not confirmed by the experimental finding, and the structure of the 4^- could have a defined K value. Theoretical g factors calculated for the $\pi[301]3/2 \otimes \nu[422]5/2$ and $\pi[301]1/2 \otimes \nu[413]7/2$ configurations that fulfill the condition $\Omega_p + \Omega_n = 4^-$ are illustrated in Fig. 9 for a comparison with the experimental value. The assumed proton and neutron Nilsson orbitals are in accordance with the experimental levels in the neighboring odd-mass nuclei. As seen in Fig. 9, the coupling of the [301]1/2 proton orbital with the [413]7/2 neutron gives a negative g factor, in contrast to the experimental value. However, the coupling of the proton in the [301]3/2 orbital (strongly mixed with the [312]3/2 orbital) with the neutron in the [422]5/2 orbital reproduces the experimental g factor for a prolate deformation of $\varepsilon_2 \approx 0.16$. It is interesting to note that a similar quadrupole deformation has been established in Refs. [24,25] from lifetime measurements in the collective bands observed in this odd-odd transitional nucleus. As seen in Table II, the 4^- state de-excites to the 2^- state by a noncollective $E2$ transition slightly retarded compared to the single-particle estimate. A similar strength was reported in the neighboring ^{86}Y for the transition from the 2^- isomeric state at 248.2 keV to the 4^- ground state [54].

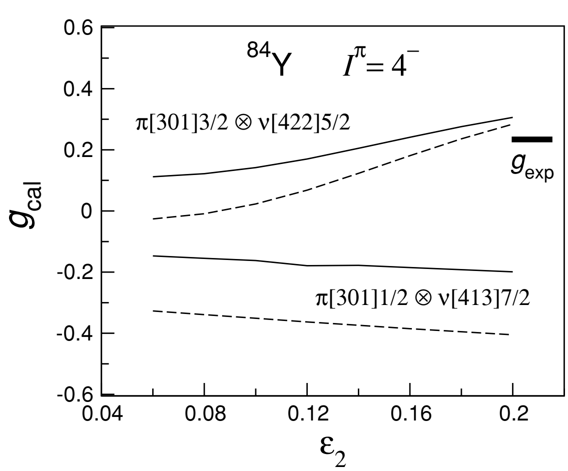

FIG. 9. g factor of the 4^- state compared with calculated values for two selected proton-neutron configurations as a function of the quadrupole deformation ε_2. Two different g_s factors have been used: $g_s = g_s^{\rm free}$ and $g_s = 0.7 g_s^{\rm free}$, given by dashed and solid lines, respectively.

IV. CONCLUSIONS

In this work we have investigated in detail the properties of two new isomeric states in the odd-odd ^{84}Y nucleus, populated in the ^{84}Sr(p, n) reaction at $E_p = 13.5$ MeV. A half-life of $T_{1/2} = 79(2)$ ns has been determined for the level at 112.4 keV assigned as $I^\pi = 4^+$. This state decays to the 6^+ ground state by an $E2$ transition enhanced by a factor of 11 over the single-particle estimate. A new level at 210.4 keV with $I^{\pi} = 4^{-}$ has been identified also as an isomer with $T_{1/2} = 292(10)$ ns. The g factor of the 4^{+} state was remarkably reproduced with the $\pi 1g_{9/2} \otimes \nu 1g_{9/2}$ configuration using the additivity rule and experimental g factors for the odd proton and neutron. TQRM calculations were performed for describing the positive- and negative-parity low-lying states in ^{84}Y. Within this model the low-lying positive-parity states could be interpreted as moderately oblate deformed. Note, however, that this result based on a description restricted to a rigid shape of the core has to be taken with care, as ^{84}Y belongs to a transitional region characterized by the shape coexistence at low excitation energies [46]. An important feature of the TQRM calculations is that very strongly mixed two-quasiparticle states are obtained. The large K mixing predicted for the 4^{-} state is however not supported by the measured g factor, which was found in accordance with the calculated value for the pure $\pi[301]3/2 \otimes \nu[422]5/2$ configuration at a prolate quadrupole deformation of $\varepsilon_2 \approx 0.16$.

ACKNOWLEDGMENTS

The authors thank the staffs of the Bucharest Cyclotron and Tandem accelerators. This work has been supported by the Romanian Ministry of Education and Research through Contract No. 81/2001 of the CERES Programme and Contract No. 10 N/2003, Project No. PN 03 20 02 01.

[1] D. G. Jenkins, N. S. Kelsall, C. J. Lister, D. P. Balamuth, M. P. Carpenter, T. A. Sienko, S. M. Fischer, R. M. Clark, P. Fallon, A. Görgen, A. O. Macchiavelli, C. E. Svensson, R. Wadsworth, W. Reviol, D. G. Sarantites, G. C. Ball, J. Rikovska Stone, O. Juillet, P. Van Isacker, A. V. Afanasjev, and S. Frauendorf, Phys. Rev. C **65**, 064307 (2002).

[2] D. Rudolph, C. J. Gross, J. A. Sheikh, D. D. Warner, I. G. Bearden, R. A. Cunningham, D. Foltescu, W. Gelletly, F. Hannachi, A. Harder, T. D. Johnson, A. Jungclaus, M. K. Kabadiyski, D. Kast, K. P. Lieb, H. A. Roth, T. Shizuma, J. Simpson, O. Skeppstedt, B. J. Varley, and M. Weiszflog, Phys. Rev. Lett. **76**, 376 (1996).

[3] C. D. O'Leary, C. E. Svensson, S. G. Frauendorf, A. V. Afanasjev, D. E. Appelbe, R. A. E. Austin, G. C. Ball, J. A. Cameron, R. M. Clark, M. Cromaz, P. Fallon, D. F. Hodgson, N. S. Kelsall, A. O. Macchiavelli, I. Ragnarsson, D. Sarantites, J. C. Waddington, and R. Wadsworth, Phys. Rev. C **67**, 021301(R) (2003).

[4] J. Uusitalo, D. Seweryniak, P. F. Mantica, J. Rikovska, D. S. Brenner, M. Huhta, J. Greene, J. J. Ressler, B. Tomlin, C. N. Davids, C. J. Lister, and W. B. Walters, Phys. Rev. C **57**, 2259 (1998).

[5] C. Longour, J. Garces Narro, B. Blank, M. Lewitowicz, Ch. Miehe, P. H. Regan, D. Applebe, L. Axelsson, A. M. Bruce, W. N. Catford, C. Chandler, R. M. Clark, D. M. Cullen, S. Czajkowski, J. M. Daugas, Ph. Dessagne, A. Fleury, L. Frankland, W. Gelletly, J. Giovinazzo, B. Greenhalgh, R. Grzywacz, M. Harder, K. L. Jones, N. Kelsall, T. Kszczot, R. D. Page, C. J. Pearson, A. T. Reed, O. Sorlin, and R. Wadsworth, Phys. Rev. Lett. **81**, 3337 (1998).

[6] J. W. Holcomb, T. D. Johnson, P. C. Womble, P. D. Cottle, S. L. Tabor, F. E. Durham, and S. G. Buccino, Phys. Rev. C **43**, 470 (1991).

[7] G. Garcia-Bermudez, M. A. Cardona, A. Filevich, R. V. Ribas, H. Somacal, and L. Szybisz, Phys. Rev. C **59**, 1999 (1999).

[8] D. F. Winchell, L. Wehner, J. X. Saladin, M. S. Kaplan, E. Landulfo, and A. Aprahamian, Phys. Rev. C **55**, 111 (1997).

[9] E. Landulfo, D. F. Winchell, J. X. Saladin, F. Cristancho, D. E. Archer, J. Döring, G. D. Johns, M. A. Riley, S. L. Tabor, V. A. Wood, S. Salém-Vasconcelos, and O. Dietzsch, Phys. Rev. C **54**, 626 (1996).

[10] I. Ray, P. Banerjee, S. Bhattacharya, M. Saha-Sarkar, S. Muralithar, R. P. Singh, and R. K. Bhowmik, Nucl. Phys. **A678**, 258 (2000).

[11] A. Harder, M. K. Kabadiyski, K. P. Lieb, D. Rudolph, C. J. Gross, R. A. Cunningham, F. Hannachi, J. Simpson, D. D. Warner, H. A. Roth, O. Skeppstedt, W. Gelletly, and B. J. Varley, Phys. Rev. C **51**, 2932 (1995).

[12] R. A. Kaye, J. Döring, J. W. Holcomb, G. D. Johns, T. D. Johnson, M. A. Riley, G. N. Sylvan, P. C. Womble, V. A. Wood, S. L. Tabor, and J. X. Saladin, Phys. Rev. C **54**, 1038 (1996).

[13] R. A. Kaye, L. A. Riley, G. Z. Solomon, S. L. Tabor, and P. Semmes, Phys. Rev. C **58**, 3228 (1998).

[14] M. A. Cardona, G. Garcia Bermudez, R. A. Kaye, G. Z. Solomon, and S. L. Tabor, Phys. Rev. C **61**, 044316 (2000).

[15] J. Döring, D. Ulrich, G. D. Johns, M. A. Riley, and S. L. Tabor, Phys. Rev. C **59**, 71 (1999).

[16] J. Döring, H. Schatz, A. Aprahamian, R. C. de Haan, J. Gorres, M. Wiescher, W. B. Walters, J. Rikovska, L. T. Brown, C. N. Davids, C. J. Lister, D. Seweryniak, and B. Foy, Phys. Rev. C **57**, 1159 (1998).

[17] J. J. Ressler, W. B. Walters, R. Grzywacz, J. C. Batchelder, C. R. Bingham, C. J. Gross, Z. Janas, M. Lipoglavsek, J. McConnell, S. D. Paul, A. Piechaczek, K. Rykaczewski, D. Radford, and J. Shergur, Phys. Rev. C **63**, 067303 (2001).

[18] D. Bucurescu, C. A. Ur, M. Ionescu-Bujor, A. Iordachescu, D. Bazzacco, F. Brandolini, G. de Angelis, M. De Poli, A. Gadea, S. Lunardi, N. Marginean, N. H. Medina, D. R. Napoli, P. Pavan, C. Rossi Alvarez, and P. Spolaore, Nucl. Phys. **A705**, 3 (2002).

[19] R. A. Kaye, O. Grubor-Urosevic, S. L. Tabor, J. Döring, Y. Sun, R. Palit, J. A. Sheikh, T. Baldwin, D. B. Campbell, C. Chandler, M. W. Cooper, S. M. Gerbick, C. R. Hoffman, J. Pavan, L. A. Riley, and M. Wiedeking, Phys. Rev. C **69**, 064314 (2004).

[20] P. C. Womble, J. Döring, T. Glasmacher, J. W. Holcomb, G. D. Johns, T. D. Johnson, T. J. Petters, M. A. Riley, V. A. Wood, S. L. Tabor, and P. Semmes, Phys. Rev. C **47**, 2546 (1993).

[21] J. Mukai, A. Odahara, H. Tomura, S. Suematsu, S. Mitarai, T. Kuroyanagi, D. Jerrestam, J. Nyberg, G. Sletten, A. Atac, S. E. Arnell, H. A. Roth, and Ö. Skeppstedt, Nucl. Phys. **A568**, 202 (1994).

[22] S. D. Paul, H. C. Jain, S. Chattopadhyay, M. L. Jhingan, and J. A. Sheikh, Phys. Rev. C **51**, 2959 (1995).

[23] G. Garcia-Bermúdez, H. Somacal, M. A. Cardona, A. Filevich, E. Achterberg, and L. Szybisz, Phys. Rev. C **51**, 1181 (1995).

[24] S. Chattopadhyay, H. C. Jain, J. A. Sheikh, Y. K. Agarwal, and M. L. Jhingan, Phys. Rev. C **47**, 1(R) (1993).

[25] S. Chattopadhyay, H. C. Jain, S. D. Paul, J. A. Sheikh, and M. L. Jhingan, Phys. Rev. C **49**, 116 (1994).

[26] N. Marginean, D. Bucurescu, C. A. Ur, D. Bazzacco, S. M. Lenzi, S. Lunardi, C. Rossi Alvarez, M. Ionescu-Bujor, A. Iordachescu, G. de Angelis, M. De Poli, E. Farnea, A. Gadea, D. R. Napoli, P. Spolaore, and A. Buscemi, Eur. Phys. J. A **4**, 311 (1999).

[27] M. Wiedeking, R. A. Kaye, G. Z. Solomon, S. L. Tabor, J. Döring, G. D. Johns, F. Cristancho, M. Devlin, F. Lerma, D. G. Sarantites, I. Y. Lee, and A. O. Macchiavelli, Phys. Rev. C **62**, 024316 (2000).

[28] F. J. D. Serduke, R. D. Lawson, and D. H. Gloeckner, Nucl. Phys. **A256**, 45 (1976).

[29] G. Winter, R. Schwengner, J. Reif, H. Prade, J. Döring, R. Wirowski, N. Nicolay, P. von Brentano, H. Grawe, and R. Schubart, Phys. Rev. C **49**, 2427 (1994).

[30] J. Döring, G. Winter, L. Funke, B. Cederwall, F. Lidén, A. Johnson, A. Atac, J. Nyberg, G. Sletten, and M. Sugawara, Phys. Rev. C **46**, R2127 (1992).

[31] C. Chandler, P. H. Regan, B. Blank, C. J. Pearson, A. M. Bruce, W. N. Catford, N. Curtis, S. Czajkowski, Ph. Dessagne, A. Fleury, W. Gelletly, J. Giovinazzo, R. Grzywacz, Z. Janas, M. Lewitowicz, C. Marchand, Ch. Miehe, N. A. Orr, R. D. Page, M. S. Pravikoff, A. T. Reed, M. G. Saint-Laurent, S. M. Vincent, R. Wadsworth, D. D. Warner, J. S. Winfield, and F. Xu, Phys. Rev. C **61**, 044309 (2000).

[32] M. Ionescu-Bujor, A. Iordachescu, E. A. Ivanov, G. Pascovici, D. Plostinaru, M. Dumitru, and A. Ivan, Z. Phys. A **349**, 129 (1994).

[33] M. Ionescu-Bujor, A. Iordachescu, E. A. Ivanov, and D. Plostinaru, Z. Phys. A **355**, 347 (1996).

[34] M. Ionescu-Bujor, A. Iordachescu, and D. Bucurescu, Phys. Rev. C **62**, 014306 (2000).

[35] J. K. Tuli, Nucl. Data Sheets **81**, 331 (1997).

[36] T. Yamazaki, H. Ohnuma, Y. Hashimoto, M. Fujioka, E. Takekoshi, A. Hashizume, H. Ikegami, and M. Sakai, J. Phys. Soc. Jpn. **17**, 1223 (1962).

[37] Y. Maxia, W. H. Kelly, and D. J. Horen, J. Inorg. Nucl. Chem. **24**, 1175 (1962).

[38] R. Iafigliola and J. K. P. Lee, Phys. Rev. C **13**, 2075 (1976).

[39] S. K. Saha, P. E. Haustein, D. E. Alburger, C. J. Lister, J. W. Olness, R. A. Dewberry, and R. A. Naumann, Phys. Rev. C **26**, 2654 (1982).

[40] C. F. Liang, P. Paris, D. Bucurescu, S. Della Negra, J. Obert, and J. C. Putaux, Z. Phys. A **309**, 185 (1982).

[41] J. Döring, A. Aprahamian, and M. Wiescher, J. Res. Natl. Inst. Stand. Technol. **105**, 43 (2000).

[42] M. Ionescu-Bujor, A. Iordachescu, D. Bucurescu, N. Marginean, and C. A. Ur, to be published.

[43] R. S. Hager and E. C. Seltzer, Nucl. Data A **4**, 1 (1968).

[44] P. M. Endt, At. Data Nucl. Data Tables **23**, 547 (1979).

[45] M. Ionescu-Bujor, E. A. Ivanov, A. Iordachescu, D. Plostinaru, and G. Pascovici, Nucl. Phys. **A272**, 1 (1976).

[46] W. Nazarewicz, J. Dudek, R. Bengtsson, T. Bengtsson, and I. Ragnarson, Nucl. Phys. **A435**, 397 (1985).

[47] P. Möller, J. R. Nix, W. D. Myers, and W. J. Swiatecki, At. Data Nucl. Data Tables **59**, 185 (1995).

[48] S. Goriely, F. Tondeur, and J. M. Pearson, At. Data Nucl. Data Tables **77**, 311 (2001).

[49] N. J. Stone, At. Data Nucl. Data Tables **90**, 75 (2005).

[50] I. Ragnarsson and P. B. Semmes, Hyperfine Interact. **43**, 425 (1988).

[51] R. Zheng, S. Zhu, N. Cheng, and J. Wen, Phys. Rev. C **64**, 014313 (2001).

[52] T. Bengtsson and I. Ragnarsson, Nucl. Phys. **A436**, 14 (1985).

[53] J. K. Tuli, Nucl. Data Sheets **98**, 209 (2003).

[54] B. Singh, Nucl. Data Sheets **94**, 1 (2001).