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Level structures in ^{240}Np

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Whereas the 7.2 min ^{240}Np, first identified over 60 years ago, has been assigned conflicting configuration by various investigators, the 62 min ^{240}Np is assigned a "probable" configuration, deduced in each case by primarily focusing on just a single β-connected pair of levels in either ^{240}Np (β^-) ^{240}Pu or ^{240}U (β^-) ^{240}Np decay. We evaluate the level energies of physically admissible 2qp configurations in $^{240}_{93}$Np$_{147}$ employing a three-step procedure, with experimental inputs at each step, and using a well tested two-particle rotor model with inclusion of residual n-p interaction and other contributions. This exercise clearly establishes that the 62 min ^{240}Np and the 7.2 min ^{240}Np isomers constitute a Gallagher-Moszkowski (GM) doublet corresponding to the two-quasiparticle (2qp) configuration $5^+\{p5/2^+[642] \pm n5/2^+[622]\}0^+$ with $J^\pi K = 1^+0$ for the higher-lying 7.2 min isomer. This assignment is conclusively confirmed in a level-by-level analysis of data on 23 β transitions in these decays. Structures of a few other ^{240}Np levels populated in ^{240}U β decay are also discussed.

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I. INTRODUCTION

Neptunium ($Z = 93$) is the first human-made transuranic element. It was synthesized in Berkeley in 1940 [1] through neutron irradiation of naturally occurring uranium ($Z = 92$) samples to produce 23 min ^{239}U, which underwent β-decay to yield 2.3 day ^{239}Np as a new element. In the post World War II era, availability of high flux neutron sources enabled successive n captures leading to production of heavier isotopes. Using the Chicago pile as a n source, Hyde *et al.* [2] of Argonne National Laboratory (ANL) reportedly identified 14 hr ^{240}U, and also 7.3 min ^{240}Np as its β-decay product in 1948. The first published confirmation of these β-decaying $A = 240$ isobars was provided in 1953 by Knight *et al.* [3] of Los Alamos. Use of heavy ion reactions, which preferably yield high spin states, provided evidence of a new ^{240}Np species. Bombardment of natural uranium with 35 MeV α particles from the 60″ Berkeley cyclotron led to identification of a 1 hr Np activity which was assigned to ^{240}Np by Lessler and Michel [4]; a comparison of decay energies of each of the two ^{240}Np isomers led these authors to conclude that the 1 hr ^{240}Np lies lower in energy, and hence constitutes the ^{240}Np ground state (gs), with a 7.3 min isomer lying above it. Henceforth we denote these isomers as ^{240}Np and ^{240}Np^m respectively.

Following the initial Argonne report [2], the decay chain ^{240}U (β^-) ^{240}Np^m (β^-) ^{240}Pu (hereafter referred to as the "^{240}U decay chain") has been successively investigated at Berkeley (quoted as private communication in [5,6]), Los Alamos [3,7], Oak Ridge [8,9], and Brookhaven [10]. However, as described briefly in our next section, each of these studies primarily focused on just one of the intense β branches either from ^{240}U $\rightarrow$ ^{240}Np^m or from ^{240}Np^m $\rightarrow$ ^{240}Pu decays to suggest a two-quasiparticle (2qp) configuration for ^{240}Np^m which substantially differed from its earlier proposed assignment in each instance. None of these investigators [5–10] simultaneously took into consideration both ^{240}U and ^{240}Np^m decays, or multiple β branches, nor did they convincingly argue to rule out the previously suggested assignments.

Decay of 62 min ^{240}Np species has been investigated at a number of laboratories [4,11,12]. Although there is no conflict regarding the suggested 2qp configuration for this isomer, the same has been deduced primarily on consideration of only one β branch and hence listed as "probable" in the latest Nuclear Data Sheets (NDS2008) [13]. In the present study, we take an inclusive approach by simultaneously evaluating 2qp level energies using a well tested formulation for odd-odd deformed nuclei, and seeking a fit to multiple β branches from both the decay chains with a view to arrive at a credible characterization of both the isomers and other proposed levels of ^{240}Np.

In Sec. II, results from various experimental reports to date are summarized, highlighting the suggested structures, and the basis thereof, for the two ^{240}Np isomers. In Sec. III, we outline our three-step procedure involving (a) mapping of the available experimental single particle (1qp) configuration space, (b) enumeration of the physically admissible 2qp bands in the deformed odd-odd $^{240}_{93}$Np$_{147}$ nucleus as GM doublets in accordance with the Gallagher-Moszkowski (GM) spin-spin coupling rule [14], and (c) evaluating respective 2qp band-head energies using the rotor particle model with inclusion of residual n-p interaction contribution [15,16]. These calculated level energies, together with our level-by-level analysis of 23 β populated levels in ^{240}Pu are then used in Sec. IV for characterizing the ^{240}Np level structures. Summary and conclusions of our study are presented in the final section.

II. SUMMARY OF EXPERIMENTAL RESULTS

(i) Knight *et al.* [3] of Los Alamos were the first investigators to publish in 1953 detailed results on the ^{240}U decay chain. They observed only one β branch ($E_\beta = 0.36$ MeV; log $ft = 5.6$) in ^{240}U decay and four β branches in ^{240}Np^m decay. They opined that log $ft = 6.5$ for the β branch to 0^+(gs) of ^{240}Pu suggests that this β transition is first forbidden ($1f$: $\Delta J = 0,1$; $\Delta\pi =$ yes); hence ^{240}Np^m has negative parity "in agreement with shell model predictions," but in conflict with log $ft = 5.6$ for the ^{240}U(0^+) (β^-) ^{240}Np^m transition.

(ii) Both the decay chains were presumably investigated in Berkeley in the mid-1950s; unpublished results therefrom are quoted as "private communication (March 1957)" in the 1958 Table of Isotopes [5] and also in a book by Hyde *et al.* [6]. They are said [11] to have suggested the following assignments on the basis of Nilsson model:

$$^{240}\mathrm{Np}^m : 0^-\{p5/2^-[523] \otimes n5/2^+[622]\}, \quad (1)$$

$$^{240}\mathrm{Np} : 5^+\{p5/2^+[642] \otimes n5/2^+[622]\}. \quad (2)$$

(iii) The Los Alamos group reported in 1959 [7] a more detailed investigation of the ^{240}U decay chain. They proposed a nine-level ^{240}Pu scheme from $^{240}\mathrm{Np}^m$ decay. Taking note of intense β transitions with log ft ranging from 6.2 to 7.2 to levels with $J = 0$, 1, and 2 in ^{240}Pu, they assigned $J = 1$ for the parent $^{240}\mathrm{Np}^m$ level, and positive parity for it from the observed log $ft = 5.7$ in ^{240}U decay. Further, they suggested the following as the "most reasonable choice" of Nilsson orbitals for this $J^\pi = 1^+$ level:

$$^{240}\mathrm{Np}^m : 1^+\{p5/2^+[642] \otimes n7/2^+[624]\}. \quad (3)$$

(iv) Using 99.1% enriched ^{244}Pu as equilibrium grandparent activity for $^{240}\mathrm{Np}^m$, Schmorak *et al.* [8] investigated its decay to ^{240}Pu levels. As listed in NDS1977 [9], they invoked Alaga rules [17] to conclude that $K(\text{parent}) = 0$. Further, they took into account the log ft values for decays to $J = 0$, 1, and 2 levels to assign $J(\text{parent}) = 1$. They suggested the following as its 2qp configuration:

$$^{240}\mathrm{Np}^m : J^\pi K = 1^-0\{p5/2^-[523] \otimes n5/2^+[622]\}. \quad (4)$$

They also designated the level connected through the 44 keV $M1$ γ transition to it as the $J^\pi K = 0^-0$ level of this band.

(v) The latest available spectroscopic study of the ^{240}U decay chain has been reported by Hseuh *et al.* [10] of Brookhaven. They confirmed $J = 1$ and $K = 0$ assignment for $^{240}\mathrm{Np}^m$. For inferring its configuration, they focused on the β branch which populates the one-phonon octupole vibrational level at 597.4 keV having $J^\pi K = 1^-0$ in ^{240}Pu. These authors then invoked the Soloviev model [18,19] to determine relative estimates of the n-n and p-p constituents of the collective state. Consideration of available Nilsson orbitals, and the condition that it must have one common orbital with the parent $^{240}\mathrm{Np}^m$ level, led them to consider three 2qp configurations including one in Eq. (4) above, and the other two as follows:

$$^{240}\mathrm{Np}^m : J^\pi K = 1^+0\{p5/2^+[642] \otimes n5/2^+[622]\}. \quad (5)$$

$$^{240}\mathrm{Np}^m : J^\pi K = 1^+0\{p7/2^+[633] \otimes n7/2^+[624]\}, \quad (6)$$

With qualifications, they concluded that the proposed configuration $(p7/2^+, n7/2^+)$ of Eq. (6) is "more probable" than the $(p5/2, n5/2)$ configurations of Eqs. (4) and (5). However, NDS2008 [13] missed the qualifying *more probable* while listing the $^{240}\mathrm{Np}^m$ configuration.

(vi) Wapstra and Goudsmit [11] studied the intense decay of 62 min ^{240}Np to 1309 keV, $J^\pi = 5^-$ level of ^{240}Pu. Identifying the 1309 keV ^{240}Pu level as a 2qp state with configuration $5^-\{p5/2^+[642] \otimes p5/2^-[523]\}$, they proposed the assignment of Eq. (2) for 62 min ^{240}Np.

(vii) Decay of 62 min ^{240}Np was later studied at Brookhaven by Parekh *et al.* [12]. Combining their data with $^{240}\mathrm{Np}^m$ decay results from the same laboratory [10], they "classified ^{240}Pu levels as members of various rotational bands." The assignments from these two BNL studies [10,12] have been essentially adopted in the latest Nuclear Data Sheets [13].

Thus we note that while several conflicting configuration assignments have been suggested for $^{240}\mathrm{Np}^m$ by different investigators, only one "probable" 2qp assignment of Eq. (2) has been suggested for ^{240}Np(gs).

III. MODEL FORMULATION AND CALCULATION

Sood and Singh [15] had developed a formalism for calculating band-head energies of 2qp intrinsic structures of odd-odd deformed nuclei by including residual n-p interaction contribution $\langle V_{np}\rangle$ in the traditional two-particle rotor model. This formulation has been effectively employed to describe, and to predict, the location and character of 2qp bands, in particular the frequently occurring long-lived isomer pairs of several odd-odd actinides ranging from $_{93}$Np through $_{101}$Md [20–27]. Exhaustive data on 2qp bands and associated rotational levels of the actinides [16] and the rare-earth nuclei [28,29] have since been presented in a series of review articles, wherein a semiempirical version of the earlier formulation is introduced. Very recently, we have reported [30–32] the results of our analysis for level structures, including characterization of isomer pairs, in n-rich Pm ($Z = 63$) odd-odd isotopes; the procedure adopted therein is employed here as well.

Our approach involves a three-step process. First, the available 1qp configuration space for a specific case is mapped by using the experimentally observed 1qp excitation energies of respective Nilsson orbitals in the odd-A isotopes for proton and isotones for neutron constituents of the odd-odd nucleus. Our results of this exercise for $^{240}_{93}\mathrm{Np}_{147}$ are presented in Fig. 1 using the latest available data [33].

In the rotor particle model of odd-odd deformed nuclei, each 2qp (Ω_p, Ω_n) structure couples to give rise to two bands with quantum numbers $K^\pm = |\Omega_p \pm \Omega_n|$. Relative energy ordering of these two bands is governed by the Gallagher-Moszkowski (GM) rule [14] which places the spins-parallel triplet ($\Sigma = 1$) K_T band lower in energy than its GM doublet partner spins-antiparallel singlet ($\Sigma = 0$) K_S band. As our second step, we identify the physically admissible 2qp bands in ^{240}Np within the energy range constrained by the fact that the ^{240}U decay, which populates ^{240}Np low-spin levels, has $Q_\beta = 390(17)$ keV [34]. Results of this exercise for ^{240}Np are presented in Table I. Finally we evaluate the 2qp energies

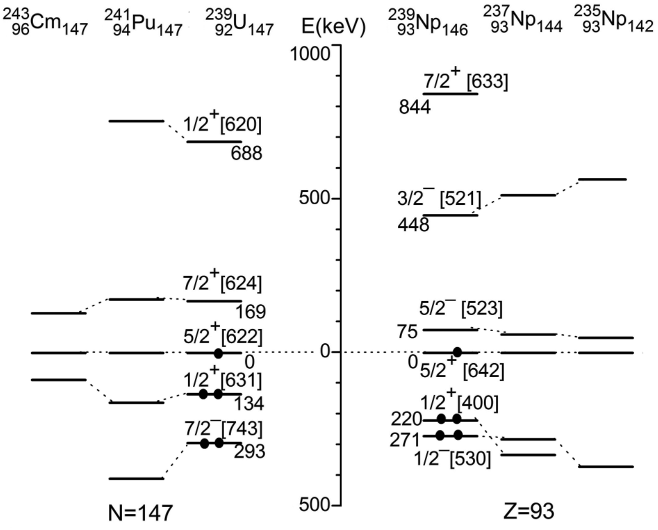

FIG. 1. Experimental excitation energies (in keV) of single particle Nilsson orbitals in the $Z = 93$ odd-A Np isotopes and $N = 147$ odd-A isotones defining the available configuration space for $^{240}_{93}$Np$_{147}$. The–•–denotes the occupied orbitals in $(A-1)$ core nuclei.

using the following expression [16,28]:

$$E(K:\Omega_p,\Omega_n) = E_0 + E(\Omega_p) + E(\Omega_n) + E_{\rm rot} + \langle V_{pn}\rangle, \tag{7}$$

wherein $E(\Omega)$ are the observed excitation energies of the corresponding Nilsson orbital state in the neighboring odd-A isotope/isotone, and

$$E_{\rm rot} = \frac{\hbar^2}{2I}[K-(\Omega_p+\Omega_n)] = -\frac{\hbar^2}{2I}(2\Omega_<)\delta_{K,K^-}, \tag{8}$$

$$\langle V_{pn}\rangle = -\left(\frac{1}{2}-\delta_{\Sigma,0}\right)E_{GM} + (-)^I E_N\delta_{K,0}. \tag{9}$$

The term $\hbar^2/2I$ in Eq. (8) is the usual rotational band inertial parameter. The terms E_{GM} and E_N in Eq. (9) denote respectively the GM doublet splitting energy and the Newby odd-even shift (for the $K = 0$ bands) arising from the residual n-p interaction V_{np} for the specified configuration.

TABLE I. Low-lying (<400 keV) 2qp bands, K_T^π and K_S^π expected in ^{240}Np and their zeroeth order energies ($E_p + E_n$) in parentheses. The listed E_p (top row) and E_n (second column) are the experimental [33] excitation energies for the respective orbital in ^{239}Np and ^{239}U spectra. All energies are in keV.

E_p →	p_0 0		p_1 75	
E_n ↓	5/2$^+$[642↑]		5/2$^-$[523↓]	
	K_T	K_S	K_T	K_S
n_0 0	5^+	0^+	0^-	5^-
5/2$^+$[622↑]	(0)		(75)	
n_1 134	2^+	3^+	3^-	2^-
1/2$^+$[631↓]	(134)		(209)	
n_2 169	1^+	6^+	6^-	1^-
7/2$^-$[624↓]	(169)		(244)	
n_3 293	6^+	1^+	1^-	6^-
7/2$^+$[743↑]	(293)		(368)	

In principle the model parameters (e.g., E_{GM}, $\hbar^2/2I$, E_N, etc) can be evaluated theoretically [15,35]. But in the semiempirical approach adopted here [16,28–32] we use the experimental data in any odd-odd neighbor wherein a specific 2qp band, expected in ^{240}Np, has been experimentally identified. These experimental data are then used as inputs to deduce the parameters for respective structures, to be used in Eqs. (7)–(9), along with E_p and E_n from latest available data files [33], to evaluate ^{240}Np level energies. In case a 2qp GM doublet is not observed in any neighbor, we use $E_{GM} = 82$ keV [36] obtained by fitting the gs band in ^{238}Np. Results of this exercise are shown in Fig. 2, which also includes rotational levels with $J \leqslant 2$ for $K = 0$ and 1 bands as given by the usual $I(I+1)$ law with due consideration of Newby term.

A firm conclusion of our evaluation is that the ^{240}Np and ^{240}Np^m isomers constitute the GM doublet corresponding to the (p_0n_0) 2qp configuration $5^+\{p_05/2[642] \pm n_05/2[622]\}0^+$ with the $J^\pi K = 1^+0$ being the lowest level populated in ^{240}U(0^+) decay. To evaluate $\Delta E(1^+ - 5^+)$, we adopt the $E_{GM} = 82$ keV from the ^{238}Np gs doublet [36] along with other parameters from experimentally observed [33] levels for the $K^\pi = 0^+(p_0n_0)$ band in isotonic ^{242}Am. Using these values in Eqs. (7)–(9), we determine $\Delta E(1^+ - 5^+) = 12(10)$ keV, to be compared with the experimentally deduced NUBASE2012 [37] value of 18(14) keV. This agreement strongly supports our configuration assignments to ^{240}Np isomers.

Another significant result from our model evaluation is that the first excited state, populated in ^{240}U decay and placed 44 keV above the ^{240}Np^m 1^+0 level, has $J^\pi K = 1^-0$ with the configuration $\{p5/2^-[523] - n5/2^+[622]\}$. Comparison of our ^{240}Np level scheme shown in Fig. 2 with data listed in NDS2008 is discussed in the following section.

IV. ANALYSIS AND DISCUSSION

In this section, we take up a critical analysis of all the experimental data [13] available so far from ^{240}U and ^{240}Np decays, keeping in view the physically admissible configuration space, rotor particle model calculated energies of low-lying 2qp structures in ^{240}Np and 2qp structures [12,18,19,38] of ^{240}Pu levels populated in β decays of both the ^{240}Np isomers. In the following discussion, we use an abbreviated notation $(p/n\Omega^\pi)$ to denote various Nilsson orbitals indicated in our Fig. 1 and Table I.

A. 62 min ^{240}Np high spin isomer (HSI)

The odd-odd nucleus $^{240}_{93}$Np$_{147}$ can, in principle, be synthesized from $^{239}_{93}$Np$_{146}$$(p_05/2^+)$ by adding the 147th neutron, which is experimentally [33] observed to occupy the $n_05/2^+$ orbital in every known isotone. Alternately, it can be synthesized from $^{239}_{92}$U$_{147}$ $(n_05/2^+)$ by adding the 93rd proton which is experimentally observed to occupy the $p_05/2^+$ orbital in every known isotope. In either scenario, the lowest energy level in ^{240}Np is seen to have $J^\pi K = 5^+5$, being the K$_T$ member

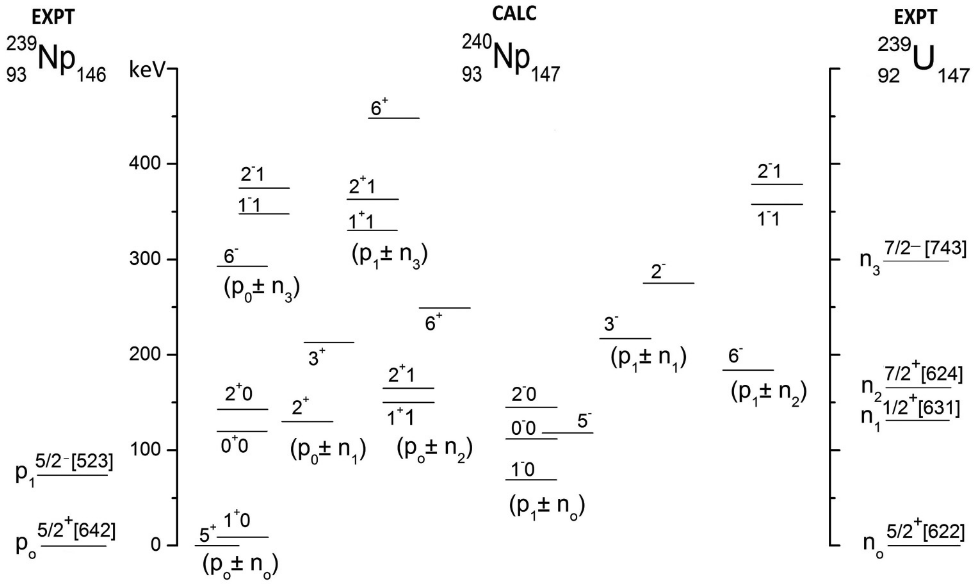

FIG. 2. Plot of experimental low-lying (up to 400 keV) [33] band-head energies in isotopic ^{239}Np (on the left) and in isotonic ^{239}U (on the right), and model calculated 2qp level energies in ^{240}Np (in the middle). Rotational levels with $J \leqslant 2$ for $K = 0$ and $K = 1$ bands are labeled with $J^\pi K$.

of the GM doublet with ($p_0 5/2^+$,$n_0 5/2^+$) 2qp configuration assignment. Our model calculations, described in Sec. III, also yield this assignment for ^{240}Np(gs).

NDS2008 [13] lists $J^\pi = (5^+)$ for the 62 min ^{240}Np having "probable" configuration $\{p5/2^+[642] + n5/2^+[622]\}$ based on its β decay with log $ft = 5.7$ to 1309 keV (5^-) ^{240}Pu level. This assignment is based on just one β branch. NDS2008 lists 12 other β branches, deduced mainly from intensity balances, as shown in Fig. 3. In this figure J^π and K assignments to ^{240}Pu levels are from the band structure proposed by Parekh *et al.* [12] *based on analysis of all the radioactivity studies and nuclear reaction data*. Examination of these data reveals that NDS2008 listed β-feeding to the 959 keV $J^\pi K = 2^- 1$ ^{240}Pu level corresponds to $\Delta J = 3$, $\Delta\pi =$ yes and is hence highly forbidden; this transition is accordingly not shown in our Fig. 3. As explicitly stated in NDS2008, all the 12 β transitions are K-forbidden and hence have log $ft \geqslant 7.0$ [39]. The listed 2qp constituents/components in ^{240}Pu levels shown in Fig. 3 are from earlier studies [12,18,19,38]. Examination of data in Fig. 3 reveals that the $5/2^+[642]$ proton orbital is the common constituent of 2qp structure of eight p-p daughter states, and the $5/2^+[622]$ neutron orbital is likewise a common constituent of the other four n-n states. These observations clearly mandate that the parent ^{240}Np state is composed of these two orbitals.

We accordingly conclude that consideration of physically admissible structures, model evaluated energies, and consistency with the experimental data on all the 12 β branches unambiguously confirm the $J^\pi K = 5^+ 5\{p5/2^+[642] + n5/2^+[622]\}$ configuration assignment to 62 min ^{240}Np.

B. 7.2 min ^{240}Np^m low-spin isomer (LSI)

As early as 1959, Bunker *et al.* [7] had assigned $J = 1$ for 7.2 min ^{240}Np on basis of log ft values (< 7.2) of strong β transitions to ^{240}Pu levels with $J^\pi = 0^+$, 2^+, and 1^-. Later Schmorak [9], and also Hseuh *et al.* [10], deduced that, according to Alaga rules [17], "the observed β-branching

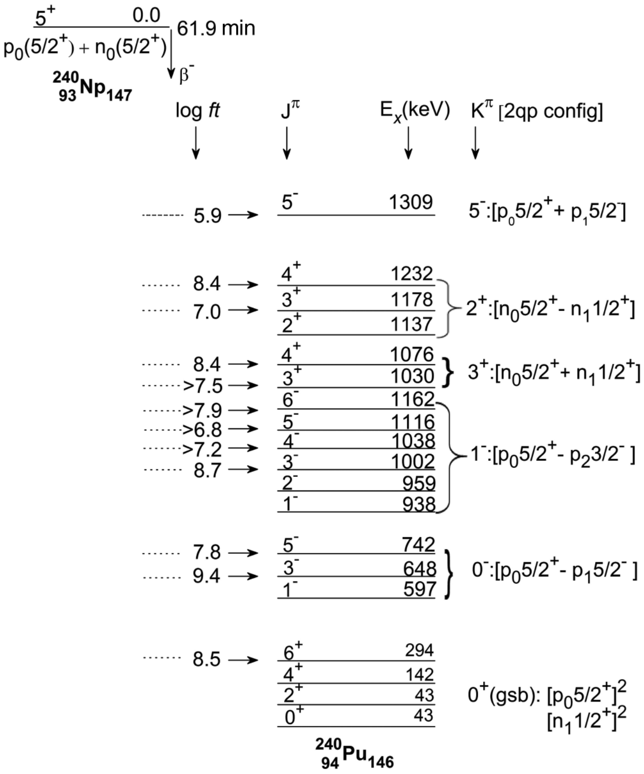

FIG. 3. Schematic plot (not to scale) of the experimental data [13] on β branches to levels in ^{240}Pu from decay of 62 min ^{240}Np. The structures mentioned on the right are the operative 2qp components for each transition, as discussed in the text.

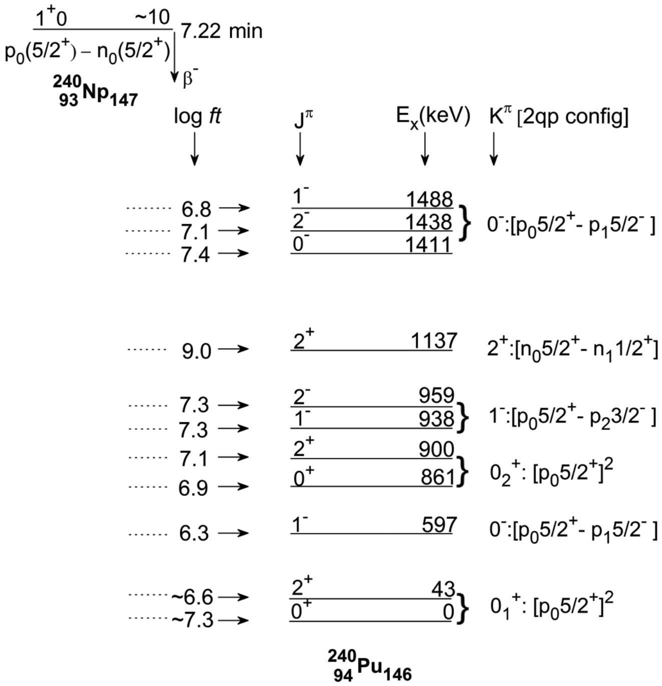

FIG. 4. Schematic plot (not to scale) of the experimental data [13] on β branches to levels in ^{240}Pu from decay of 7.2 min ^{240}Np. The structures mentioned on the right are the operative 2qp components for each transition as discussed in the text.

ratios to $J = 0$ and $J = 2$ levels of $K = 0$ excited bands point to a predominantly $K = 0$ character for ^{240}Np^m." However, as summarized in Sec. II, its parity and configuration assignment have differed from investigator to investigator.

As discussed in Sec. III, the experimentally observed configuration space around the Fermi surface (see Fig. 1), the physically admissible 2qp band structures in accordance with GM rule (see Table I), and the calculated band-head energies using a well tested formulation (see Fig. 2) all point to $(p_05/2^+,n_05/2^+)$ as the only acceptable configuration for ^{240}Np^m. However, as mentioned in Sec. II (v), Hseuh *et al.* [10] list $(p7/2^+,n7/2^+)$ of Eq. (6) as its "more probable" configuration, primarily based on consideration of just one of its numerous β branches. In the following we critically examine their expressed preferences and reservations, and also analyze the other ten β branches as sketched in Fig. 4.

(i) A serious reservation explicitly noted by them [10] states that the excitation energy of the proposed configuration expected from Nilsson diagram is about 500 keV rather than roughly 10–30 keV derived from experiment. On the other hand, the alternative $(p5/2,n5/2)$ configurations of Eqs. (4) and (5) are known [33] to have low enough excitation energies compatible with the experiment.

(ii) Over 55% of β intensity in ^{240}Np^m decay is reported [13] to populate the ^{240}Pu gs $K^\pi = 0_1^+$ band levels "through the allowed hindered $n7/2[624] \rightarrow p7/2[633]$ transition [10]." This process can occur only if the 7/2[633] proton pair is a major constituent of the ^{240}Pu gs band. However, Soloviev [18] determines only 0.01% contribution in the $K^\pi = 0_1^+$ band from the $p7/2^+$ pair, whereas it has a dominant (20.7%) $p5/2^+$ pair constituent. Accordingly these intense β branches would be forbidden from $(p7/2^+,n7/2^+)$ parent to the ^{240}Pu gs band (since they involve simultaneous change of both the orbitals), and would be quite intense from the $(p5/2^+,n5/2^+)$ parent as seen experimentally.

(iii) ^{240}Np^m decay also populates [13] 0^+ and 2^+ levels of the 861 keV based β-vibrational $K^\pi = 0_2^+$ band with log *ft* values of 7.1 and 6.9 respectively. Soloviev [18] determines only negligible (0.2%) contribution to the $K^\pi = 0_2^+$ band levels from the $p7/2^+$ pair and 24.2% component from the $p5/2^+$ pair. These β branches would have been forbidden (due to simultaneous change of both orbitals) if the parent has $(p7/2^+,n7/2^+)$ configuration. Alternatively, the observation of these β branches is consistent with $(p5/2^+,n5/2^+)$ configuration for the parent.

(iv) Hseuh *et al.* [10] also note that, since Soloviev calculations [18] predict the 1137 keV 2^+ vibrational state to consist almost entirely (95%) of $(n5/2^+,n1/2^+)$ configuration, β transition to it from the $(p7/2^+,n7/2^+)$ parent involves simultaneous change of both orbitals and hence should be forbidden. However, experimentally this transition is seen to occur with log $ft = 9$ [13], consistent with $(p5/2^+,n5/2^+)$ configuration for the parent. This somewhat higher value for log *ft* can be ascribed to K-forbiddeness [39].

(v) Next we consider a set of three levels of the $K^\pi = 0^-$ band based on the 1411 keV $J^\pi K = 0^-0$ level in ^{240}Pu which are populated in ^{240}Np^m β decay with log $ft \approx 7$. Parekh *et al.* [12], who incidentally have three common authors with Hseuh *et al.* [10], classify this band as the GM doublet partner of "the well characterised 1308.7 keV $J^\pi K = 5^-5$ level" having a two-proton configuration $(p_05/2^+,p_15/2^-)$. Evidently, these three experimentally observed β transitions would be forbidden from a $(p7/2^+,n7/2^+)$ parent since it would involve simultaneous change of both orbitals. On the other hand, with a $(p5/2^+,n5/2^+)$ parent, they would occur through $n5/2^+[622] \rightarrow p5/2^-[523]$ transformation, in conformity with the observed log $ft \approx 7$ for all the three $1f$ transitions.

Summarizing, it has been established that 8 (out of 11) β-populated ^{240}Pu levels shown in Fig. 4 do not have any p or n orbital with $\Omega^\pi = 7/2^+$ as its constituent. Accordingly β transition from a $(p7/2^+,n7/2^+)$ parent to every one of these 8 levels, though experimentally observed with log $ft \approx 7$, would be forbidden, since it would involve simultaneous change of both the orbitals. On the other hand, all the 11 β-populated ^{240}Pu levels shown in Fig. 4 have either p or n orbital with $\Omega^\pi = 5/2^+$ component and hence all these 11 observed β transitions are consistent with a $(p5/2^+,n5/2^+)$ assignment for the ^{240}Np^m parent state.

An experimental feature, that definitely rules out the $p7/2^+[633]$ as a constituent of ^{240}Np^m, is inherent in the fact that the said ^{240}Np^m in each and every experiment is produced in 14 hr ^{240}U β decay wherein $Q_\beta \approx 400$ keV. The $p7/2^+$

orbital is experimentally placed [33] at an excitation energy of 844 keV in the ^{239}Np core nucleus, and is hence inaccessible in a transition with $Q_\beta \approx 400$ keV. On the other hand, $p5/2^+$ as the core nucleus gs is certainly accessible.

Another experimental observation, which decisively rules out the $(p7/2^+,n7/2^+)$ suggested structure for $^{240}\mathrm{Np}^m$, is as follows. This $K^\pi = 0^+$ $(p7/2^+,n7/2^+)$ band is observed [33] in ^{244}Am with a band head at 375 keV; in this band the lowest energy level is $J^\pi K = 0^+0$ and the Newby shifted $J^\pi K = 1^+0$ is observed higher at 452 keV. However, the lowest energy level in $^{240}\mathrm{Np}^m$ is experimentally determined to have $J^\pi K = 1^+0$ thus negating the $(p7/2^+,n7/2^+)$ $^{240}\mathrm{Np}^m$ assignment, but in agreement with its $(p5/2^+,n5/2^+)$ configuration.

An experimental feature, that unequivocally confirms the same Nilsson orbitals constituents, and hence their characterization as GM doublet, in both the ^{240}Np isomers, is revealed by simultaneous examination of data in Figs. 3 and 4. Therein it is seen that all the β transitions from 62 min isomer decay populate high-spin ($J \geqslant 3$) levels of the same structure bands whose low spin ($J \leqslant 2$) levels are populated in 7.2 min isomer decay. Additional support for this assignment comes from the fact that our evaluated excitation energy, as given in Sec. III, for this $J^\pi K = 1^+0$ level agrees with the experimental [37] value from β-decay energies.

Thus all the experimental data from both the decays in the $^{240}\mathrm{U} \rightarrow {}^{240}\mathrm{Np}^m \rightarrow {}^{240}\mathrm{Pu}$ chain and the physical considerations detailed above decisively and unambiguously confirm $J^\pi K = 1^+0\{p5/2^+[642] - n5/2^+[622]\}$ configuration for $^{240}\mathrm{Np}^m$ and its characterization as a GM doublet partner of $J^\pi K = 5^+5$ ^{240}Np(gs).

C. Other levels in ^{240}Np

Bunker *et al.* [7] had found that “aside from the 0.36 MeV β group from 14 hr ^{240}U decay (which populates the 7.2 min $^{240}\mathrm{Np}^m$ level), the only other accompanying radiation is a highly converted 44 keV transition in ^{240}Np.” Based on “visually estimated” L-subshell ratios, they deduced $M1 + E2$ multipolarity for this 44 keV γ transition, and accordingly introduced a $J^\pi = (1^+)$ level in the ^{240}Np spectrum at 44 keV above the 7.2 min $^{240}\mathrm{Np}^m$ level. Even though the corresponding β group for 44 keV γ could not be confirmed, they concluded that “it is involved in about 25% of ^{240}U disintegrations.” With no other conversion electron studies reported since then, all later investigators and NDS evaluators have adopted these assignments, namely $M1 + E2$ multipolarity for the 44 keV γ transition and the same J^π for the $44 + x$ keV level and the 7.2 min $^{240}\mathrm{Np}^m$ isomeric level.

However, careful examination of the experimentally available 1qp configuration space (see Fig. 1), and the physically admissible 2qp structures therefrom clearly reveal (see Table I and Fig. 1) that the $^{240}\mathrm{Np}^m$ spectrum does not have any $J^\pi = 1^+$ excited level below 150 keV. Quantitative evaluation of level energies places a $J^\pi K = 1^-0$ level of the $(p5/2^-,n5/2^+)$ configuration around $E_x \approx 50(10)$ keV relative to the 7.2 min isomeric level, and hence it is the only acceptable assignment for the experimentally observed $44 + x$ keV level.

Further experimental support for this assignment comes from a side-by-side examination of $^{239}\mathrm{U} \rightarrow {}^{239}\mathrm{Np}$ and $^{240}\mathrm{U} \rightarrow {}^{240}\mathrm{Np}$ β decays. These two decays are very similar. For instance, almost all the β intensity in each of these decays goes into the lowest two low-lying states ($E_x < 80$ keV). Also, barring the β group to the lowest state, no other β branch is experimentally observed in either case. β-feeding to each of the excited levels in either decay is deduced from transition intensity balances. Experimental β population of gs band levels in ^{239}Np is seen to proceed through the $n_0 5/2^+ \rightarrow p_0 5/2^+$ transformation, and that for the 75 keV based negative parity band levels through the $n_0 5/2^+ \rightarrow p_1 5/2^-$ transformation. Considering that ^{240}U decay essentially populates the two ^{240}Np levels with $E_x < 50$ keV, these β branches can be reasonably assumed to respectively proceed through the above mentioned two transformations, with the additional $n5/2^+$ orbital in ^{240}U acting as a spectator. Accordingly, the ^{240}Np isomeric level has the $(p5/2^+,n5/2^+)$ configuration and the $44 + x$ keV level clearly corresponds to the $(p5/2^-,n5/2^+)$ configuration, yielding negative parity for it, and hence $E1$ multipolarity for the 44 keV γ transition conflicting with its 1959 deduced $M1 + E2$ character. This situation calls for a more careful and precise study of conversion electron spectra in ^{240}U decay.

Hseuh *et al.* [10] reported 16 additional γ transitions in ^{240}U decay and thence proposed a ^{240}Np level scheme deduced mainly from transition energy and intensity balances which are in turn calculated from the theoretical conversion coefficients under the assumption that all transitions are $M1$. NDS2008 evaluator argued that the transition multipolarity may be $M1$ or $E1$; this assumption drastically changes the calculated transition intensities, e.g., I_β for the 7.2 min isomeric level is now about 75%, contrasting with the 38% quoted by Hseuh *et al.* NDS-2008 has put a question mark on six out of the eight new levels proposed by them. A close look at our level scheme of Fig. 2 reveals that some of the γ transitions may indeed have $E2$ multipolarity; such an eventuality would again significantly change the scenario. Our level scheme of Fig. 2 includes eight new $J \leqslant 2$ levels in the energy range 80–300 keV; this may tempt one to work out their correspondence with some of the eight new levels proposed by Hseuh *et al.* However, we are of the considered opinion that, with the presently available questionable data input, such an exercise would be highly speculative.

V. SUMMARY AND CONCLUSIONS

Examination of all the available experimental data revealed that, whereas multiple, and conflicting, configuration assignments for 7.2 min ^{240}Np have been suggested by different investigators primarily on consideration of data from just one β branch in each case, a “probable” configuration for 62 min ^{240}Np has been suggested, again on consideration of just one β branch. Our study aimed at deducing an unambiguous credible configuration for these isomers and other ^{240}Np levels. In this exercise, our three-step procedure—involving mapping of experimentally available 1qp configuration space, enumeration of physically admissible 2qp structures, and model based evaluation of level energies—provided us with a blueprint of ^{240}Np level scheme. These results were used, alongside a level-by-level structure analysis of 23 β branches to ^{240}Pu levels from decays of both the ^{240}Np isomers, and a side-by-side examination of ^{239}U and ^{240}U β decays, to arrive at the following conclusions.

Our detailed analysis firmly rules out $(p7/2^+,n7/2^+)$ 2qp assignment for the 7.2 min ^{240}Np isomer. Among other arguments, we specifically note that this configuration has no overlap with 8 ^{240}Pu levels which are experimentally populated in ^{240}Np^m decay. Even more convincing is the fact that the $p7/2^+$ orbital is experimentally inaccessible in ^{240}U ($Q_\beta \approx 400$ keV) decay.

Our analysis unambiguously establishes that the two ^{240}Np isomers constitute a GM doublet with the 2qp configuration $5^+\{p5/2^+[642] \pm n5/2^+[622]\}0^+$. The $J^\pi K = 1^+0$ level of the $K^\pi = 0^+$ spins-antiparallel band of this GM doublet is identified with the 7.2 min ^{240}Np isomer, and its $K^\pi = 5^+$ spins-parallel band is identified with the 62 min ^{240}Np gs. In a level-by-level analysis of β decays from each of these isomers, this assignment is shown to be consistent with all the 23 β branches. This characterization is further confirmed by noting that our calculated separation energy $\Delta E(1^+ - 5^+)$ is in good agreement with its experimental value derived from β-decay energies. Additional experimental (model independent) support for characterizing the two ^{240}Np isomers as GM doublet partners having the same 2qp constituents comes from the observation that all β transitions from 62 min ^{240}Np decay populate high-spin ($J \geqslant 3$) levels of the same structure bands whose low spin ($J \leqslant 2$) levels are populated in 7.2 min isomer decay. Our analysis also yields $J^\pi K = 1^-0\{p5/2^-[523] - n5/2^+[622]\}$ assignment for the $44 + x$ keV level. This assignment implies an $E1$ character for the 44 keV γ transition which conflicts with its $M1 + E2$ multipolarity deduced earlier from "visually estimated L-subshell ratios" in a study conducted over half a century ago. Detailed conversion electron and coincidence studies with presently available experimental and analysis techniques are sought to substantiate the findings of this study and to deduce a credible ^{240}Np level scheme.

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