High-K, two-quasiparticle states in ^{160}Gd

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Excited states in ^{160}Gd were populated via β decay from the low- and high-spin isomers in ^{160}Eu. The high-spin, $K^{\pi} = 5^{-}$ state feeds several two-quasiparticle levels, as well as a sequence associated with a γ vibration and a $K^{\pi} = 4^{+}$, hexadecapole vibrational structure. The decay scheme was significantly improved with the observation of new transitions and states when compared with the two competing level schemes from over four decades ago. Configuration assignments for some of the multiquasiparticle levels have been suggested, based upon decay properties, systematics from neighboring nuclei, and comparisons with theoretical calculations. In addition, 15 new low-spin states and approximately 60 new transitions were observed resulting from the decay of the low-spin ^{160}Eu isomer.

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I. INTRODUCTION

The neutron-rich, rare-earth nuclei have emerged as belonging to an important region to explore in view of its significance in both nuclear astrophysics and nuclear structure. Much of the recent work in this region has resulted from the analysis of spontaneous fission fragments that populate excited states along the yrast line. However, by producing the rare-earth nuclei at a radioactive beam facility, such as the Californium Rare Isotope Breeder Upgrade (CARIBU) [1], the isotopes of interest can be studied via β decay so that the non-yrast configurations may be observed and the location of important Nilsson orbitals can be determined.

Information from these rare-earth nuclei has astrophysical relevance, especially for the rapid-neutron capture process (r process) that is responsible for the creation of a large fraction of the heavy elements. For example, a complete explanation of the elemental rare-earth peak (REP) in the abundance distribution is still lacking [2–5]. The astrophysical models are dependent on nuclear masses, lifetimes, as well as on the single-particle structure of these neutron-rich nuclei. Mass measurements have been made recently [6–8] with the Canadian Penning Trap and CARIBU, as well as with the JYFLTRAP [9], in order to provide these data. In addition, lifetime measurements of ground states and isomers are being conducted via β-decay experiments at CARIBU, including the one discussed in the present paper.

The β-decay information is not only useful input for astrophysical models, it also addresses nuclear structure effects observed in the region. Indeed, a sizable gap in the energy levels of neutrons at $N = 98$ was recently reported [6] based upon such β-decay studies. The focus of the present work is on the structure of ^{160}Gd populated by the β decay of the $K^{\pi} = 5^{-}$ state in ^{160}Eu [6]. New two-quasiparticle states have been identified, and two collective structures based on a γ vibration and on a more exotic hexadecapole vibration were observed. In addition, levels populated by the proposed $K^{\pi} = 0^{-}$, β-decaying state in ^{160}Eu are also reported.

II. EXPERIMENTAL DETAILS

Isobarically separated $A = 160$ nuclei were obtained from the CARIBU source [1] at Argonne National Laboratory. These nuclei were implanted in the SATURN moving tape collection system, which was surrounded by four germanium clover detectors, as well as by four plastic scintillators of the X-Array spectrometer [10]. A digital acquisition system recorded energy and time information from the clover detectors (γ rays) and the plastic scintillators (β particles). All events were time stamped through the use of a 10 MHz

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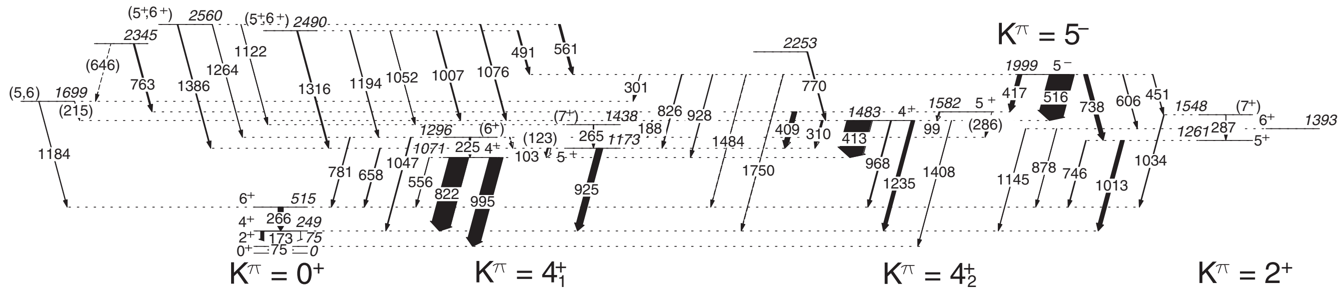

FIG. 1. Partial level scheme of ^{160}Gd resulting from states populated by the high-K isomer in ^{160}Eu.

clock. A tape cycle of 180 s growth time (beam on), 180 s decay time (beam off), 1 s tape movement, and 4 s for background accumulation was based on the previous ^{160}Eu evaluated half-life of $t_{1/2} = 38(4)$ s [11]. A β-gated, E_γ vs. time coincidence matrix was constructed to measure the half-lives of the strongest γ-ray transitions, where the times were measured from the beginning of the tape cycle. In addition, a β-gated, E_γ-E_γ coincidence matrix was utilized to build the level scheme of ^{160}Gd. Approximately 59×10^6 β-γ events were recorded in 33 h of beam time.

III. RESULTS

Various reactions have been used to study ^{160}Gd, and the ground-state sequence has been observed to a spin/parity of 16^+, while the γ and octupole vibrational bands are known up to 12^+ and 11^-, respectively [11]. However, it has been over four decades since the last β-decay investigation of this nucleus. Two earlier works published in 1973 [12,13] provided conflicting level schemes. Although many of the same transitions were observed in the present data, the higher sensitivity of the X-Array (compared with the systems used in Refs. [12,13]) together with the high intensity and beam purity of CARIBU beams allowed for weaker transitions to be observed in the present data. The observation of these weaker γ rays required changing the placement of many of the previously reported γ rays. The level scheme resulting from the β decay of the high-spin, $K^\pi = 5^-$ isomer in ^{160}Eu is given in Fig. 1.

It was previously assumed that a single β-decaying state from ^{160}Eu, with a spin of 1 $\hbar$, fed the levels in the ^{160}Eu daughter. However, in our recent publication [6], mass-measurement results clearly identified two ^{160}Eu long-lived isomers separated by 93.0 (12) keV. One of these states feeds levels in ^{160}Gd with spins 4–6 $\hbar$, while the other primarily feeds low-spin ones ($\leqslant 2$ $\hbar$). The high-spin β-decaying state in ^{160}Eu was identified in Ref. [6] as being associated with the $K^\pi = 5^-$, $\pi[413]5/2$, $\nu[523]5/2$ configuration, and a possible configuration for the low-spin state is discussed in Sec. III B. Time spectra from the strongest transitions resulting from the high-spin and low-spin decays were summed into their respective spectra shown in Fig. 3(a) of Ref. [6]. Half-lives of 42.6(5) s and 30.8(5) s were determined for the high- and low-K isomers of ^{160}Eu, respectively.

A spectrum of the β-gated γ transitions observed in the experiment is provided in Fig. 2(a). A time cut starting 50 s after the tape movement and extending to the end of the cycle was selected to generate this spectrum. Such a time cut greatly reduces the presence of γ transitions associated with the β decay of ^{160}Sm whose half-life is 9.6(3) s, and was also present in the $A = 160$ beam from CARIBU. In addition, two other spectra are provided in Fig. 2 to demonstrate the quality of the data. Figure 2(b) displays a sum of spectra resulting from coincidence events with the 491.1- and 560.8-keV γ rays, which originate from the 2489.9- and 2559.9-keV levels, respectively (see Fig. 1). Both of these transitions feed the 1999.0-keV state, and the spectrum displays many of the γ rays associated with the levels fed by the high-K isomer from ^{160}Eu. Figure 2(c) is a sum of the transitions in coincidence with the 1149.1- and 1214.5-keV γ rays that depopulate the 1224.3-keV and 1289.9-keV levels, respectively, from the octupole-vibration sequence. In addition, a transition from

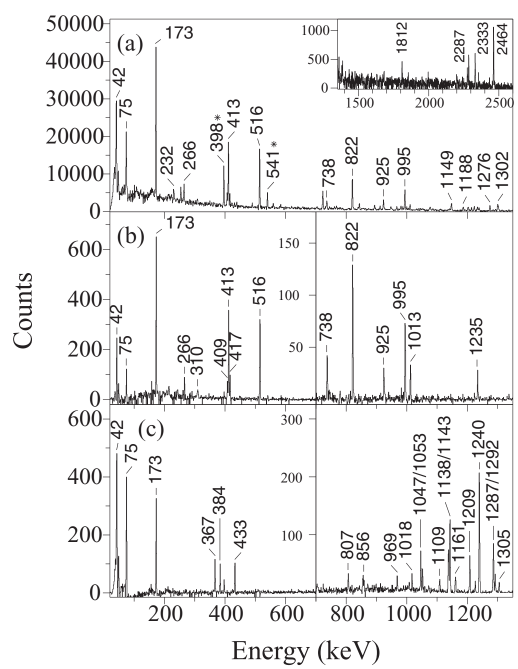

FIG. 2. (a) Spectrum of all β-gated transitions falling within the range of 50 s following tape movement to the end of the cycle. The peaks denoted with an asterisk result from a contaminant nuclei in the $A = 160$ beam. (b) Summed spectrum resulting from coincidence events with the 491.1- and 560.8-keV γ rays. (c) Summed spectrum for coincidence with the 1149.1- and 1214.5-keV transitions.

the 1464.0-keV state has nearly the same energy as the 1214.5-keV γ ray; therefore, coincident transitions from that γ ray are also observed. The transitions shown in this panel result from new states that lie above the previously known octupole levels, and were populated from the low-K isomer in ^{160}Eu.

A. States populated by the $K^\pi = 5^-$ β-decaying state in ^{160}Eu

Table I contains the level energies (E_{level}), spins/parities (J^π), β-feeding intensity (I_β), logft values, γ-ray energies and intensities for the states fed by the high-K β-decaying state.

1. Ground-state $K^\pi = 0^+$ sequence: 0-, 75.4-, 248.7-, and 515.1-keV states

Although the previous β-decay measurements [12,13], only identified the ground-state band up to the 4^+ level, the current data enable the observation of the 6^+ level as well. This latter state is well known from the study of ^{160}Gd using various reaction mechanisms [11].

2. γ-vibration $K^\pi = 2^+$sequence: 1261.3-, 1393.4-, and 1548.4-keV states

Similar to the ground-state band, the sequence associated with the γ vibration (labeled as $K^\pi = 2^+$ in Fig. 1) is well established from previous reaction studies [11], but none of the states shown in Fig. 1 were reported in the earlier β-decay publications [12,13]. The assigned spins and parities are from Ref. [11]; however, these quantum numbers are tentative for the 1548.4-keV state.

3. $K^\pi = 4_1^+$ sequence: 1070.7-, 1173.3-, 1295.7-, and 1437.7-keV states

The 1070.7-keV level, and its two strongest transitions were observed in the earlier β-decay experiments [12,13]. No multipolarity assignments have been made for these transitions; however, the fact that this state decays into the 2^+, 4^+, and 6^+ levels of the ground-state sequence requires that it has spin/parity of $J^\pi = 4^+$. It has been labeled as $K^\pi = 4_1^+$ in Fig. 1.

Although an angular correlation analysis is not possible with this data set, other methods can be used to help assign spin and parity for some of the observed levels. For example, by determining the total internal conversion coefficient (α_T) of the 102.7-keV line that feeds the 4^+, 1070.7-keV level, an assignment can be made for the 1173.3-keV level. A coincidence gate was placed on the 408.9-keV transition (from the 1582.1-keV state), and the efficiency-corrected intensities for the 102.7-, 555.6-, 822.0-, and 995.3-keV γ rays were determined. The α_T value of the 102.7-keV line was calculated in order to balance the intensity into the 1173.3-keV state with the outgoing one. From this analysis a value of $\alpha_T = 2.5(3)$ was found for the 102.7-keV transition, which is consistent with the predicted value of 1.87 [14] for an $M1$ multipolarity. Therefore, a $J^\pi = 5^+$ assignment to this level can be made, and it appears likely to be a member of the rotational band based on the $K^\pi = 4_1^+$ level.

TABLE I. Level energies, logft values, γ-ray energies and intensities for the states fed by the $K^\pi = 5^-$ isomer in ^{160}Eu.

E_{level} (keV)	J^π	I_β (%)	logft	E_γ (keV)	I_γ [a]
75.4	2^+			75.4(1)	231(12) [b]
248.7	4^+			173.3(1)	1000(50) [b]
515.1	6^+			266.4(2)	173(9)
1070.7	4^+	5	6.7	555.6(4)	9.7(23)
				822.0(1)	661(33)
				995.3(1)	541(27)
1173.3	5^+	2.7	6.9	102.7(2)	62(4)
				658.2(3)	27.8(19)
				924.6(1)	207(11)
1261.3	5^+	0.9	7.4	746.1(3)	30.8(20)
				1012.6(2)	135(7)
1295.7	(6^+)	2.9	6.8	(123)	<4.4
				225.1(3)	40.7(24)
				780.7(3)	19(4)
				1046.9(2)	25(8)
1393.4	6^+	0.2	7.9	878.3(3)	11(4)
				1144.7(3)	15(9)
1437.7	(7^+)	0.39	7.6	264.5(3)	21(3)
1483.4	4^+	4	6.6	187.5(3)	17(6)
				310.0(2)	64(4)
				412.7(1)	845(43)
				968.4(3)	39(5) [c]
				1234.6(2)	113(6)
				1408.1(3)	11(5)
1548.4	(7^+)	0.5	7.4	286.9(3)	5.3(2.6)
				1033.4(3)	26.6(18)
1582.1	5^+	2.2	6.8	98.8(3)	16(4)
				(286)	<2.5
				408.9(2)	179(9)
1698.5	(5,6)	0.53	7.3	(215)	6.1(13)
				1183.5(3)	15(4)
1999.0	5^-	60	5.1	300.6(3)	4.9(20)
				417.1(2)	151(8)
				450.7(3)	20(4)
				515.7(1)	879(44)
				605.7(3)	22(5)
				737.6(2)	144(8)
				825.6(3)	19.6(18)
				928.0(3)	18(6) [c]
				1483.6(3)	5.6(26)
				1750.2(3)	11(4) [c]
2253.0		2.2	6.3	769.6(3)	42.0(25)
2344.8		2.2	6.3	(646)	2.5(13)
				762.7(3)	41.4(25)
2489.9	$(5^+, 6^+)$	6.8	5.6	491.1(2)	51(3)
				1006.5(3)	35.5(22)
				1052.1(3)	8.5(12)

TABLE I. *(Continued.)*

E_{level} (keV)	J^π	I_β (%)	logft	E_γ (keV)	I_γ [a]
				1194.1(3)	2.5(9)
				1316.4(3)	32.0(20)
2559.9	$(5^+, 6^+)$	8.7	5.5	560.8(2)	74(4)
				1076.4(3)	42(3)
				1122.4(3)	7.0(8)
				1264.1(3)	11.8(16)
				1386.5(3)	31(4)

[a]Relative intensity where the strongest transition (173.3 keV) was normalized to 1000.
[b]The intensities of the γ rays depopulating this state are affected by the feeding from low-spin states. Due to the similar lifetimes of the β-decaying levels in ^{160}Eu, it was not possible to separate the different feeding components. Therefore, the reported values are the result of balancing the intensity out of the state with the intensity to that feeding it, and assuming no direct β-decay feeding these levels.
[c]Since the γ-ray energies were determined by summing the values observed in the four crystals of the clover detectors, there is a possibility that there may be a contribution to the intensity that results from the summing of the strongest transitions observed in the data.

The 1295.7-keV state has been previously observed [11], together with the 225.1-, 780.7-, and 1046.9-keV γ rays depopulating it. However, previously reported transitions from this level to the γ-vibration band were not observed. The tentative 123-keV line feeding the 1173.3-keV state is new; although it is too weak to determine the associated α_T value, as was done above for the 102.7-keV transition. A tentative $(4^+, 5^+)$ assignment was proposed for this state in Ref. [11]. However, data from a recent Coulomb excitation experiment [15] indicate that this state, and the 1437.7-keV level are part of the rotational sequence based on the $K^\pi = 4^+_1$ level. Therefore, tentative spins/parity of 6^+ and 7^+ have been assigned to the 1295.7- and the newly observed 1437.7-keV levels, respectively. Additional arguments for the configuration of this sequence are given in the following section.

4. $K^\pi = 4^+_2$ sequence: 1483.4- and 1582.1-keV states

The 1483.4-keV state was observed for the first time, and it is most strongly depopulated by the 412.7-keV transition to the $J^\pi = 4^+$, 1070.7-keV level. As seen in Fig. 1, five other γ rays depopulate the level and feed 2^+, 4^+, 5^+, and 6^+ states. This behavior restricts the possible J^π assignment to 4^+ for the 1483.4-keV state. It is likely that this level is an intrinsic state, and is closely associated with the 1070.7-keV state due to the predominant 412.7-keV transition. Specifically, the 1483.4-keV level is also likely to have $K^\pi = 4^+$ resulting from a two-quasiproton configuration, as discussed in the following section. Therefore, it is labeled as $K^\pi = 4^+_2$ in Fig. 1.

A new level at 1582.1 keV was observed, which only feeds the 4^+, 1483.4- and 5^+, 1173.3-keV states (see Fig. 1). In a manner similar to the analysis carried out for the 102.7-keV transition, the 98.8-keV γ ray was found to have an $\alpha_T = 1.6(3)$ conversion coefficient, which is consistent with the predicted value of 2.07 for an $M1$ transition of this energy [14]. Thus, the state has been assigned $J^\pi = 5^+$ and is likely the first rotational level of the high-K sequence based on the 1483.4-keV state.

5. $K^\pi = 5^-$ 1999.0-keV state

This level was previously discussed in Ref. [6], and was given a $K^\pi = 5^-$ assignment, based on the strong feeding from the $K^\pi = 5^-$ β-decaying state in ^{160}Eu. The state feeds 10 other levels, all of which have spin/parity of 4^+, 5^+, 6^+, or (7^+). As discussed in Ref. [6], and in Sec. IV below, the most probable configuration for the 1999.0-keV state is the $K^\pi = 5^-$ $\pi^2([413]5/2, [532]5/2)$ one, leading to a $J^\pi = 5^-$ assignment.

The transitions feeding the $K^\pi = 4^+_1$ and 4^+_2 states from this level will be addressed in the discussion concerning configuration assignments to those sequences. Three transitions (450.7, 605.7, and 737.6 keV) are observed to decay into the γ band from the 1999.0-keV state. While this band is associated with $K^\pi = 2^+$, which implies these three γ rays are hindered $\Delta K = 3$ transitions, it is likely that the γ band experiences a degree of K mixing due to the asymmetric deformation and, therefore, deexcitation from a $K^\pi = 5^-$ state is feasible as a result. However, the 450.7-keV transition to the 1548.4-keV level is puzzling as a tentative $J^\pi = (7^+)$ assignment has been proposed to this state from (n, n') studies [16,17]. If this spin/parity assignment were correct, the 450.7-keV transition would be of $M2$ character, and would normally be associated with a longer lifetime. The lifetime of the 1999.0-keV state was investigated by determining the time differences between the 560.8-keV γ ray that feeds it from the 2559.9-keV state, and the depopulating 515.7-keV line. No indication of a substantial lifetime was found. Thus, further information is required to understand the nature of the 450.7-keV transition.

Finally, it should be noted that there is no evidence for this 5^- state decaying to the negative-parity levels that form the octupole vibrational sequence, in particular for the 3^- level at 1290.0 keV. This can be understood as the octupole vibration is associated with $K^\pi = 0^-$ quantum numbers, and $\Delta K = 5$ transitions would be required. Such a large difference in K leads to a high hindrance value, and a small probability for transitions between the states [18].

6. Other states: 1698.5 keV, 2253.0 keV, 2344.8 keV, 2489.9 keV, and 2559.9 keV

Experimental information for these five states is limited in comparison to that for the previously discussed levels. The states above 2 MeV appear to be directly fed by the β decay of ^{160}Eu, as no γ transitions were observed feeding them. Tentative spin/parity assignments have been proposed in Fig. 1 and Table I, when possible. However, none appear to have $J^\pi = 6^-$ quantum numbers, which is relevant for the discussion below.

B. States populated by the $K^\pi = 0^-$ β-decaying isomer in ^{160}Eu

Fifteen new levels were also observed following the decay of the low-spin isomer in ^{160}Eu. These states likely have spin 1 or 2 $\hbar$ based upon their decay patterns. This suggests that the low-spin isomer in ^{160}Eu could have a spin of 1 $\hbar$. A possible configuration for this state is the unfavored $K^{\pi} = 0^{-}$ coupling of the $\pi[413]5/2$, $\nu[523]5/2$ quasiparticles. Even though this configuration has $K^{\pi} = 0^{-}$, the 1^{-} state can be lowest in energy due to a Newby shift [19]. In fact, this scenario is observed in ^{176}Lu [20], where the favored $K^{\pi} = 7^{-}$ coupling of a $g_{7/2}$ proton to an $h_{9/2}$ neutron ($\pi[404]7/2$, $\nu[514]7/2$) creates a ground state of 7^{-} and the unfavored $K^{\pi} = 0^{-}$ coupling produces a low-spin isomer at 122.8 keV with spin 1^{-}. Therefore, a nearly identical scenario may be present in ^{160}Eu, where the $K^{\pi} = 5^{-}$ favored coupling of the $g_{7/2}$ proton with an $h_{9/2}$ neutron ($\pi[413]5/2$, $\nu[523]5/2$) describes the ground state, and the $K^{\pi} = 0^{-}$ coupling creates (after a Newby shift) a 1^{-} isomer at 93.0(12) keV [6].

Since the decay of the low-spin isomer in ^{160}Eu is spread across many states in ^{160}Gd, there is insufficient information to determine the structures of the daughter levels. Therefore, only a table with level and γ-ray information is provided in the Appendix for this β-decay branch. It should be noted that since the β-decay branch from the 1^{-} isomer in ^{160}Eu to the 0^{+} ground state in ^{160}Gd cannot be determined in the present work, no β-decay feeding intensities or $\log ft$ values are reported.

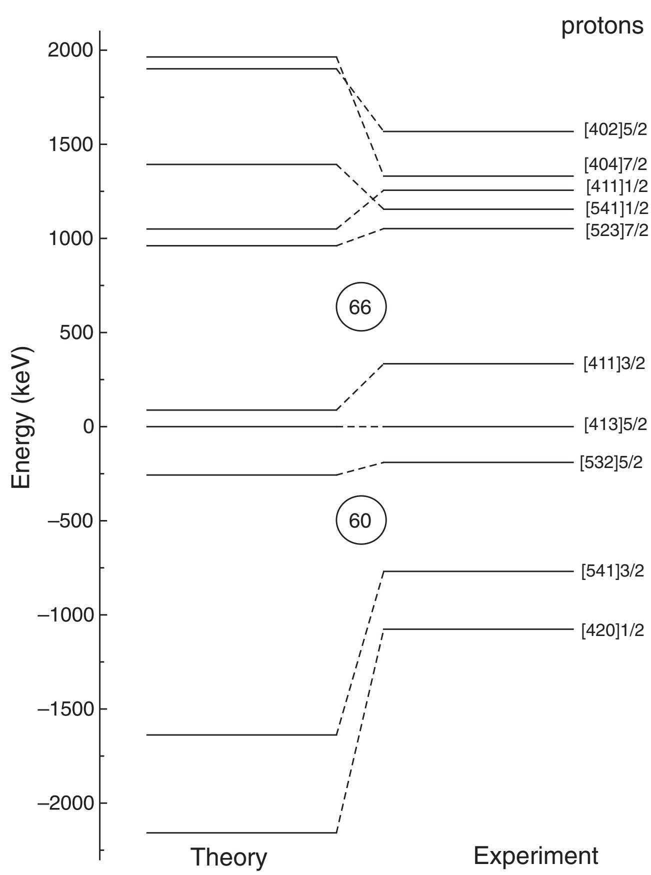

FIG. 3. Comparison between excitation energies for one-quasiproton states calculated using the procedure described in the text and the experimentally observed orbitals ([413]5/2, [532]5/2, [411]3/2, [523]7/2, [420]1/2) in ^{159}Eu [25], [541]3/2 in ^{155}Eu [26], and ([541]1/2, [404]7/2, [402]5/2, and [411]1/2) in ^{161}Tb [27] (labeled as Experiment in the figure). The positive/negative energies indicate states above/below the Fermi level, respectively.

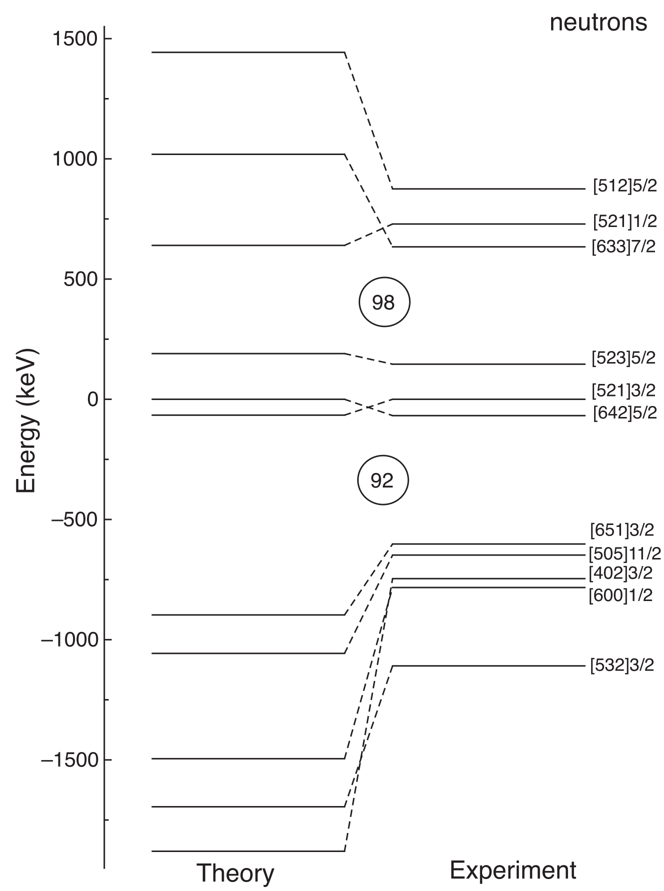

FIG. 4. Comparison between excitation energies for one-quasineutron states calculated using the procedure described in the text, and the experimentally observed levels in ^{161}Gd [25] with the [521]1/2 and [633]7/2 orbitals from ^{171}Yb [28] (labeled as Experiment in the figure). The positive/negative energies indicate states above/below the Fermi level, respectively.

IV. DISCUSSION

The proposed configurations of the 1070.7-, 1483.4-, and 1999.0-keV states are addressed in this section. In order to help with the configuration assignments, predictions for the excitation energy, spin, and parity for the intrinsic states in ^{160}Gd were obtained using multiquasiparticle calculations, similar to those reported in Ref. [21]. Specifically, the set of single-particle orbitals originating from the $N = 4$, 5, and 6 oscillator shells (for the neutrons) and $N = 3$, 4, and 5 ones (for the protons) were taken from the Woods-Saxon potential with universal parameters [22] and deformation parameters β_2, β_4, and β_6 were adopted from Ref. [23]. The pairing correlations were treated using the Lipkin-Nogami prescription [24] with fixed strengths of $G_{\pi} = 23.5/A$ MeV and $G_{\nu} = 15.5/A$ MeV and they included blocking.

Figures 3 and 4 display the calculated one-quasiparticle states near $Z = 64$ and $N = 96$ and compare these with the experimentally known values. As can be seen, the model

TABLE II. Selection of predicted two-quasiparticle states from multiquasiparticle calculations described in the text.

Quasiprotons	K^π	Energy (keV)	Quasineutron	K^π	Energy (keV)
[413]5/2, [411]3/2	4^+	1567	[523]5/2,[521]3/2	4^+	1353
[532]5/2, [411]3/2	4^-	1874	[523]5/2,[642]5/2	5^-	1463
[413]5/2, [532]5/2	5^-	2129	[642]5/2,[521]3/2	4^-	1719
[413]5/2, [523]7/2	6^-	2233	[523]5/2,[633]7/2	6^-	1905
[413]5/2, [404]7/2	6^+	2513	[512]5/2,[521]3/2	4^+	2015
			[642]5/2,[512]5/2	5^-	2097
			[523]5/2,[512]5/2	5^+	2165

correctly predicts the ordering of the proton orbitals, but fails to do so for several neutron states. Thus, the Woods-Saxon single-particle energies have then been adjusted to correctly reproduce the experimentally known orbitals in the region and then perform the calculations for the two-quasiparticle (and higher) states without any further adjustment. The calculated excitation energies for a number of intrinsic two-quasiparticle states in ^{160}Gd are summarized in Table II.

The 1999.0-keV level is primarily fed by β decay of the $K^\pi = 5^-$ isomer in ^{160}Eu that has the π[413]5/2, ν[523]5/2 configuration, where the quasiproton and the quasineutron have $g_{7/2}$ and $h_{9/2}$ parentage, respectively. A low logft value for the population of this state was observed, which is indicative of an allowed decay. As can be seen in Table II, a 5^- state is expected at 2129 keV, based on the two-quasiproton excitation π^2([413]5/2,[532]5/2), where the latter orbital originates from the $h_{11/2}$ shell. By assigning this configuration to the 1999.0-keV level, the β decay effectively corresponds to the allowed ν[523]5/2 $\rightarrow$ π[532]5/2 transition that accounts for the low logft value.

Although the decay of the 1999.0-keV state is highly fragmented, the strongest transition is to the $K^\pi = 4^+$ level at 1483.4 keV. This implies that the two states are likely correlated. Once again, referring to Table II, a $K^\pi = 4^+$ level is predicted at 1567 keV with a two-quasiproton configuration of π^2([413]5/2, [411]3/2), where the latter orbital is of $d_{5/2}$ parentage. Assigning this configuration to the 1483.4-keV state implies an $E1$ character for the 515.7-keV γ ray resulting from the π[532]5/2 $\rightarrow$ π[411]3/2 decay. Such transitions are observed in nearby terbium nuclei [29]; therefore, the observation of such a strong branch between the two levels in ^{160}Gd is not surprising. In addition, this assignment is consistent with the energies of states having the same configuration in ^{158}Gd [30] (1380 keV), ^{156}Gd [31] (1511 keV), and ^{154}Gd [32] (1646) keV. The energies of these states are plotted in Fig. 5 and one can observe a general trend of a lowering in energy with N. However, the 1483.4-keV level in ^{160}Gd (denoted as 4_2^+ in Fig. 5) breaks the trend of this two-quasiproton configuration as it lies higher in energy when compared with the $N = 94$ ^{158}Gd nucleus. A possible explanation for this occurrence as resulting from a two-state interaction with the 1070.7-keV level is described below.

The low-lying 4^+ states of $^{154-158}$Gd shown in Fig. 5 were once suggested to be associated with double-γ-phonon vibra-

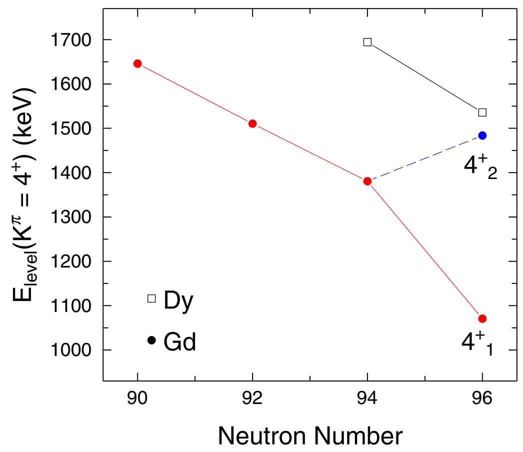

FIG. 5. Excitation energy of the $K^\pi = 4^+$ states of possible hexadecapole vibration states in gadolinium and dysprosium nuclei. Note that both $K^\pi = 4^+$ states in ^{160}Gd are shown in the figure.

tions. However, Burke [33] offered evidence from transfer-reaction studies that these levels were better interpreted as being based on a hexadecapole vibration with $K^\pi = 4^+$. In addition, proposed hexadecapole vibrations in ^{160,162}Dy are also given in Fig. 5. Soloviev *et al.* [34] investigated the possible nature of these states and also concluded that they are likely associated with hexadecapole vibrations, including the state in ^{160}Gd at 1070.7 keV, which is denoted as 4_1^+ in Fig. 5. However, it appears to lie at a much lower excitation energy than one would expect, based on the trend from the lighter gadolinium nuclei.

The lowest predicted $K^\pi = 4^+$ state is the two-quasineutron ν^2([523]5/2, [521]3/2) one, as seen in Table II, where the [521]3/2 orbital originates from the $f_{7/2}$ shell. Assigning this configuration to the 1070.7-keV level is consistent with the dominant two-quasiparticle component of the $K^\pi = 4^+$ band in the isotone ^{162}Dy, see Ref. [33] and the references therein. However, as seen in Fig. 5, the 4_1^+ state associated with a hexadecapole vibration in ^{160}Gd is lower in energy than the trend observed in this figure. Indeed, this raises the question of why the 4_1^+ state is observed at such low energy. The answer may lie in a two-state mixing between the ν^2([523]5/2, [521]3/2) and π^2([413]5/2, [411]3/2) $K^\pi = 4^+$ bands, similar to that observed in the $K^\pi = 6^+$ and 8^- bands in ^{176}Hf and ^{178}Hf [35,36]. For the ^{160}Gd case, the ν^2([523]5/2, [521]3/2) state is driven to lower energy than expected, and conversely the π^2([413]5/2, [411]3/2) level is driven to higher energy (as discussed in the previous paragraph). This scenario is consistent with the interpretation of Soloviev *et al.* [34] who suggested that the 1070.7-keV state is a nearly equal mixture between the two configurations. This would also account for the strong transition between the 1483.4- and 1070.7-keV levels. It is interesting to note that the observation of this non-yrast 4_2^+ state at 1483.4-keV via β decay was critical for the understanding of the surprisingly low energy of the proposed hexadecapole vibration.

Finally, a remark should be made concerning the fact that the $K^\pi = 6^-$ state, based on the π^2([413]5/2, [523]7/2) configuration, was not observed in the present data. As seen in Table II, this level is predicted to be only $\approx$ 100 keV higher in excitation than the $K^\pi = 5^-$ state that was observed at 1999.0 keV. In addition, the population of this state through β decay would involve the $\nu[523]5/2 \rightarrow \pi[523]7/2$ spin flip transition, which is allowed and expected to have a low $\log ft$ value [37]. One may inquire if either the 2489.9- or 2559.9-keV levels are possibilities for the $K^\pi = 6^-$ state; however, both of these strongly feed the $K^\pi = 4^+_2$ level, herewith making the $K^\pi = 6^-$ assignment highly unlikely. The calculated energy of the $K^\pi = 6^-$ level is based on knowledge of the location of the [523]7/2 proton orbital, and there is uncertainty in its value. Hence, it is possible that the π^2[413]5/2, [523]7/2 configuration lies higher than shown in Table II. Or perhaps it lies very close in energy to the $K^\pi = 5^-$ state, and all of $K^\pi = 6^-$ decay feeds the 1999.0-keV level through a highly converted, unobserved $M1$ transition.

V. SUMMARY

The structure of ^{160}Gd was studied via β decay of ^{160}Eu at the CARIBU facility. Two β-decaying states were observed, one with (5$^-$) and another with low (1$\hbar$) spin. The high-spin state populates several high-K levels in the ^{160}Gd daughter nucleus, in particular it strongly feeds a $K^\pi = 5^-$ state at 1999.0 keV with the [413]5/2, [523]5/2 quasiproton configuration. Two $K^\pi = 4^+$ states were also observed and it appears likely that these undergo two-state mixing moving the energetically favored level to a low excitation energy of 1070.7 keV. This state is likely based on the [523]5/2,[521]3/2 quasineutron configuration and it has been previously associated with a hexadecapole vibration. The other $K^\pi = 4^+$ state can be associated with the [413]5/2,[411]3/2 quasiproton configuration. In addition, many low-spin levels were populated from the low-K isomer in ^{160}Eu. These are reported in the Appendix.

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APPENDIX

Data for the levels and γ rays that result from the decay of the low-spin isomer in ^{160}Gd are given below. Note that the intensities are relative to the strongest transition that solely results from the low-spin isomer decay in ^{160}Eu, *e.g.* the 2464.4-keV transition. Since the 2464.4-keV state is so strongly fed, it is possible that it is the 1$^-$ state from the

TABLE III. Level energies, γ-ray energies and intensities for the states fed by the $K^\pi = (0^-)$ isomer in ^{160}Eu.

E_{level} (keV)	J^π	E_γ (keV)	I_γ[a]
75.4[b]	2^+	75.4	
248.7[b]	4^+	173.3	
988.5	2^+	913.1	2607(48)
		988.4	2681(52)
1057.6	3^+	809.0	804(37)
		982.3	3796(56)
1224.3	1^-	235.8	181(22)
		1149.1	7722(56)
		1224.2	4944(63)
1289.9	3^-	1041.2	1904(44)
		1214.5	3280(150)
1351.2	1^-[c]	1275.7	3520(160)
		1351.1	630(30)
1376.9	(2^+)[d]	319.3	119(15)
		1128.3	89(11)
		1301.6	8330(110)
1436.6	2^+	1187.9	4504(59)
		1361.2	1774(41)
		1436.4	285(15)
1464.0	(3^-)[c]	1215.3	2610(120)
		1388.5	1674(37)
1608.4[f]		384.1	919(37)
1657.3[f]	$(1^-, 2)$	367.4	867(37)
		433.2	912(59)
1887.0[f]	1,2	898.2	167(15)
		1811.6	2426(44)
1932.1	2^+	874.5	585(37)
		943.7	293(26)
		1683.5	767(30)
		1856.6	1178(33)
		1932.1	426(26)
1965.8	2^+[e]	908.2	385(37)
		977.3	215(19)
		1717.0	200(19)
		1890.4	219(19)
		1965.8	626(30)
2242.2[f]	(1,2)	865.4	41(7)
		891.0	104(11)
		1017.9	278(26)
2277.5	1	841.1	141(15)
		1288.9	96(11)
		2202.1	1526(41)
		2277.5	2070(44)
2283.6[f]	1^+,2	1059.3	104(11)
		1226.1	81(11)
		1295.0	170(19)
2315.7[f]	(1,2)	1327.2	156(19)
2327.5[f]	$(1^+$,2)	976.3	115(11)

TABLE III. (Continued.)

E_{level}(keV)	J^{π}	E_{γ} (keV)	I_{γ} [a]
		1269.9	919(33)
		1339.0	1374(37)
2333.6[f]	(1,2$^+$)	897.1	74(7)
		982.5	33(7)
		1109.3	367(37)
		1344.9	111(15)
		2333.3	15(4)
2362.4[f]	(1$^+$,2)	705.1	81(11)
		898.4	174(15)
		985.3	81(11)
		1138.1	1133(37)
		1304.9	567(37)
		1373.9	67(7)
		2287.0	4478(63)
2385.6[f]	(1,2)	1034.5	263(19)
		1161.2	526(37)
2432.8[f]	(1$^-$, 2$^+$)	968.9	333(22)
		1055.8	460(45)
		1081.6	180(19)
		1142.8	2081(44)
		1208.5	807(33)
		2357.5	1178(33)
		2432.9	111(19)
2464.4[f]	(1$^-$)	807.2	185(15)
		856.1	448(30)
		1027.8	96(7)
		1087.5	1889(44)
		1113.1	1459(44)
		1240.1	2260(160)
		1475.9	122(7)
		2389.2	663(26)
		2464.4	10000(11)
2470.0	1$^-$	2394.6	141(11)
		2470.0	485(22)
2510.8[f]	(1,2$^-$)	1046.7	770(44)
		1159.6	263(19)
		1286.5	1533(37)
		1522.3	144(15)
		2435.2	1037(33)
2516.6[f]	(2)	1052.6	1111(41)
		1165.3	511(52)
		1226.7	456(48)
		1292.4	933(74)
		1459.0	422(37)
2530.0[f]	(1$^-$,2)	1153.2	85(11)
		1178.7	281(19)
		1240.0	1259(74)
		1305.7	189(15)

[a]Relative intensity where the strongest transition (2464.4 keV) was normalized to 10000.
[b]The intensities of the γ rays depopulating this state are affected by the feeding from high-spin states; therefore, no intensity is given.
[c]Assignment taken from Ref. [17] based on the reported angular distribution coefficients.
[d]This state was assigned as 2^- in Ref. [17]; however, the observed 1128.3-keV line to the 4^+ state at 248.7 keV makes that assignment unlikely.
[e]This state was assigned as 1^- in Ref. [11]; however, the observed 908.2-keV transition to the 3^+ state at 1057.6 keV makes that assignment unlikely.
[f]New state observed in the present data.

unfavored coupling of the $\pi^2([413]5/2, [532]5/2)$ configuration, or perhaps the $K^{\pi} = 1^-$ state from the unfavored coupling of the $\pi^2([413]5/2, [523]7/2)$ configuration. In addition, the β-feeding intensities could not be obtained due to the fact that the strength of a direct transition from the low-spin isomer in ^{160}Eu to the ^{160}Gd ground state could not be determined. New states are indicated by an asterisk on the energy of the level, and spin/parity assignments were made, when possible, for these new levels based on the observed decay properties. For states that were previously known, the spin and parity assignments from Ref. [11] were adopted, except for the cases noted in Table III.

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