PHYSICAL REVIEW C **76**, 034318 (2007)

Study of 0^+ excitations in ^{158}Gd with the $(n, n'\gamma)$ reaction

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(Received 12 March 2007; published 19 September 2007)

We have examined ^{158}Gd with the $(n, n'\gamma)$ reaction at neutron energies up to 3.3 MeV to determine the collective character of 0^+ excitations revealed in previous ^{160}Gd(p,t) reaction studies. Moderately large $B(E2; 0^+ \rightarrow 2_1^+)$ values are observed for transitions from some of the 0^+ states lying above the pairing gap. From its excitation energy and decay properties, the 0^+ excitation at 2276.7 keV is suggested as exhibiting two-phonon $\gamma\gamma$ strength. The high density of levels at similar excitation energies makes the identification of the other two-phonon states improbable.

DOI: 10.1103/PhysRevC.76.034318 PACS number(s): 21.10.Tg, 21.10.Re, 25.40.Fq, 27.70.+q

I. INTRODUCTION

Low-lying 0^+ collective excitations in well-deformed nuclei can arise from various mechanisms and are not yet fully understood. Bohr and Mottelson [1] associate the lowest $K^\pi = 0^+$ and $K^\pi = 2^+$ excitations with the β and γ one-phonon vibrational modes, respectively. Rotational bands are expected to be built on these excitations [1]. Whereas γ vibrations seem to be well characterized and exhibit a systematic behavior across the regions of deformed nuclei with typical $B(E2; 2_\gamma^+ \rightarrow 0_1^+)$ values of several W.u., the identification of β vibrations remains elusive. This ambiguity led Garrett [2] to emphasize the role of pairing in 0^+ excitations. At the same time, he suggested criteria for identifying β vibrations, which would include $B(E2; 0_\beta^+ \rightarrow 2_1^+) = 12$–$33$ W.u. or $B(E2; 2_\beta^+ \rightarrow 0_{gs}^+) \approx 6$ W.u., $\rho^2(E0) \times 10^3 = 85$–$230$, when expressed as a fraction of the $E2$ decay strength, and small two-nucleon transfer strengths [2]. Due to the increasing level density at higher energies, the existence of two-phonon γ and β vibrations is even more arguable. In principle, these two-phonon excitations would give rise to another two 0^+ excitations, $0_{\beta\beta}^+$ and $0_{\gamma\gamma}^+$; however, only the latter has been identified in exceptional cases, such as ^{156}Gd [3] and ^{166}Er [4,5]. Additional 0^+ excitations may arise through other mechanisms, e.g., multi-quasiparticle configurations, pair excitations, or shape coexistence.

Recently, the subject of 0^+ excitations has been expanded with searches for low-lying 0^+ states in the rare earth and actinide regions [6–9]. In a high-resolution two-neutron transfer study with the ^{160}Gd$(p, t)^{158}$Gd reaction, it was proffered that ^{158}Gd, a well-deformed nucleus with $E(4_1^+)/E(2_1^+) = 3.29$, exhibits at least 13 0^+ states below 3.2 MeV [6]. Meyer *et al.* [8] have utilized the same technique to further extend the identification of 0^+ states, and large numbers of excited 0^+ states have been observed in many structurally different nuclei—^{152}Gd, ^{154}Gd, ^{162}Dy, ^{176}Hf, ^{180}W, ^{184}W, ^{190}Os [8], and ^{168}Er [8,9]. The number of known 0^+ states in these nuclei has more than doubled [8] and some of the 0^+ excitations occur below the pairing gap. These findings, together with the lack of energy systematics to support the character of these states, led Meyer *et al.* [8] to question their collective nature.

In ^{158}Gd, three 0^+ excitations are observed below the pairing gap of $\approx$1.77 MeV [10]. This nucleus was extensively studied by Greenwood *et al.* [11] through radiative neutron capture on ^{157}Gd, and a level scheme up to around 2.2 MeV was proposed. In that work, the γ-rays associated with the lowest five 0^+ levels were identified along with other states feeding these excitations. In a recent study with the same reaction, Börner *et al.* [12] applied the GRID technique to measure the lifetimes of a few of the lowest-lying levels in ^{158}Gd and to determine their respective transition probabilities. Interpretations of noncollective and collective character were proposed for the lowest excited 0^+ levels (see discussion).

Understanding the character of 0^+ excitations is challenging and has prompted a number theoretical treatments [13–19]. Although most of these calculations predict a high number of 0^+ states, in agreement with the experimental data, their character, as noted above, is not clear. Thorough spectroscopic studies focused on the determination of transition strengths are needed to gain further insight into the interpretation of 0^+ excitations. For this reason, we initiated a study of ^{158}Gd with the low energy, nonselective $(n, n'\gamma)$ reaction, which should permit the population of all of the low-lying 0^+ states and lead to detailed characterization of their decay properties.

II. EXPERIMENTAL PROCEDURES

An extended set of experiments, including γ-ray excitation functions, angular distributions and γ-γ coincidences, was performed with the ^{158}Gd$(n, n'\gamma)$ reaction at the University of Kentucky accelerator facility, with neutron production by the ^{3}H(p, n) reaction. The scattering sample was 54.73 g of 95.81% enriched $^{158}Gd_2O_3$ contained in a thin-walled

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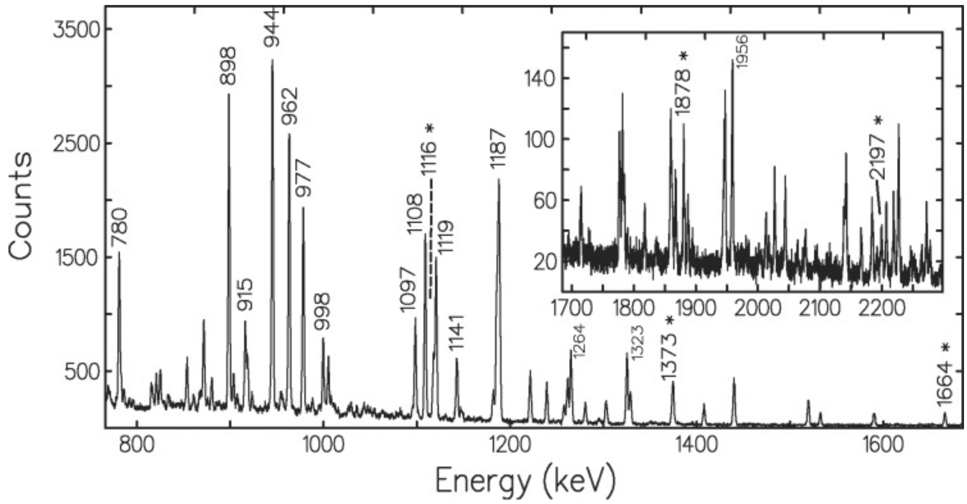

FIG. 1. Portion of the prompt γ-ray energy spectrum from the ^{158}Gd$(n, n'\gamma)$ reaction at 2.42-MeV neutron energy, recorded at 90° with respect to the beam axis. γ-ray energies are given in keV and asterisks indicate γ-ray transitions depopulating 0^+ excitations.

polyethylene cylinder 4 cm high and 2.6 cm in diameter. In singles measurements, the emitted γ rays were detected with a 50% efficient HPGe detector, with time-of-flight gating for background suppression and a BGO shield for active Compton suppression [20]. A portion of the γ-ray spectrum is illustrated in Fig. 1.

An excitation function measurement, providing yields as a function of neutron energy, was performed in 0.1-MeV steps from $E_n = 1.4$ to 3.3 MeV, with the detector at an angle of 90° to the beam axis. Excitation functions were used to place γ rays by their thresholds and energy dependencies, because γ rays from the same level must have the same neutron-energy dependence. Angular distribution measurements were performed at incident neutron energies of 2.2, 2.8, and 3.5 MeV, over an angular range from 40° to 150°. These neutron energies were selected to reduce feeding to the levels of interest and to promote obtaining accurate level-lifetime information. The angular distributions of the γ-ray intensities, W(θ), were fitted with even-order Legendre polynomials,

$$W(\theta) = \mathrm{I}_\gamma\ [1 + a_2 P_2(\cos\theta_\gamma) + a_4 P_4(\cos\theta_\gamma)], \quad (1)$$

where the parameters a_2 and a_4 depend on the multipolarities and mixing amplitudes of the transitions. The angular distribution measurements also yielded lifetimes of excited states shorter than about 1 ps [21], as determined by the Doppler-shift attenuation method (DSAM). Here, the γ rays have energies with angular dependence,

$$E_\gamma(\theta_\gamma) = E_{\gamma_0}\left[1 + \frac{v_0}{c} F(\tau)\cos\theta_\gamma\right], \quad (2)$$

where E_{γ_0} is the unshifted γ-ray energy, v_0 is the initial recoil velocity in the center-of-mass frame, θ_γ is the angle of observation, and $F(\tau)$ is the attenuation factor that depends on the electronic and nuclear stopping powers [21]. By examining the energy of a γ ray as a function of angle, the $F(\tau)$ value can be determined using the Winterbon formalism [22], and the lifetime of the state, τ, can be extracted. Lifetimes determined using γ rays arising from the same level must match within experimental uncertainties, providing additional consistency tests of placements and thus aiding in the assignment of γ rays to specific levels.

Further information on the decay scheme comes from γ-γ coincidence measurements performed at 3 MeV with four ⩾50% HPGe detectors in the close geometrical arrangement described in Ref. [23]. The placements of γ rays in the level scheme were confirmed from excitation function threshold information. In all measurements, ^{226}Ra and ^{152}Eu standard sources were used out-of-beam for energy and efficiency calibrations. At higher neutron energies, an additional ^{24}Na in-beam source was employed for accurate energy identification, as the energies of higher energy γ rays are less certain in the literature. In this case, NaCl rings irradiated with neutrons from a ^{252}Cf source were used to produce ^{24}Na, which emits 1368.63 and 2754.03 keV γ rays. The methods and techniques used are described in detail in other publications [20,24].

III. RESULTS AND DISCUSSION

The initial challenge of this study was the observation of γ rays de-exciting these 0^+ excitations. The level density in a deformed nucleus such as ^{158}Gd increases rapidly with increasing excitation energy and associating the observed γ rays with specific excited states is not always trivial. It was expected that $E2$ transitions from the excited 0^+ states to the first excited 2^+ state would be the dominant decay mode; however, the data were also queried for transitions to other low-lying 2^+ and 1^- states. Moreover, it was required that level-energy thresholds from γ-ray excitation functions were consistent with level energy assignments. It was further required that the angular distributions of γ rays from these states must be isotropic, i.e., $a_2 = 0$ in Eq. (1); examples are shown in Fig. 2. From the angular distribution data, we also sought to determine the lifetimes of these states. Examples of lifetimes determined in the present work are presented in Fig. 3. A search for 2^+ band members decaying to 0^+ states was conducted, although due to absorption in our thick sample and internal conversion, we are generally unable to observe <100 keV γ rays. Figure 4 shows a partial level scheme focusing on 0^+ excitations and γ-ray transitions feeding and depopulating such states. Table I provides a listing of 0^+ states for which new spectroscopic information has been obtained.

TABLE I. Properties of 0^+ states observed in the ^{158}Gd$(n, n'\gamma)$ measurements. Level excitation energies, initial and final spins of the states, γ-ray energies, relative intensities, level lifetimes, and experimental $B(\mathrm{E1}) \downarrow$ and $B(\mathrm{E2}) \downarrow$ transition rates are listed.

E_L (keV)	E_f (keV)	$J_i^\pi \to J_f^\pi$	E_γ (keV)	I_γ	τ (fs)	$B(E1) \times 10^{-3}$ (W.u.)	$B(E2)$ (W.u.)	Level studied in
1195.91(24)	79.44	$0_2^+ \to 2_1^+$	1116.40(6)	100			1.1[a]	(n,γ), (p,t) & $(n,n'\gamma)$
1452.10(24)	79.44	$0_3^+ \to 2_1^+$	1372.66(5)	100			2.1[a]	(n,γ), (p,t) & $(n,n'\gamma)$
1742.86(22)	977.06	$0_4^+ \to 1_2^-$	479.37(7)	28(10)[b]	>1080	<0.6		(n,γ), (p,t) & $(n,n'\gamma)$
	79.44	$0_4^+ \to 2_1^+$	1663.52(6)	100(10)[b]			<1.0	
1956.96(24)	79.44	$0_5^+ \to 2_1^+$	1877.52(5)	100	170^{+50}_{-35}		4.2(10)	(n,γ), (p,t) & $(n,n'\gamma)$
2276.66(21)	1263.39	$0_6^+ \to 1_2^-$	1013.88(10)	2(1)	70^{+20}_{-15}	$0.09^{+0.08}_{-0.05}$		(n,γ), (p,t) & $(n,n'\gamma)$
	1187.14	$0_6^+ \to 2_\gamma^+$	1089.36(21)	2(1)			3^{+3}_{-2}	
	79.44	$0_6^+ \to 2_1^+$	2197.08(5)	100(1)			$4.3^{+1.2}_{-1.0}$	
2340.0(2)	1263.51	$0_7^+ \to 1_2^-$	1076.6(1)[c]		240^{+265}_{-100}			(p,t) & $(n,n'\gamma)$
	1187.14	$0_7^+ \to 2_\gamma^+$	1152.8(2)[c]					
	977.06	$0_7^+ \to 1_1^-$	1362.29(16)[c]					
	79.44	$0_7^+ \to 2_1^+$	2260.54(5)[d]					
2644.18(24)	79.44	$0_8^+ \to 2_1^+$	2564.73(5)	100	19(4)		$7.6^{+1.5}_{-0.7}$	(p,t) & $(n,n'\gamma)$
2688.8(8)[e]		0_9^+						(p,t)
2911.48(64)	79.44	$0_{10}^+ \to 2_1^+$	2832.02(14)[f]	100	47^{+64}_{-26}		$1.9^{+2.3}_{-1.1}$	(p,t) & $(n,n'\gamma)$
3076.7(16)[e]		0_{11}^+						(p,t)
3109.9(11)[e]		0_{12}^+						(p,t)

[a]B(E2) value taken from Ref. [12].
[b]Branching ratio taken from Ref. [11].
[c]Seen only in coincidence measurements.
[d]This γ ray is a triplet.
[e]No γ-ray decay observed. Energies adopted from Ref. [6].
[f]Placement uncertain.

When lifetimes or lower limits were obtained, $B(E2)$ values were determined and are also listed in Table I. As internal conversion electron data were not available, the $E0$ decays to the ground state were assumed to be negligible.

We have combined the information from the singles and coincidence measurements when possible. In many cases, γ rays present in the coincidence spectra were not observed in

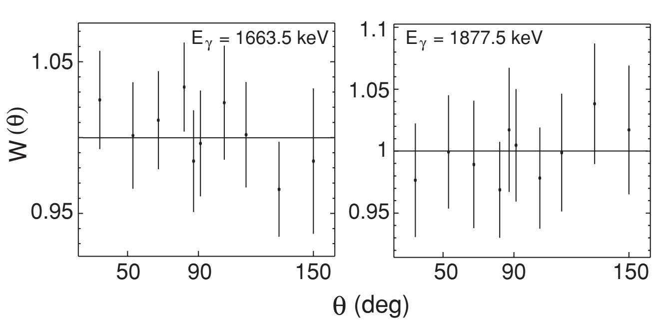

FIG. 2. Plots of isotropic angular distributions for $0^+ \to 2_1^+$ γ-ray transitions.

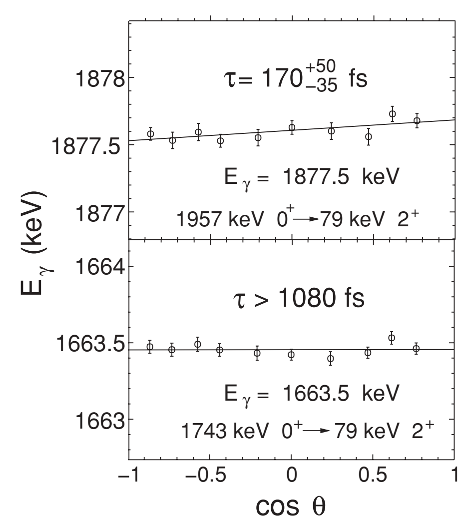

FIG. 3. Examples of DSAM data from the ^{158}Gd$(n, n'\gamma)$ measurements showing level lifetimes. In the case of the 1663.5-keV γ ray depopulating the 0^+ state at 1742.9 keV, only a lower limit to the lifetime was obtained.

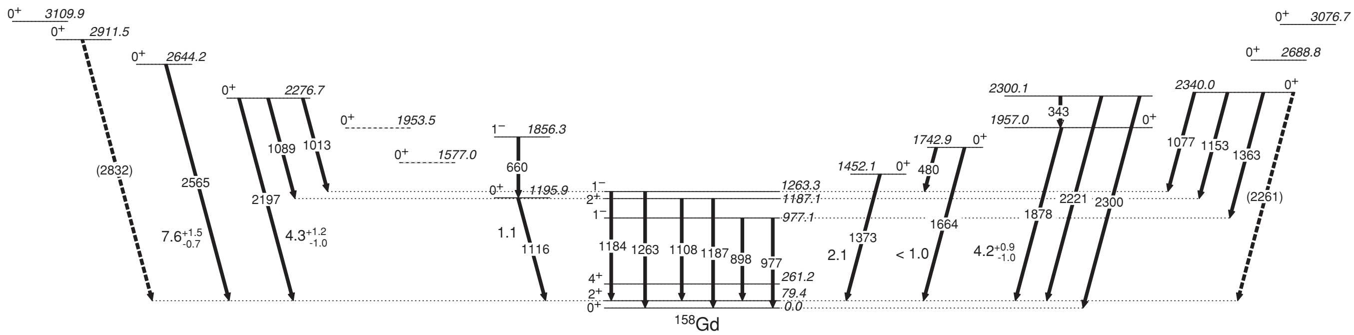

FIG. 4. Partial level scheme of ^{158}Gd showing the 0^+ excitations and γ rays feeding and depopulating 0^+ states. $B(E2)$ values (in W.u.) are given beside the arrows. The $B(E2; 0^+ \rightarrow 2_1^+)$ values from the 1195.9- and 1452.1-keV levels are taken from Ref. [12], whereas the remainder are from the present work. All energies are in keV.

singles measurements; therefore, we were not able to obtain branching ratios for some levels. We were generally unable to observe γ rays in singles measurements with branchings of less than 3%. If the energy was obtained only from the coincidence measurements, the γ-ray branch was assumed to be <3% and only upper limits are given for the transition strengths. The new data are too extensive to consider a discussion of every level, and we simply focus on each 0^+ state separately.

A. 1195.9- and 1452.1-keV levels (0_2^+ and 0_3^+)

The 0_2^+ and 0_3^+ states at 1195.9 and 1452.1 keV have been discussed in detail [11,12]. We have obtained no new spectroscopic information from the excitation functions and angular distributions for the 0_2^+ state because its 1116.4-keV γ ray to the 2_1^+ level is part of a doublet (see Fig. 1). An excitation function for the 1372.7-keV γ ray depopulating the 0_3^+ state is shown in Fig. 5(a) and confirms the threshold placement. From (n, γ) measurements [11], a 475.2-keV transition was proposed from the 0_3^+ state to the 1^- level at 977.1 keV. We do not observe such a decay in our coincidence data in agreement with Börner *et al.* [12], who placed a 475.8-keV γ ray instead from the 1517.4-keV 2^+ state to the 1041.6-keV 3^- level. We also confirmed the latter placement for the 475.8-keV transition from our coincidence spectra and find no evidence for the putative 475.2-keV γ ray.

The previously established band built on the 0_2^+ level [11] was confirmed by Börner *et al.* [12], and large $B(E2)$ values were determined between the 4^+ state at 1406.4 keV (built on the 0_2^+ excitation) and the 2_γ^+ and 3_γ^+ members of the γ band at 1187.1 and 1265.1 keV, respectively [12]. Although the possible collective multiphonon nature of this 0_2^+ excitation is not eliminated, a simple band-mixing calculation performed by Greenwood *et al.* seems to explain better its decay properties [11]. Moreover, we have identified a new 660.4-keV γ ray feeding the 0_2^+ state from a known 1^- level at 1856.3 keV. A background-subtracted coincidence spectrum gated on the 660.4-keV transition is shown in Fig. 5(b), where the 1116.4-keV γ ray from the 0_2^+ level is evident.

Because the $0^+ \rightarrow 2_1^+$ γ-ray transitions from both 0_2^+ and 0_3^+ levels are contained in unresolved doublets, corresponding lifetime and angular distribution data are unreliable; however, we can obtain good excitation function data and energies. Therefore, we have adopted $B(E2; 0^+ \rightarrow 2_1^+)$ values of 1.1 and 2.1 W.u. for the 1116.4 ($0_2^+ \rightarrow 2_1^+$) and 1372.7 keV ($0_3^+ \rightarrow 2_1^+$) transitions, respectively, from Ref. [12].

B. 1577.0-keV level

A new low-lying 0^+ state at 1577.0 keV was proposed in the recent (p, t) reaction study of ^{158}Gd [6]. As the 0^+ states are expected to decay to the 2_1^+ level at 79.4 keV, we first investigated this possibility. There was evidence of a very weak 1499-keV decay in singles measurements at high neutron energies; however, a coincidence gate at 1498 keV indicates that this transition feeds the 3^- level at 1041.6 keV. This placement is also in agreement with the excitation function

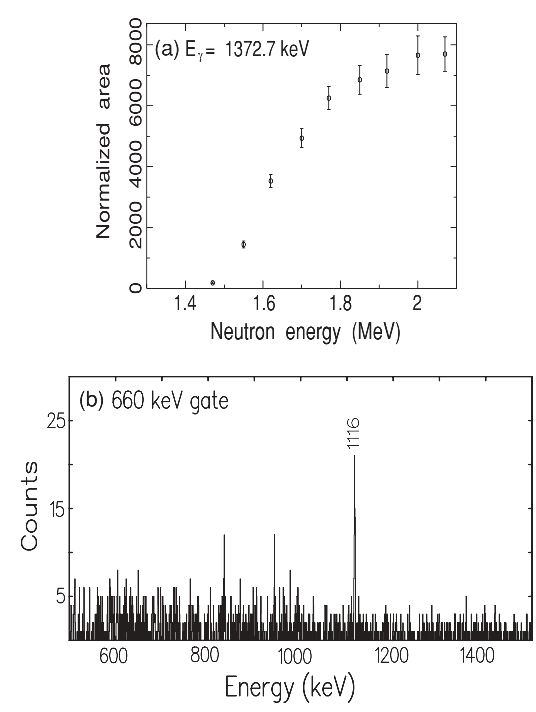

FIG. 5. (a) Excitation function for the 1372.7-keV γ ray from the 0^+ state at 1452.1 keV. (b) A background-subtracted γ-ray spectrum gated on the 660.4 keV transition in the γ-γ coincidence matrix.

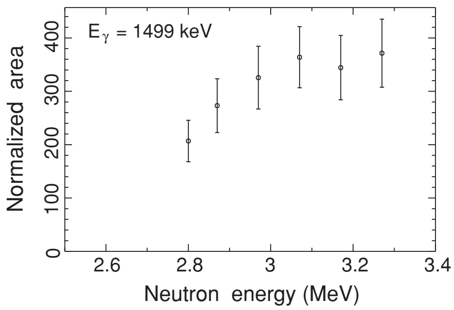

FIG. 6. Excitation function plot for the 1499-keV γ ray.

presented in Fig. 6 for the 1499-keV γ ray, which exhibits the appropriate energy threshold.

Additional γ rays of 388.5 and 600.1 keV had been reported in (n,γ) measurements [11]. These unassigned transitions were suggested as decays from the putative 1577.0-keV level [6], but no evidence is seen in our singles or coincidence data for either of these γ rays. Although it is also conceivable that a 1577.0-keV level could decay via other methods, i.e., entirely by internal conversion, we conclude that there is currently no substantial evidence for the 1577.0-keV level in ^{158}Gd. As pointed out by Lesher *et al.* [6], the triton energy associated with the proposed 1577.0-keV level is near that for the ground state in the ^{156}Gd$(p,t)^{154}$Gd reaction. Although a minor (0.33%) ^{156}Gd isotopic contaminant in the ^{160}Gd target was considered when assigning the peak as a 0^+ state [6], we suggest that the isotopic contaminant was greater than reported and, therefore, could account for the full peak strength.

C. 1742.9-keV level (0_4^+)

The 0_4^+ state at 1742.9 keV was observed to decay through 479.4- and 1663.5-keV γ rays to the 1_2^- and 2_1^+ levels, respectively. The excitation function for the 1663.5-keV γ ray depopulating the 0_4^+ state is plotted in Fig. 7(a). The energy threshold of the excitation function supports this placement and $a_2 = -0.07 \pm 0.04$ from the angular distribution. Figure 7(b) shows the coincidence spectrum from a gate on the 479.4-keV transition, where coincidences with the 1184.0- and 1263.5-keV γ rays support the placement of the $0_4^+ \to 1_2^-$ transition (see Fig. 4).

A lower limit for the lifetime of >1080 fs yields a $B(E1; 0_4^+ \to 1_2^-)$ limit of $<6 \times 10^{-4}$ W.u., and a $B(E2; 0_4^+ \to 2_1^+)$ limit of <1.0 W.u. This level, which is just below the pairing gap (1.77 MeV), is clearly not collective.

D. 1953.5-keV level

A 0^+ level at 1952.34 ± 0.05 keV had been tentatively proposed from neutron capture data [11], and peaks at 1953.5 ± 0.6 and 1960.1 ± 3.8 keV, both assigned 0^+, are close-lying in the (p,t) spectrum of Ref. [6], as shown in Fig. 8. The strong population of the 1953.5-keV level in the (p,t) reaction and its characteristic angular distribution [6] confirm the 0^+ assignment. All possible decays to and from this 0^+ level were explored, including suggested decays from

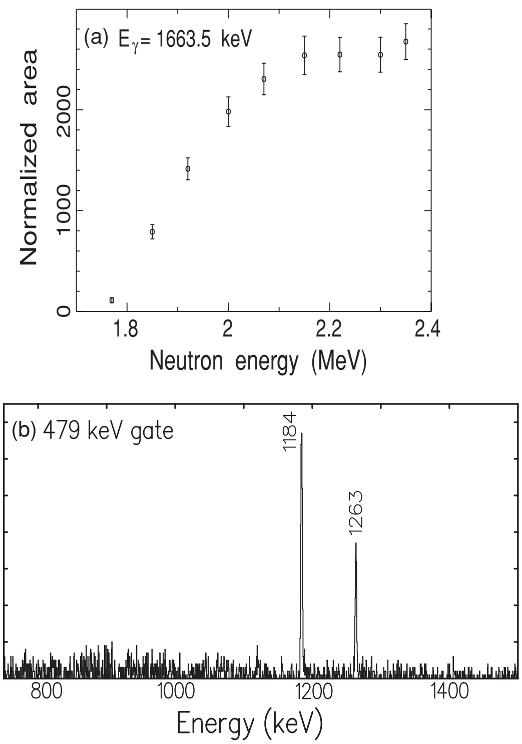

FIG. 7. (a) Excitation function for the 1663.5-keV γ ray. (b) Background-subtracted γ-ray spectrum gated on the 479.4-keV transition.

the (n,γ) work [11] to the 1_1^-, 2_2^+, and 1_2^- levels by 975.4-, 765.3-, and 688.8-keV γ rays, respectively, with the 688.8-keV γ ray being the strongest transition by far. Nonetheless, none of these decays could be confirmed in our work. Greenwood *et al.* [11] even suggested a 2083.6-keV level as the 2^+ member of a rotational band built on the 1953.5-keV 0^+ state, but such a possibility could not be verified with our data either. Additional difficulties in identifying decays from this 0^+ level arise from a nearly degenerate 4^- state at 1953.8 keV; a 688.2-keV γ ray has been proposed to de-excite this state to the 3_1^+ level at 1265.1 keV [11] (see level scheme in Fig. 9). In addition, and confirmed in our data, the 4^- level decays through stronger 795.2- and 1693-keV transitions to the 4_1^- and 4_1^+ levels, respectively (see level scheme in Fig. 9).

The most intense γ ray assigned [11] from the 0^+ level at 1953.5 keV is the 688.8-keV transition. The coincidence measurements, shown in Fig. 10, support a 689-keV γ-ray transition to the 3^+ state at 1265.1 keV. However, Fig. 10

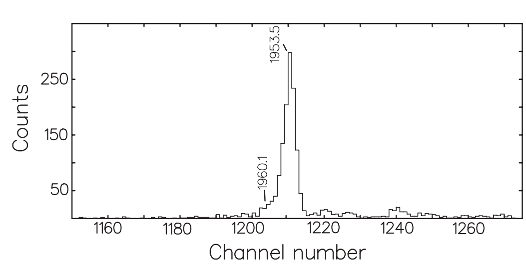

FIG. 8. Portion of the ^{160}Gd(p,t) spectrum at 6° showing the 1953.5- and 1960.1-keV levels, taken from the data of Ref. [6].

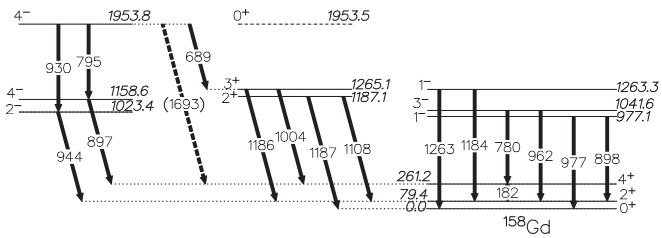

FIG. 9. Partial level scheme of ^{158}Gd showing the previously proposed 0^+ and 4^- excitations at 1953.5 and 1953.8 keV, respectively, and γ rays proposed depopulating these.

shows that a 689 keV γ ray is in coincidence with the 1119.1- and 1301.0-keV transitions depopulating the 4_3^+ level at 1380.5 keV. Hence, a new level is proposed at 2070 keV, which is also in agreement with the 689-keV excitation function. Through the same process, the 975.4-keV γ ray has been assigned to a new level at 2152.30 keV decaying to the 1176.2-keV level. Therefore, neither the 688.8-keV nor the 975.4-keV γ rays decay from the 1953.5-keV 0^+ state.

With all the proposed γ decay placed elsewhere, we face the dilemma of how the 1953.5 0^+ peak appears to be so strong in the (p,t) reaction and how the nonselective $(n,n'\gamma)$ reaction does not apparently populate this state. If we assume the 1953.5-keV level does not decay solely through an $E0$ transition, the only possibility remaining is to question the (p,t) data [6].

In a recent series of (p,t) experiments [8] more information was gathered for the ^{160}Gd$(p,t)^{158}$Gd reaction. By using the well-known states in ^{170}Yb populated in the ^{172}Yb(p,t) reaction, a new, more accurate energy calibration of the ^{160}Gd$(p,t)^{158}$Gd data was performed [25]. This new calibration confirms an energy shift in some energy regions. Therefore, the putative 1953.5-keV level is now assigned an energy of 1957.0 keV, a level from which γ decay is observed (see the discussion of this level below).

E. 1957.0-keV level (0_5^+)

As discussed above and as shown in Fig. 8, a 0^+ excitation was placed at 1960.1 keV from the ^{160}Gd(p,t) data [6], on the left shoulder of a much stronger peak at 1953.5 keV. The 0^+ level at 1957.0 keV is now confirmed by Bucurescu and Meyer [25] to be the strong peak in Fig. 8. Moreover, they find no evidence of the suggested 1960.1-keV level; this small peak shown in Fig. 8 is most likely a result of the tail from the 1957.0-keV peak. The 1957.0-keV level decays to the 2_1^+ state through the 1877.5-keV γ-ray transition. The excitation function shown in Fig. 11(a) presents the expected energy threshold and an a_2 value of -0.02 ± 0.04 is in agreement with a 0^+ assignment. No other branches have been observed.

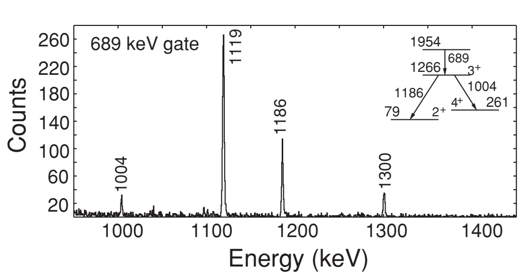

FIG. 10. Background-subtracted γ-ray spectra gated on the 689-keV transition.

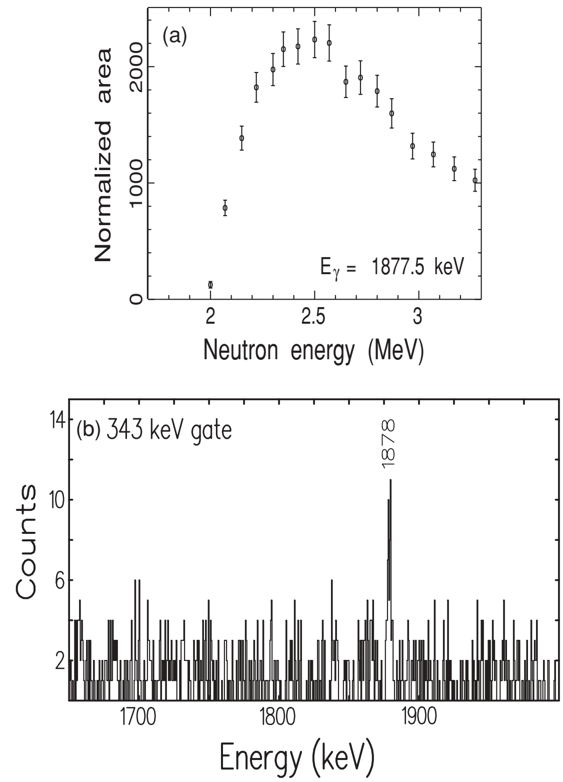

FIG. 11. (a) Excitation function for the 1877.5-keV γ ray from the 0^+ state at 1957.0 keV. (b) Background-subtracted γ-ray spectrum gated on the 343-keV transition.

Greenwood *et al.* [11] suggest the 2035.4-keV level as a 2^+ member built on the 1957.0-keV 0^+ band head. Although we were able to confirm the existence of this level by the placement of a decay γ ray and assign a level lifetime of $\tau = 59 \pm 8$ fs, we could not observe the low-energy transition between the levels, as it would be highly converted and the γ ray would also be significantly absorbed in our massive scattering sample. With an upper limit for the $B(E2; 2^+ \rightarrow 2_1^+)$ value of <6.1 W.u. (the δ value is unavailable), the transition rate of the decay to the ground state is only 0.27 W.u.

Interestingly, a higher-lying state is observed to decay to the 0_5^+ level. From the excitation function, clear evidence for a new level at 2300.1 keV exists with γ-ray decay to the ground state and the 2_1^+ state. However, because the peaks are weak, we were not able to obtain useful lifetime or angular distribution information. From the coincidence data, a weak 343.1-keV transition [as shown in Fig. 11(b)] is placed to the 0_5^+ state at 1957.0 keV. Although a $J^\pi = 2^+$ assignment is most likely, we cannot rule out the possibility of this level having a spin of 1.

F. 2276.7-keV level (0_6^+)

The excitation function for the 2197.1-keV γ ray, shown in Fig. 12, presents the expected threshold to be a transition from the 2276.7-keV level to the 2_1^+ level at 79.4 keV. An a_2 value of

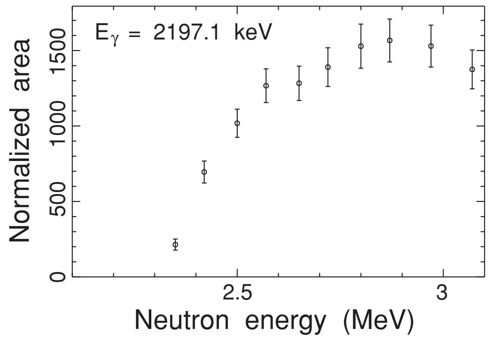

FIG. 12. Excitation function for the 2197.1-keV γ ray from the 0_6^+ level.

0.04 ± 0.16 is consistent with a 0^+ assignment. Coincidence data show that the 2276.7-keV level also decays through the 1089.4- and 1013.9-keV transitions to the 2_γ^+ and 1_2^- states, respectively. These two very weak γ rays are distinct only in the coincidence spectra. Relative intensities of two units have been assigned to each of them (see Table I). The 1089.4-keV transition has been confirmed in this work as a weak decay to the 2_γ^+ state at 1187.1 keV, in disagreement with the nuclear data compilation [26], where this γ ray was identified as the main decay branch from the 2276.7-keV level. As shown in the coincidence spectra of Figs. 13(a) and 13(b), the 108-keV γ ray is weakly visible in coincidence with both the 1187.1- and 1107.6-keV transitions depopulating the 2_γ^+ level. The large yield of the 2197.1-keV γ ray confirms it as the main decay branch and a level lifetime of 70^{+20}_{-15} fs has been determined.

The observation of the 1089.4-keV transition could be significant, as it may indicate a candidate for the $0_{\gamma\gamma}^+$ excitation, $B(E2; 0_6^+ \rightarrow 2_\gamma^+) = 3^{+3}_{-2}$ W.u. The 2_γ^+ state has an energy of 1187.1 keV and a $B(E2; 2_\gamma^+ \rightarrow 0_1^+)$ value of 3.4(3) W.u. This 2276.7-keV 0^+ level is at the appropriate energy (twice the energy of the 2_γ^+ band head) for the $0_{\gamma\gamma}^+$ excitation. However, the stronger transition seen to the 2_1^+ state, $B(E2; 0_6^+ \rightarrow 2_1^+) = 4.3^{+1.2}_{-1.0}$ W.u., would not be expected.

In addition, we propose a 2^+ level at 2353.7 keV from the decay of the 1166.4-keV transition to the 2_γ^+ state at 1187.1 keV, as confirmed from the coincidence spectrum gated on the 1166.4-keV γ ray and shown in Fig. 13(c). This new level, at nearly 80 keV above the 0_6^+ level, is at the energy to be the second member of the band and could have a large transition probability to the γ band of $B(E2; 2^+ \rightarrow 2_\gamma^+) <$ 9.9 W.u. (only an upper limit is possible because the mixing ratio of the decay could not be determined). The energies and decay strengths provide some arguments for the presence of a $\gamma\gamma$ vibration. The high level density of states observed in this energy region makes improbable the identification of the other two-phonon γ excitation.

G. 2340.8-keV level (0_7^+)

A 0^+ state at 2340.8 keV was identified in the (p, t) data [6]. This level does not decay to the 2_1^+ state, but we found from the coincidence data that the 2340.8-keV state decays weakly through newly identified 1076.6-, 1152.2-, and 1362.3-keV transitions to the 1_2^-, 2_γ^+, and 1_1^- levels. The coincidence spectra of Figs. 13(a) and 13(b) both show a 1152-keV transition to the 2_γ^+ level.

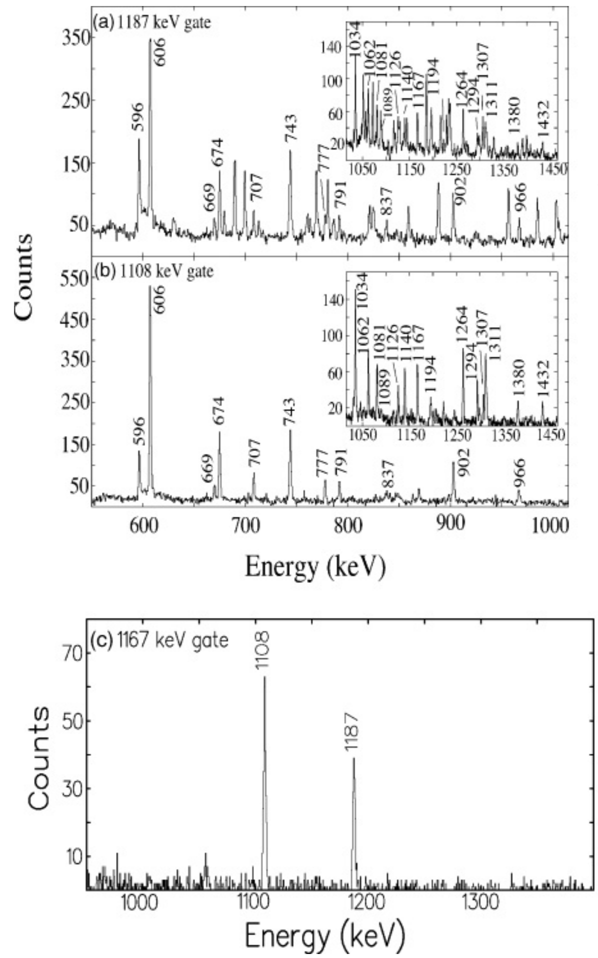

FIG. 13. The top panel shows γ-ray coincidence spectra produced by gating on (a) the 1187.3 keV transition (a triplet) and (b) the 1107.6-keV transition. Both decays de-excite the $K^\pi = 2^+$ band head. Only γ rays in coincidence in both gates are labeled. The bottom panel (c) shows a portion of the γ-ray spectrum produced by gating on the 1166.4-keV transition.

We leave open the possibility of a small branch to the 2_1^+ state via a 2260.7-keV γ ray. Our excitation function confirms placement to the 2260.7-keV 2^+ level (see Fig. 14). However,

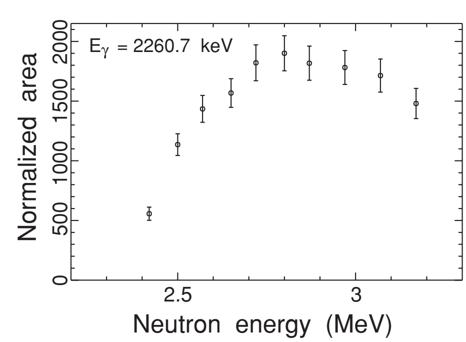

FIG. 14. Excitation function for the 2260.7-keV γ ray from the 2260.7-keV level to the ground state with a possible contribution from the 0_7^+ level.

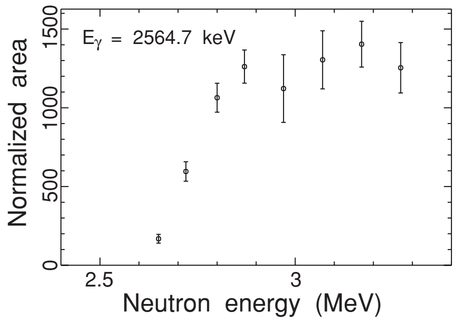

FIG. 15. Excitation function for the 2564.7-keV γ ray from the 0_8^+ level.

we were unable to compare it to other excitation functions as other decay branches were too weak to be observed in singles measurements. Therefore, we leave the 2260.7-keV γ ray tentatively assigned as it may be hidden by the larger 2260.7-keV ground-state transition in our data. Moreover, the lack of angular distribution information prevents any support for the 0^+ assignment in the (p,t) data [6].

H. 2644.2-keV level (0_8^+)

The 2644.2-keV 0_8^+ excitation was identified from the (p,t) data. A 2564.7-keV γ ray to the 2_1^+ state has been assigned from this level, and the excitation function for this γ ray shown in Fig. 15 exhibits the expected energy threshold. The observed a_2 of 0.16 ± 0.12 is not completely consistent with isotropy, so we cannot confidently confirm the 0^+ assignment. A lifetime of 19(4) fs has been determined. If this is a 0^+ excitation, the $0_8^+ \rightarrow 2_1^+$ decay has the largest transition probability, $7.6^{+1.5}_{-1.1}$ W.u., giving this state the largest collectivity of the proposed 0^+ states.

I. 0^+ States above 2.65 MeV

The (p,t) measurements [6] report additional 0^+ levels at 2688.8, 2911.5, 3076.7, and 3109.8 keV. The limited data available prevent us from offering insight into these levels.

IV. CONCLUSION

The collection of 0^+ states experimentally identified with the ^{160}Gd$(p,t)^{158}$Gd experiment [6] has presented us with an opportunity to study the nature of several 0^+ states in a deformed nucleus. Identifying the γ-ray decays and determining level lifetimes is the first step in deducing the fundamental character of 0^+ states. In this set of ^{158}Gd$(n,n'\gamma)$ experiments, we were able to determine five new lifetimes as well as lower limits for other 0^+ states. The $0^+ \rightarrow 2_1^+$ transition from the state at 2644.2 keV may have the largest $B(E2; 0^+ \rightarrow 2_1^+)$ value of $7.6^{+1.5}_{-0.7}$ W.u. but does not exhibit the expected β-vibrational characteristics outlined in Ref. [2].

A candidate for a two-phonon γ excitation is proposed. The 0^+ levels at 2276.7 and 2340.8 keV exhibit similar decay properties. In particular, both levels decay to the 2_γ^+ state and lie at about twice the energy of the 2_γ^+ band head.

The experimental status of 0^+ states in ^{158}Gd has been clarified by this work. Especially noticeable is that the states with the largest collectivity occur above the pairing gap. In fact, below the pairing gap there is very little collectivity associated with 0^+ states.

ACKNOWLEDGMENTS

We thank H. E. Baber for his help with accelerator maintenance and operation. We gratefully acknowledge discussions with A. Aprahamian, N. LoIudice, D. Meyer, D. Bucurescu, and P. E. Garrett. This work was supported by the U.S. National Science Foundation under grant no. PHY-0354656. S.R.L. was partially supported by Department of Energy grant no. DE-FG52-06NA26206.

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