PHYSICAL REVIEW C **66**, 051305(R) (2002)

New 0^+ states in ^{158}Gd

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(Received 21 December 2001; revised manuscript received 27 June 2002; published 27 November 2002)

A new high-precision (p,t) study of the ^{158}Gd nucleus was carried out with the Q3D spectrometer at the University of Munich. The result is the observation for the first time of a deformed nucleus with 13 excited 0^+ states below an excitation energy of approximately 3.1 MeV. Seven of these 0^+ states are observed for the first time and an additional three are new confirmations of previous tentative assignments. This abundance of 0^+ states provides significant new information on these poorly understood excitations. ^{158}Gd can now be viewed as a unique laboratory for further investigations on the nature of 0^+ excitations in nuclei.

DOI: 10.1103/PhysRevC.66.051305 PACS number(s): 21.10.Re, 24.10.Eq, 25.40.Hs, 27.70.+q

The nature of low lying $K^\pi = 0^+$ bands in deformed nuclei remains a mystery. Traditionally the first excited $K^\pi = 0^+$ bands along with the $K^\pi = 2^+$ bands were labeled as single-phonon "β" and "γ" vibrational excitations. The $K^\pi = 2^+$ excitations are well understood theoretically and shown to vary smoothly in collectivity across a given isotopic chain [1–3]. The nature of $K^\pi = 0^+$ excitations however still remains enigmatic and therefore the focus of intense discussions as well as a flurry of activity from both theoretical and experimental aspects. Data on $K^\pi = 0^+$ bands have traditionally been relatively sparse. However, recent improvements in technology have remedied the situation by enabling spectroscopy, reaction, and lifetime measurements of a large number of $K^\pi = 0^+$ bands that were previously inaccessible in nuclei.

The results are puzzling at best. First, in many deformed nuclei of the rare-earth region, there are several excited $K^\pi = 0^+$ bands below the pairing gap. Second, there are variations in collectivity amongst the $K^\pi = 0^+$ bands in the same nucleus, as well as enormous variations in collectivity of the first excited $K^\pi = 0^+$ bands in very narrow isotopic regions.

Numerous attempts have been made to address the nature of low-lying $K^\pi = 0^+$ bands via various nuclear models. The IBM and the newly developed critical point symmetries [4–6] or partial dyamical symmetries [7,8] are amongst the newest approaches as well as the more traditional QPNM [9] (quasi-particle-phonon nuclear model).

The microscopic calculations of Soloviev *et al.* within the QPNM [9] yield a Hamiltonian of phonons, quasiparticles (qp), and phonon-qp interactions. Calculations have been done for several rare-earth deformed nuclei and in each case, the result is a spectrum that typically includes five excited $K^\pi = 0^+$ bands below 2.3 MeV. The exact nature of these $K^\pi = 0^+$ bands then depends on the number of phonons and qp pairs included.

A review of existing data and a discussion of several possible interpretations is given in Ref. [10]. Suffice it to say that $K^\pi = 0^+$ bands are one of the fundamental excitations in nuclear spectra and their nature is not yet fully understood. The numerous recent publications addressing this subject point to the immense current interest on this topic. In order to carry out a meaningful discussion or a comprehensive theoretical effort to understand the nature of these $K^\pi = 0^+$ bands, it is first necessary to establish a more complete set of $K^\pi = 0^+$ excitations in deformed nuclei.

The purpose of this Rapid Communication is to present the results of a new high-precision ^{160}Gd$(p,t)^{158}$Gd measurement. The ^{158}Gd nucleus prior to this work had three positively identified excited $K^\pi = 0^+$ bands and four tentatively assigned 0^+ states below 3 MeV [11–14]. In this Rapid Communication, we report on the existence of 13 excited 0^+ states in one nucleus below an excitation energy of approximately 3.1 MeV. This number is by far the largest ever seen in any nucleus and provides a unique laboratory for developing and testing new models on the nature of $K^\pi = 0^+$ excitations in nuclei.

The experiment was carried out at the high-precision Q3D spectrometer of the University of Munich MP tandem accelerator laboratory using a 27 MeV proton beam on a 122 μg/cm^2 target of isotopically enriched ^{160}Gd (98.10%) with a 14 μg/cm^2 carbon backing. Known impurities in the target material consisted of ^{158}Gd (0.99%), ^{156}Gd (0.33%), and ^{157}Gd (0.44%). A 1.8 m long focal plane detector provided the particle identification of the ejectiles of mass 1–4

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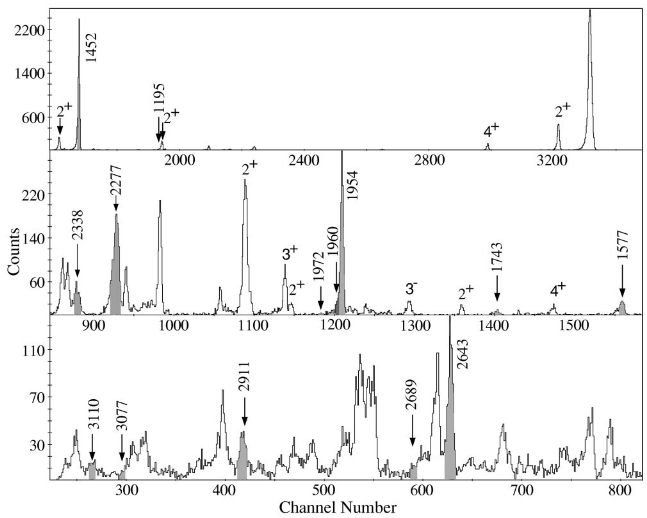

FIG. 1. The $\theta = 6°$ triton spectrum. The excited 0^+ states have been labeled with their corresponding energies in keV and shown as shaded peaks.

in the Q3D spectrometer [15] with an energy resolution of approximately 4–6 keV for the energy range of interest from 1 to 3 MeV. This resolution is a spectacular achievement for transfer reactions. The tritons were recorded at lab angles 6°, 10°, 15°, 20°, and 30°. Figure 1 shows the triton spectrum taken at 6°. The triton peaks from the ground state and the 1452 keV 0^+ states are the most intense. This peak has 31% of the ground state strength compared to previous studies [16] that reported somewhat smaller intensities for the same peak: ≈23% and ≈15%. The remaining peaks are not as strongly populated with all of them falling below 5% of the ground state strength. More than 90 states were populated in this experiment below an excitation energy of 3.5 MeV. Approximately half of them were identified as 0^+, 2^+, and 4^+ states in ^{158}Gd. In this paper we concentrate on the 0^+ states. Results on new 2^+ and 4^+ states will be published separately as a Brief Report.

Peaks from each of the data at various angles were fit with RADWARE [17], and energy calibrated for peak identification. Efficiency corrections were also made by angle. The resulting angular distributions are shown for the states of interest in Fig. 2. The observed distributions are compared with calculations using the distorted wave Born approximation DWBA (DWUCK4). The optical parameters were taken from Ref. [18] changing the proton imaginary well depth $W_D = 14.5$ MeV and $r_c = 1.25$ fm for the Coulomb radius [18,19]. The experimental points are plotted with their error bars while the Q-corrected DWBA calculations are shown as solid lines.

Previous (p,t) [11,16,20] and (t,p) [14] measurements resulting in ^{158}Gd were done with 18–19 MeV proton and 17 MeV triton beams, respectively. Additional reaction studies include (d,d') [21], (n,γ) [13], and (t,α) [22]. The

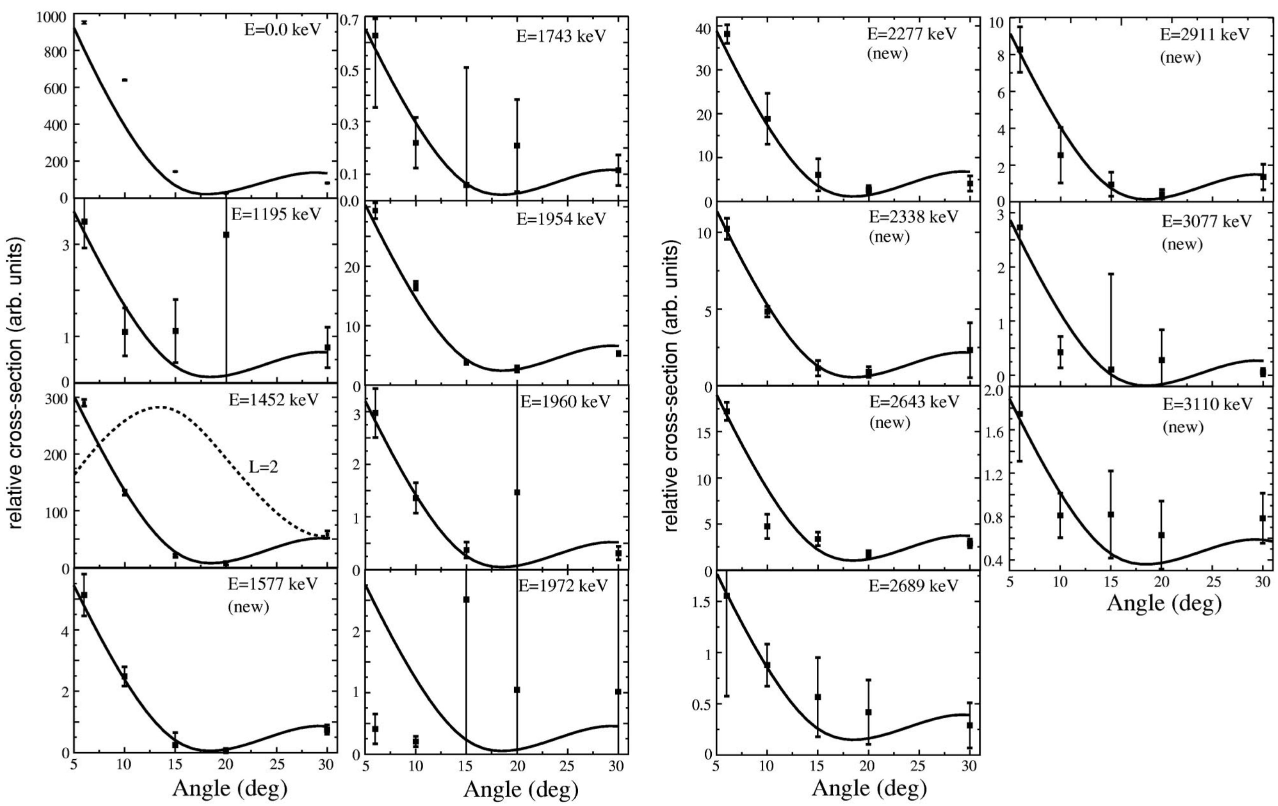

FIG. 2. Angular distributions of all the 0^+ states. The data points are given with their error bars. The solid curve is the Q-corrected DWBA curve normalized to each data set. We have shown in addition to the $L=0$ calculation, an $L=2$ distribution as a dotted line for the 1452.4 keV angular distribution.

TABLE I. Results of this new (p,t) measurement in comparison with previous studies. The first column shows the measured energies and errors from this work (the systematic error is 0.6 keV), the second column lists previous (p,t) or other measurements where the level was seen, the third column gives the relative cross sections with errors for each level in the $\theta=6°$ spectrum.

Present work E_{exc}(keV)	Previous work E_{exc}	Cross sections $6° \pm$ Error
0 ± 0.6	0 [11,13,14,16]	1000 ± 8
1194.8 ± 1.3	1196.10 ± 0.30 [13,14,16]	3.7 ± 0.6
1452.4 ± 0.6	1452.30 ± 0.36 [11,13,14,16]	305 ± 6
1577.0 ± 1.2 [a]		5.4 ± 0.7
1742.7 ± 0.9	1743.08 ± 0.44 [13,14]	0.6 ± 0.3
1953.5 ± 0.6	$(1952.34) \pm 0.52$ [13,14] [b]	30.8 ± 1.4
1960.1 ± 3.8	1957.8 ± 0.8 [13,14]	3.2 ± 0.5
1972.2 ± 3.1	(1971) [14] [c]	0.4 ± 0.2
2277.3 ± 2.2 [a]		39.6 ± 2.2
2338.0 ± 0.8 [a]		10.7 ± 0.7
2643.4 ± 0.8 [a]		18.1 ± 1.0
2688.8 ± 0.8	(2689) [14] [b, d]	1.7 ± 1.0
2911.2 ± 1.1 [a]		8.7 ± 1.3
3076.7 ± 1.6 [a]		2.9 ± 4.9
3109.9 ± 1.1 [a]		1.2 ± 0.5

[a]New level found in this work.
[b]Previously tentative assignment confirmed to be 0^+ in this work.
[c]We cannot support a 0^+ assignment based on our data.
[d]This level was identified as a 0^+ by Lovhoiden *et al.* [14]. A level at 2687.1 ± 0.3 keV was identified as a potential 4^+ state by Greenwood *et al.* [13]. NDS [12] seems to have adopted the latter energy level as a potential 0^+ in error.

combined result of these reactions was the definite assignment of three excited 0^+ states at 1196.1, 1452.3, and 1743.1 keV. We were able to confirm all three of these states since they show excellent agreement with the DWUCK calculations. There were additionally four tentative 0^+ assignments at 1952.3, 1957.8, 1971 [14], and 2689 keV [14]. The angular distributions for all four are shown in Fig. 2. The angular distribution for the 1971 keV state does *not* support a 0^+ assignment. We did however confirm that the other three states are 0^+. Additionally, we found seven new 0^+ states at 1577, 2277, 2338, 2643, 2911, 3077, and 3110 keV. Table I lists the observed states in comparison with previous work, and the relative cross sections at 6° where the normalization is 1000 for the g.s. 0^+. In advance, we expected to observe 0^+ states higher in excitation energy than all previous (p,t) measurements since our proton beam energy was 27 MeV in comparison with 18-19 MeV. The one 0^+ state that warrants some explanation for its non-observation in previous measurements is the 1577 keV state. The Q value difference for the ^{156}Gd(p,t)^{154}Gd and the ^{160}Gd$(p,t)^{158}$Gd reactions is exactly 1577 keV. The target in this experiment had a 0.33% ^{156}Gd component, therefore one would expect some portion of the 1577 keV peak in the observed spectrum here to be a contaminant from the g.s. of ^{156}Gd. However, the fitted peak area for 1577 shows a 40% higher number of counts than we can account for by the impurity indicating the existence of a new 0^+ state. Additionally, a closer examination of the γ-ray data from Ref. [13] shows a number of transitions that fit in quite well and support the existence of this level in ^{158}Gd. The data come from an (n,γ) [13] study of states in ^{158}Gd where the authors had been kind enough to give a list of all unassigned γ rays belonging to this nucleus [12]. For the new 0^+ states, we made a search to see if we could assign any γ rays to the new levels using the accepted level energies. Table II shows the results for two of the new 0^+ states. There are several transitions that fit into the population and depopulation scheme of the 0^+ state at 1577 keV. While this would not on its own be strong evidence for the existence of the level, the (p,t) data along with the probable placement of the unassigned γ rays from the (n,γ) reaction give us some confidence in the assignment of the new 0^+ level at 1577 keV.

In summary, we carried out a new high-precision (p,t) reaction on an isotopically enriched target of ^{160}Gd. The resolution of the Q3D at Munich allowed the identification of 13 excited 0^+ states below 3.1 MeV in excitation energy in the spectrum of ^{158}Gd. Three of these 0^+ states were previously identified. Four of the 13 had previous tentative assignments. We confirm three of these four to be 0^+ states. In

TABLE II. New 0^+ levels observed in this study with possible γ-ray placements from the (n,γ) work [12,13]. The energies of the levels have been refined by using the γ-ray energies and their population or depopulation to known levels.

Initial state		Deexciting transition		Final state	
E_x (keV)	J,K^π	E_γ (keV)	$I_\gamma(error)$	E_f	J,K^π
1577.0 ± 0.1	$0,0^+$	317.012 ± 0.025	0.062(16)	1259.81 ± 0.03	$2,0^+$
		389.83 ± 0.03	0.20(3)	1187.10 ± 0.03	$2,2^+$
		600.06 ± 0.06	0.60(10)	977.10 ± 0.02	$1,1^-$
1856.4 ± 0.5	$1,1^-$	279.278 ± 0.014	0.055(9)	1577.0 ± 0.1	$0,0^+$
2275.9 ± 0.4	$0,0^+$	240.316 ± 0.011	0.037(7)	2035.44 ± 0.22	$2,0^+$
		381.34 ± 0.05	0.054(14)	1894.39 ± 0.05	$2,1^+$
		428.21 ± 0.06	0.23(7)	1847.74 ± 0.06	$1,1^+$
		1088.88 ± 0.25	5.1(10)	1187.10 ± 0.03	$2,2^+$

addition, there were seven new 0^+ assignments. The new 0^+ assignments are further strengthened by the placement of γ rays that were clearly identified to belong to the ^{158}Gd nucleus with no previous level assignments. Such an abundance of 0^+ states has not previously been seen in nuclei until the very present. A similar study of an $N=84$ nucleus with (p,t) had resulted in the observation of ten 0^+ states [23] below an excitation energy of 4.1 MeV in the ^{146}Sm nucleus. In that particular case, a particle-core coupling model could provide a remarkable explanation for the nature of the observed 0^+ states. In the case of a well-deformed nucleus, such as ^{158}Gd, it is not yet possible to decipher the nature of all the observed 0^+ states. It is therefore essential to carry out lifetime measurements of the new 0^+ states in order to get an insight into the nature of these states and their collectivity. If further studies can in fact determine if these states are band-heads and their degree of collectivity, the present measurement of ^{158}Gd will provide an unprecedented opportunity for the investigation of the nature of 0^+ bands. The observation of 13 excited 0^+ states in one nucleus below an excitation energy of 3.1 MeV will be the strongest challenge yet to our understanding of these excitations.

We gratefully acknowledge discussions with R. F. Casten, K. Heyde, and H. F. Wirth. We thank the National Science Foundation (contract No. PHY-99-01133) and the Deutsche Forschungs Gemeinschaft (grant C4-Gr894/2) without whose support this work would not have been possible.

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