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New data on 0^+ states in ^{158}Gd

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Excited states in the deformed nucleus ^{158}Gd have been studied in the (p, t) reaction using the Munich Tandem Accelerator and the Q3D spectrograph. Thirty-six excited 0^+ states (five tentative) have been assigned up to the 4.3 MeV excitation energy. This large number of excited 0^+ states in a deformed nucleus, close to a complete level scheme for this spin and parity, offers a new opportunity to test nuclear models and obtain more information on the structure of these special states.

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I. INTRODUCTION

Nuclear collective excitations even at low energies still represents a challenge for the theoretical models, especially for the excited 0^+ states in even-even nuclei. At low excitations these states can be analyzed in terms of the beta vibrations, pairing vibrations, spin-quadrupole interaction, shape coexistence, one- and two-phonon states, and above the pairing energy gap as various combinations of single-particle states. Difficulties in their theoretical description were noted as soon as a few such modes were experimentally confirmed with good accuracy [1]. Simple models extensively used to describe nuclear structure, such as the interacting boson model (IBM) [2] and the quasiparticle-phonon model (QPM) [3], had difficulties in explaining 0^+ states observed just above the β vibrational state in deformed nuclei. Theories also met difficulties in trying to explain the properties of the first excited collective states, such as the strong excitation of the first excited 0^+ state in actinide nuclei. This observation pointed to a different collective character, and led to the recognition of the importance of the monopole and quadrupole pairing field [4–6]. A review by Garrett [7] of the properties of the first excited 0^+ states in deformed nuclei shows that only in a few nuclei the states considered as β vibrational met the original definition [8]. In other nuclei they may have more complex structures, requiring more comprehensive microscopic approaches.

The use of new experimental techniques have led to results which set a new challenge to the nuclear theory. In a high-resolution (p, t) reaction experiment Lesher *et al.* [9] observed 13 excited 0^+ states up to 3.1 MeV excitation in the ^{158}Gd nucleus. Such a large number of 0^+ states was completely unexpected at that time. This pioneering work triggered off numerous theoretical attempts to explain this finding, such as the IBM [10], the QPM [11], and a model based on the monopole pairing, quadrupole-quadrupole, and spin-quadrupole interactions [12]. Such approaches are rather different in nature, for example the role of the octupole excitations in generating 0^+ states in actinides is rather different in the IBM and QPM approaches [13–15]. These approaches describe only some aspects concerning the abundance of 0^+ states in nuclei, and their properties, implying their collectivity or absence of collectivity. More advanced theoretical approaches [16–19] based on the generator-coordinate extension of the Hartree-Fock-Bogoliubov self-consistent mean-field approach were applied for the description of the octupole vibration states in ^{158}Gd and other rare-earth nuclei, and may be useful for applications to 0^+ states. The main point is related to the experimental observation of many excited 0^+ states in one nucleus, ^{158}Gd. Theoretical models have not been able yet to explain systematically these data or similar ones found later in many other nuclei.

Excited 0^+ states are usually identified via (p, t) reactions even in complicate and dense excitation spectra: they have a very distinct angular distribution. Early studies, see for example Ref. [20], were limited by excitation energy and number of 0^+ excitations observed. Intensive studies of the multiple 0^+ states were triggered by the observation of 12 excitations with zero angular-momentum transfer via the (p, t) reaction in the odd nucleus ^{229}Pa [21] and 13 such excitations in the even-even nucleus ^{158}Gd [9]. It is also worth mentioning the study of ^{146}Sm in the (p, t) reaction in which 10 new 0^+ states were observed below 4.2 MeV [22]. Then, many experiments were carried out through the (p, t) transfer campaign in the region of actinides [23–28] and rare earths [29–33]. A feature of some of these studies is that, simultaneously with 0^+ states, many states with other spins of both parities (2^+, 4^+, 3^-, etc.) were also identified.

So far, almost all the studies of the 0^+ states in the (p, t) reaction have been performed for an excitation energy below about 3 MeV. One attempt to expand this range was

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undertaken for ^{230}Th [24] in the region up to 4.5 MeV, but only for two angles. The angular distributions up to 4 MeV were measured for ^{168}Er [30]. However, a sharp minimum at about 17.5°, which is also a distinguishing feature of 0^+ excitations, was absent in most of these angular distributions above 3 MeV. The 0^+ assignments were made also for ^{170}Yb [31] up to 3.5 MeV using the ratio $\sigma(5^\circ)/\sigma(17.5^\circ)$, that is not always reliable.

This paper presents results of new measurements of 0^+ states with the $^{160}\mathrm{Gd}(p,t)^{158}\mathrm{Gd}$ reaction in the excitation region from 1.7 up to 4.2 MeV, which partly overlaps (up to 3.1 MeV) with the region investigated in Ref. [9]. We identified 230 states with different spins at energies between 1700 to 4300 keV. Results of the complete analysis for all these states will be discussed in a forthcoming paper. The purpose of this paper is to present the results for 0^+ states: we report the existence of 36 excited 0^+ states in this nucleus below the excitation energy of 4.3 MeV. For five of them, including the 1952.4 keV state, the assignment is tentative. The total number is the largest observed so far in any nucleus and provides a unique opportunity for testing new models on the nature of 0^+ excitations in nuclei.

II. EXPERIMENT, ANALYSIS, AND RESULTS

Our initial aim was to carry out the $^{160}\mathrm{Gd}(p,t)^{158}\mathrm{Gd}$ experiment for observation of the 0^+ excitations in the extended region from 3.1 to 4.2 MeV, in addition to the already observed 0^+ states at lower energies by Lesher *et al.* [9]. However, because of some problems in superposing the two spectra in the overlapping region we decided to perform also the experiment at lower energies.

A first experiment in the high energy region was performed at the Tandem accelerator of the Maier-Leibnitz-Laboratory of the Ludwig-Maximilians-University and Technical University of Munich using a 22 MeV proton beam on a 110 $\mu\mathrm{g/cm}^2$ target of isotopically enriched ^{160}Gd (98.10%) with a 14 $\mu\mathrm{g/cm}^2$ carbon backing. Known impurities in the target material consisted of ^{158}Gd (0.99%), ^{156}Gd (0.33%), and ^{157}Gd (0.44%). A long (1.4 m) focal-plane detector provided the particle identification of the light ejectiles in the high-precision Q3D spectrometer [34]. The resulting triton spectra having a resolution of 4–7 keV (FWHM) are background-free. The acceptance of the spectrograph was 14.43 msr for all angles, except for the most forward angle 5°, where it was 7.50 msr. Typical beam currents were around 1.0 μA. The angular distributions of the cross sections were obtained from the triton spectra at eight laboratory angles from 5° to 40° with step of 5°. The low-energy spectra in the interval from 0 to 3.4 MeV have been also measured at the angle of 5° for three magnetic settings, which had all overlapping sections with the neighboring regions. For the calibration of the energy scale, the triton spectra from the reaction $^{154}\mathrm{Gd}(p,t)^{152}\mathrm{Gd}$ have been measured at the same magnetic settings. In this way, the higher energy spectrum of ^{158}Gd was calibrated by the known energies of the nucleus ^{152}Gd.

A second experiment was performed in the low-energy region on the 125 $\mu\mathrm{g/cm}^2$ target of ^{160}Gd. The acceptance of the spectrograph was 9.8 msr for 6° and 14.5 msr for other angles. The resulting triton spectra have a slightly lower resolution of 8–9 keV (FWHM). For the calibration of the energy scale, the triton spectra from the reaction $^{172}\mathrm{Yb}(p,t)^{170}\mathrm{Yb}$ were measured at the same magnetic settings. The low-energy spectrum calibrated in such a way has a 250 keV overlap with the high-energy spectrum fixed by the first experiment. Many levels of ^{158}Gd well known from the resonance capture and from the $(n,n'\gamma)$ reaction [35] are correctly fitted with this calibration in the low-energy region. Among them, the states mostly strong excited in the (p,t) reactions are the following: 1894.6, 2035.7, 2089.3, 2276.8, 2355.0, 2283.2, 2594.7 2674.6, 2750.4, 2909.6, and 3200.8 keV in the low-energy spectrum. The spectra in the low and high energy intervals calibrated by the corresponding reactions $^{154}\mathrm{Gd}(p,t)^{152}\mathrm{Gd}$ and $^{172}\mathrm{Yb}(p,t)^{170}\mathrm{Yb}$ coincide in the overlapping region (see Fig. 1). The difference in the energies determined by these calibrations in the overlapping region does not exceed 1 keV.

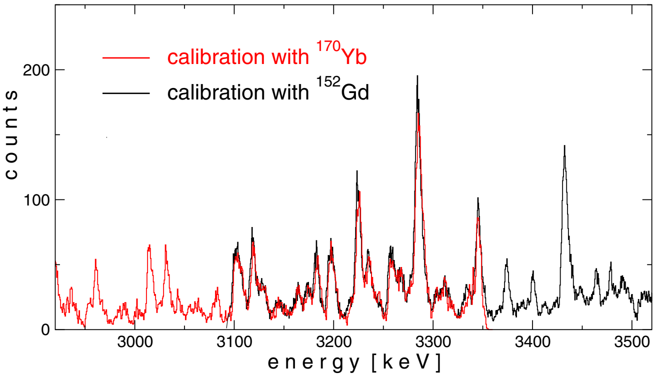

FIG. 1. The low- and high-energy spectra measured at angle 5° and calibrated by levels of ^{170}Yb (red line, lower energies) and ^{152}Gd (black line, higher energies), respectively. Their matching in the overlapping area demonstrates the accuracy of the calibration.

After completing the analysis of the results of these two experiments we became aware of the results of another independent experiment. This was the (p,t) reaction experiment performed in 2005 by a Yale-Munich-Köln-Bucharest collaboration (referred to as the YMKB experiment in the following), in which many rare-earth nuclei from ^{152}Gd to ^{190}W were studied with the aim to determine trends and types of possible 0^+ excitations [29]. The reaction $^{160}\mathrm{Gd}(p,t)^{158}\mathrm{Gd}$ was also measured in this experiment (at an incident energy of 25 MeV), just as a comparison with earlier experiments [9]. In the experiment [29], angular distributions of states up to 3.1 MeV excitation energy were measured at only three angles, as a first rough method to identify 0^+ states. The data for ^{158}Gd were not included in Ref. [29] because their full analysis became available later. Actually, they were already used as a support in the comparison between the results of Ref. [9] and those of Ref. [36] (see also the discussion and citation in Ref. [36]). In the analysis of these data the reaction $^{172}\mathrm{Yb}(p,t)^{170}\mathrm{Yb}$ was used for the energy calibration of the spectra, which allowed precise energy determinations of states up to about 2.7 MeV. The results of this investigation for the excitation energies of states in ^{158}Gd are compared with those of the present work in Table I. Good agreement of the

TABLE I. Energies of levels in ^{158}Gd and cross sections measured at the angle 5° in the reaction $^{160}\mathrm{Gd}(p,t)^{158}\mathrm{Gd}$ with proton energies of 25 MeV of the YMKB study (see text) and 22 MeV of the present study. The lowest two energies from the first column result from an extrapolation of the calibration curve which was determined only up to 2.75 MeV.

The YMKB study		Present study	
E_{exp} (keV)	$d\sigma/d\Omega$ (μb/sr)	E_{exp} (keV)	$d\sigma/d\Omega$ (μb/sr)
1452.3 *3*	496 *9*	1452.3 *3*	423 *6*
1579.4 *5*	7.6 *8*	1577.0 *4*	6.1 *7*
1743.7 *3*	2.6 *3*	1743.2 *5*	1.9 *2*
1937.5 *4*	0.9 *3*	1936.5 *11*	1.0 *2*
1957.1 *5*	47.5 *14*	1957.3 *3*	39.0 *10*
1977.9 *4*	1.6 *3*	1977.6 *8*	1.3 *2*
2277.5 *4*	43.2 *17*	2276.7 *4*	52.3 *16*
2333.0 *3*	16.4 *9*	2333.4 *5*	7.2 *4*
2436.0 *3*	10.7 *6*	2437.2 *4*	11.9 *4*
2630.6 *5*	30.7 *12*	2632.7 *4*	21.7 *9*
2646.8 *6*	2.5 *4*	2643.1 *5*	2.5 *3*
2672.2 *4*	2.3 *5*	2673.9 *8*	3.8 *8*
2723.5 *5*	21.1 *10*	2726.4 *4*	12.4 *6*
2883.1 *15*	15.0 *7*	2888.2 *4*	9.2 *5*
2910.1 *15*	18.1 *9*	2914.5 *5*	10.9 *7*

two independent sets of data (measured at different beam energies) constitutes a complementary confirmation of the energy calibration performed in the present study. A worse agreement for the last two states in Table I is due to the fact that for energies above ≈2.7 MeV an extrapolation of the calibration curve was used in the YMKB experiment.

Figures 2(a)–2(c) show the triton spectrum over the whole measured energy interval from 1.0 to 4.3 MeV, taken at the detection angle of 5°. Assigned 0^+ states are labeled by their energies in keV.

The analysis of the triton spectra was performed using the program GASPAN [37]. The peaks in the spectra which are measured at 5° have been identified for 230 levels, though the angular distributions for all eight angles were measured only for about 210 levels. The resulting angular distributions for the states assigned as 0^+ are shown in Fig. 3. Corrections for the target thickness at different angles and for the dead time of the data-acquisition system have been taken into account.

The observed angular distributions are compared with calculations using the distorted wave Born approximation (DWBA). The coupled-channel approximation (CHUCK3 code of Kunz [38]) and the optical potential parameters suggested by Becchetti and Greenlees [39] for protons and by Flynn *et al.* [40] for tritons have been used in the calculations. Angular distributions of the 0^+ states are reproduced well by the one-step process, which simplifies the calculations. The

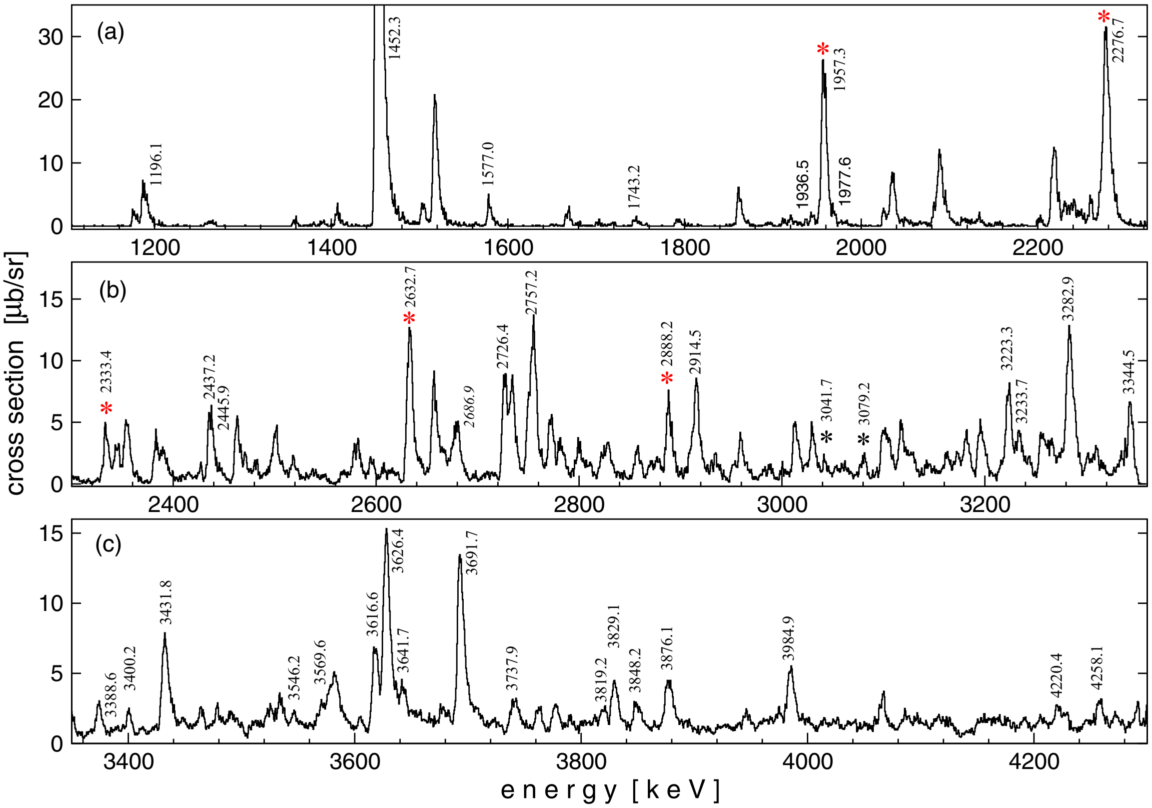

FIG. 2. The triton spectrum from the $^{160}\mathrm{Gd}(p,t)^{158}\mathrm{Gd}$ reaction measured at angle 5°. The states assigned in this study as 0^+ states are labeled by their energies. The peaks used to establish correspondence between this spectrum and the spectrum displayed in Fig. 1 of Ref. [9] are marked with a red asterisk. The two smaller peaks marked by a black asterisk have also been found in correspondence with weak peaks reported in Ref. [9] (see text).

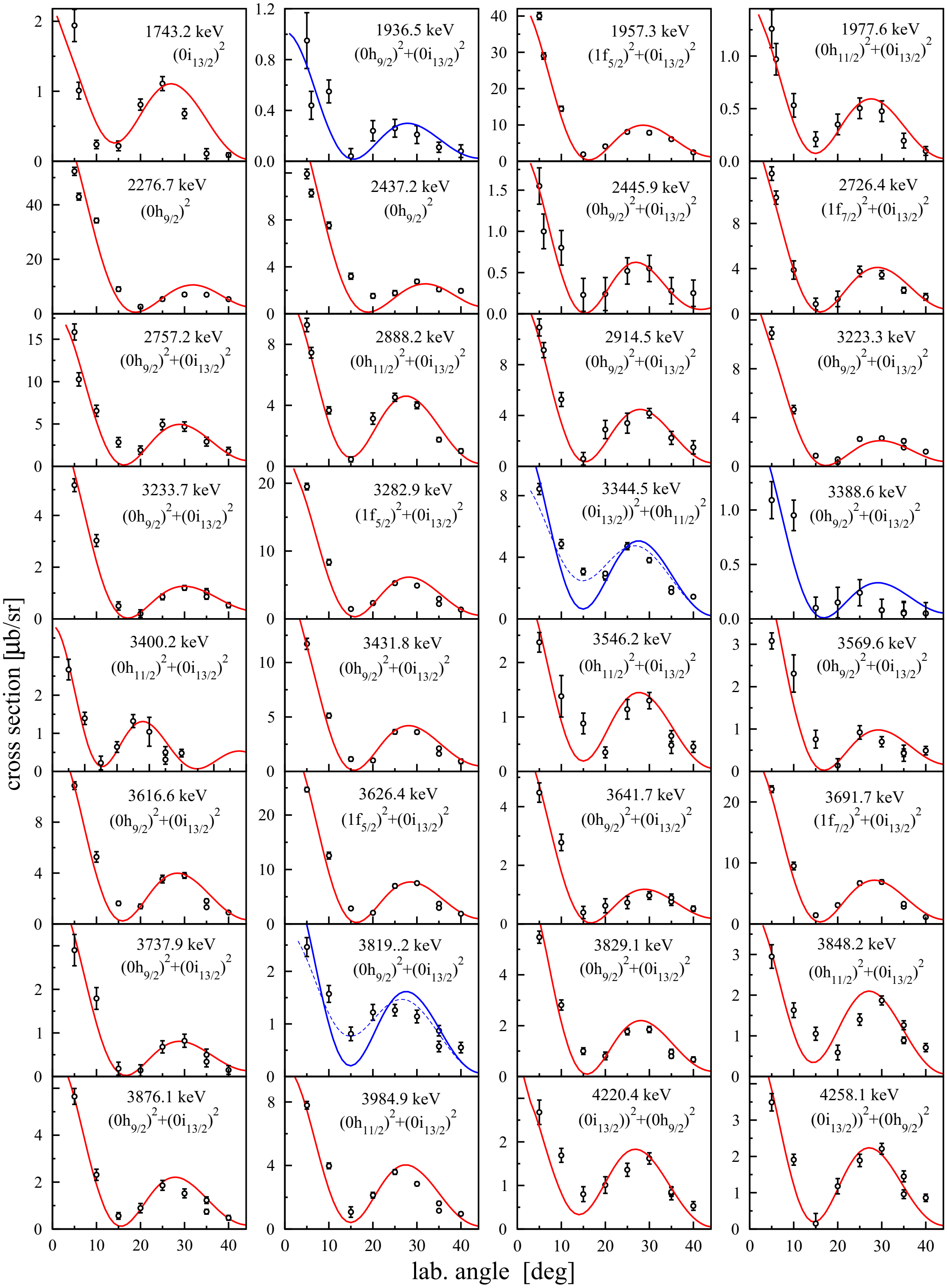

FIG. 3. Experimental angular distributions of assigned 0^+ states in ^{158}Gd and their fit with the CHUCK3 one-step calculations. The red and blue lines show the firm and tentative assignments, respectively. The transfer configurations used in the calculations for the best fit are shown for every state (see text for details). The dotted blue lines for two levels are the result of calculations for near zero excitation energy instead of the true energies of these levels.

TABLE II. Results of the present (p,t) experiment are compared with previous studies. The first three column show energies, relative (p,t) cross sections at 6°, and spins from Refs. [9,36]. The next three columns show the present results: energies, absolute (p,t) cross sections at 5°, and spin assignments. The errors of the differential cross sections are statistical, and an additional error of 10% should be taken into account due to the uncertainty in the thickness of the targets used. The last column shows the results of the (n,γ) experiment and of the early study of the (p,t) reaction.

Results of Refs. [9,36]			Results of present study			
E (keV)	$d\sigma/d\Omega$ relative	I^π	E (keV)	$d\sigma/d\Omega$ (μb/sr)	I^π	Ref. [41] E [(n,γ), keV]
0.0 *6*	1000 *8*	0^+	0.0 *3*	1435 *12*		0.0
1195.91 *24*	3.7 *6*	0^+	1196.1 *8*	3.3 *4*		1196.165 *8*
1452.10 *24*	305 *6*	0^+	1452.3 *3*	423 *6*		1452.352 *6*
1742.86 *22*	0.6 *3*	0^+	1743.2 *5*	1.9 *2*	0^+	1743.145 *14*
			1936.5 *11*	1.0 *2*	(0^+)	1935.5 *6* [c]
			1952.4 [b]	0.4 *3*		1952.424 *25*
1956.96 *24*	30.8 *14*	0^+	1957.3 *3*	39.0 *10*	0^+	1957.9 *7*
1972.2 *31*	0.4 *2*	0^+	1977.6 *8*	1.3 *2*	0^+	1972 *3* [c]
2276.66 *21*	39.6 *22*	0^+	2276.7 *4*	52.3 *16*	0^+	2276.04 *20*
2340.0 *2*	10.7 *7*	(0^+)	2333.4 *5*	7.2 *4*	4^+	
			2437.2 *4*	11.9 *4*	0^+	
			2445.9 *8*	1.5 *2*	0^+	
2644.18 *24*	18.1 *10*	(0^+)	2632.7 *4*	21.7 *9*	4^+	
			2643.1 *5*	2.5 *3*	4^+	
2688.8 *8* [a]	1.7 *10*	(0^+)	2686.9 *15*	0.5 *2*		2687.1 *3*
			2726.4 *4*	12.4 *6*	0^+	
			2757.2 *4*	15.8 *10*	0^+	2758.5 *3*
2911.48 *64*	8.7 *13*	(0^+)	2888.2 *4*	9.3 *5*	0^+	
			2914.5 *5*	10.9 *6*	0^+	2913.4 *7*
3076.7 *16* [a]	2.9 *49*	(0^+)	3041.7 *8*	1.7 *3*	(2^+)	
3109.9 *11* [a]	1.2 *5*	(0^+)	3079.2 *5*	2.3 *3*	(6^+)	3080.0 *6*
			3223.3 *3*	10.9 *5*	0^+	
			3233.7 *4*	5.2 *3*	0^+	3234.5 *5*
			3282.9 *5*	19.5 *5*	0^+	
			3344.5 *5*	8.4 *4*	(0^+)	
			3388.6 *10*	1.1 *2*	(0^+)	
			3400.2 *9*	2.7 *3*	0^+	
			3431.8 *8*	11.2 *4*	0^+	
			3546.2 *7*	2.2 *2*	0^+	
			3569.6 *7*	3.0 *3*	0^+	3570.9 *12*
			3616.6 *8*	10.8 *4*	0^+	
			3626.4 *8*	24.6 *5*	0^+	3626.9 *5*
			3641.7 *8*	4.4 *4*	0^+	
			3691.7 *8*	22.2 *6*	0^+	
			3737.9 *11*	2.9 *7*	0^+	
			3819.2 *7*	2.4 *3*	(0^+)	
			3829.1 *6*	5.5 *4*	0^+	
			3848.2 *8*	2.8 *3*	0^+	
			3876.1 *6*	5.6 *4*	0^+	
			3984.9 *6*	7.8 *4*	0^+	
			4220.4 *6*	2.7 *4*	0^+	
			4258.1 *6*	3.6 *4*	0^+	

[a] No γ-ray decay observed in Ref. [36]. Energies adopted from Ref. [9].

[b] The peak at 1952.4 keV is hidden by a much stronger peak at 1957.3 keV.

[c] Data from Ref. [42].

orbitals close to the Fermi surface have been used as the transfer configurations. For ^{158}Gd and ^{160}Gd such configurations include the orbitals which correspond to those in the spherical potential, namely, $1h_{9/2}$, $2f_{5/2}$, $1i_{13/2}$, and $1h_{11/2}$. The DWBA angular-distribution shapes depend to some extent on the transferred configurations. The most noticeable difference is obtained for the angular distribution at the $(1i_{13/2})^2$ transfer configuration. For other configurations, one finds a different height of the maximum at about 20° and minor displacements of the minimum. In addition, since the excited 0^+ states must consist of many terms in the wave function with a coherent summation of the individual amplitudes, this difference allows one to obtain a better fit to the experimental angular distributions by using mixed configurations. These configurations are shown in Fig. 3. Two transfer components are presented: the first one is the main constituent while the second one improves the fit to the peak at 20° and to the minimum at about 15°–18°. Their admixture does not exceed 10%.

In Fig. 3, the experimental cross sections are given in μb/sr and their values are plotted with error bars while the Q-corrected CHUCK3 calculations are shown by full lines. The solid (red) lines present the firm assignments while the solid (blue) lines show tentative assignments. The results of this study concerning 0^+ states as compared to previous studies are collected in Table II.

Table II shows a comparison between the 0^+ levels found in the nucleus ^{158}Gd until now and states measured in the present experiments. Some levels with other spin values are also shown to help in the following discussion. Earlier known levels are basically taken from Refs. [9,36]. The $(n, n'\gamma)$ study in Ref. [36] gives a detailed discussion of the levels up to about 2.7 MeV, and some of the energy levels previously proposed in Ref. [9] are revised (rejected or modified). Note that for higher energies, above 2.7 MeV, one cannot make precise correspondences between previous and present levels, as discussed below.

For the states below 1743.2 keV we measured only the absolute cross sections at the angle 5°. They are shown in Table II. Their angular distributions were not measured. Therefore, their spins were not assigned in this work and are not shown in Table II. In what follows, we deal with details of the identification of the 0^+ states at higher energies which is performed in this study.

1743.2 keV. The level 1743.2 keV was assigned as 0^+ in the (n, γ) reaction [43] and the (t, p) reaction [44]. Confirmation of this assignment comes also from the (p, t) experiment of Lesher *et al.* [9] and from our study.

1936.5 keV. The NDS [41] includes a level of 1935.5(6) keV assigned as 0^+ referring to early studies of ^{158}Gd in the (p, t) reaction. Careful analysis of the energy spectra revealed a weak peak with an energy of 1936.5 keV. A peak with the energy 1937.5 was observed also in the YMKB study. Its measured angular distribution demonstrates the features inherent for the 0^+ states. However, the 0^+ assignment of this level is tentative because the statistics is not good enough and the angular distribution shape at small angles is not smooth.

1952.4 keV. The level 1954(7) keV was identified tentatively as 0^+ by Løvhøiden *et al.* [44]. A 0^+ level at 1952.425 ± 0.05keV had been also tentatively proposed from the neutron capture data [43] and from the $(n, n'\gamma)$ experiment [35]. A confirmation of this would be the observation of the 0^+ state in the (p, t) reaction. However, the 1952.4 keV state is not excited or excited very weakly so that the measurement of its angular distribution turned out to be impossible. Therefore, our data cannot confirm a 0^+ assignment for this state and only a tentative spin can be inferred from the γ-ray data.

1957.3 keV. Initially, a strong peak observed at 1953.5 keV and a weak one at 1960.1 keV were identified [9] with the 1952.4 and 1957.4 keV states, respectively. The latter were known from previous works to be 0^+ states [43,44]. These two peaks were reexamined in Ref. [36] by taking into account both the γ-ray transitions observed in the $(n, n'\gamma)$ experiment and the new YMKB energy calibration of the (p, t) reaction (Table I). The energy of the strong peak from the (p, t) reaction was adopted as 1956.96 keV, which fits the new YMKB value of 1957.1 keV, and coincides with the value of 1957.3 keV found in this experiment. The angular distribution of this state clearly indicates a 0^+ assignment.

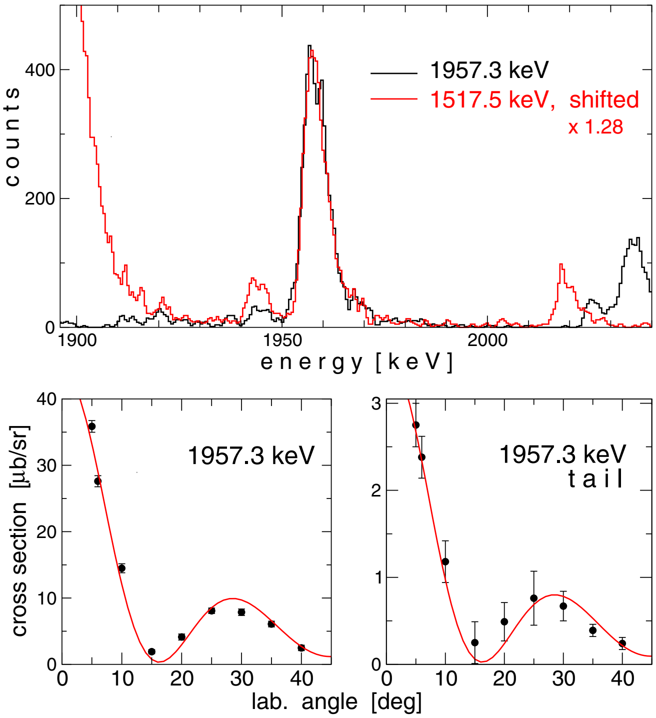

FIG. 4. Top: The shape of peak at 1957.3 keV and the peak at 1517.5 keV shifted and normalized to overlap with the 1957.3 keV peak. The two peaks have a very similar shape, including the shape of the tail. Both peaks are measured at angle 5°. Bottom: The angular distributions are related to the peak 1957.3 keV and its tail.

As for the putative level at 1960.1 keV, Ref. [36] rejected it, based on the fact that it is very likely represented by the tail of the strong 1957 keV level as shown by the YMKB spectra fits. We demonstrate this with the present data in Fig. 4. This figure shows that the 1957 keV peak has a tail which is identical to that of another peak from the spectrum. Moreover, this tail has an angular distribution similar to that of the peak.

Because of the difference in energies between the two experiments, as discussed above, and the lack of information concerning the energy calibration in Ref. [9], for the levels with higher excitation energies (up to 3.1 MeV) we have also attempted, in a similar way, to find a correspondence between the spectrum displayed in Fig. 1 of Ref. [9] and that from our experiment, Fig. 2. Although the two experiments were performed at different incident energies, and the spectrum in Ref. [9] was measured at 6° while ours was at 5°, the two spectra are rather similar in the overlapping region, and such a correspondence can be rather confidently established based on strong peaks from the two spectra. We have chosen for this purpose the peaks with energies 1957.3, 2276.7, 2333.4, 2632.7, and 2888.2 keV determined with our calibration, which are marked with a red asterisk in Fig. 2. In this way, also weaker peaks at 3041.7 and 3079.2 keV (marked by a black asterisk) could be put in correspondence with peaks of Ref. [9]. On this basis, we propose a correspondence between levels from the two works as shown in Table II (columns 1 and 4). However, it should be noted that because we did not dispose of the raw data of the spectrum shown in Fig. 1 of [9], this correspondence can be considered as tentative. In the following we discuss the next levels seen in our experiment, in the order of their energies determined in this work with the calibration based on the ^{172}Yb$(p,t)^{170}$Yb reaction.

1977.6 keV. A level at 1972(3) keV was identified as 0^+ in early studies in the (p,t) reaction [42]. At 1971(7) keV a level was assigned tentatively as 0^+ in the (t,p) reaction [44]. The angular distribution of a level at 1972.2(31) keV was measured by Lesher *et al.* [9] and 0^+ assignment for this level was not supported. A weak peak was found in our experiment at 1977.6 keV, which corresponds to that at 1977.9 keV of the YMKB study (Table I). Taking into account the energy shift, found out for the 1957 keV level and discussed above, this level may be associated with the 1972 keV one of Ref. [9]. The angular distribution clearly supports a 0^+ assignment for this state.

The assignments of 0^+ states at energies 1196.1, 1452.3, 1743.2, 1957.3, and 2276.7 keV were confirmed in Ref. [36] when studying the $(n,n'\gamma)$ reaction. The aim of that study was to define the collective nature of 0^+ excitations assigned in their previous work with the (p,t) reaction. The main way of decay of the low-lying 0^+ states is to the first excited state 2^+ at the energy of 79.5 keV as well as to some other states. Coincidences of γ rays both feeding and deexciting these states were found for all these states, confirming these assignments.

2276.7 keV. The energy 2276.7(4) keV found in this experiment to coincide with that of 2276.66(21) keV from Ref. [36]. The expected transition to the 2_1^+ level at 79.4 keV and its excitation function are strong confirmation of this assignment. The angular distribution clearly denotes the 0^+ assignment.

2333.4 keV. A state at 2338.0(8) keV was reported in Ref. [9] and assigned as 0^+. In the $(n,n'\gamma)$ reaction [36], such a level was identified at 2340.0 keV. However, the lack of angular distributions for the relevant γ rays decaying this state and only a tentative assignment of the transition to the first excited 2^+ state do not provide definite support for the 0^+ assignment. Additionally, the 2^+ level at 2340.3 keV was identified in the β decay of ^{158}Eu [45], decaying to the first 2^+ excited state. In this energy region we find only one state with the energy 2333.4(5) keV, which is also confirmed by the YMKB result (Table I). This energy differs from that of 2338 keV of Ref. [9] (see, however, the discussion of difference in energy calibrations for the 1957.3 keV state). The state 2333.4 keV is clearly different from the 2340 keV state found in Ref. [36]. As seen from Fig. 5, the angular distribution obtained in the present study for this level corresponds to a 4^+ spin assignment. The angular distribution with three angles obtained in the YMKB study confirms this assignment.

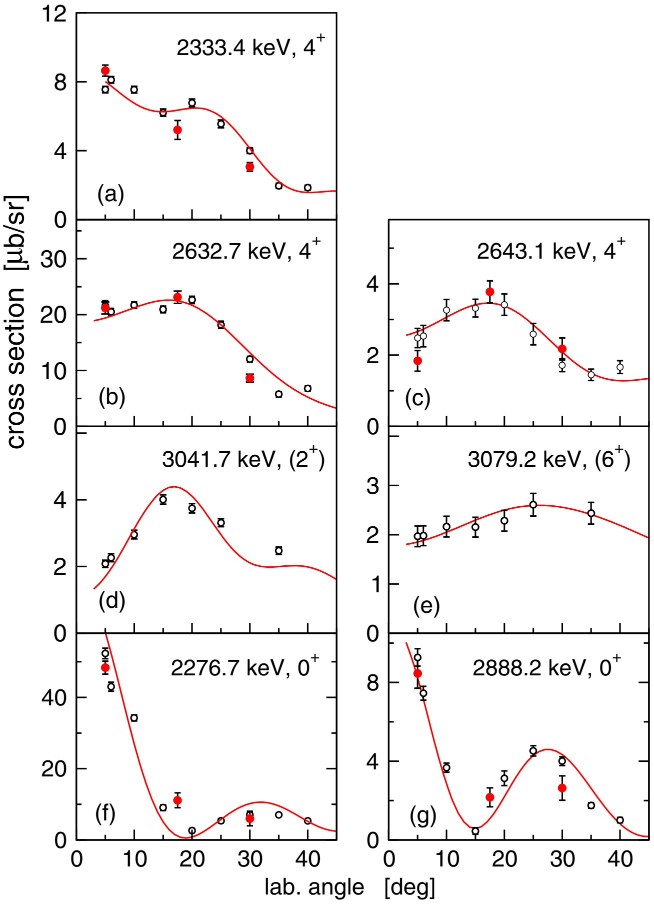

FIG. 5. Our angular distributions for the states assigned in Ref. [9] as 0^+ excitations. Open circles with bars are the results of the present work, filled red circles with bars are data from the YMKB study, and red lines are the CHUCK3 fit. The YMKB data at 25 MeV are renormalized to those at 22 MeV, the present data. Our results do not confirm the assignments for the energies 2333.4, 2632.7, 3041.7, and 3079.2 keV but confirm those for the energies 2276.7 and 2888.2 keV. The angular distribution for the energy of 2643.4 keV is included, because the state with the same energy as in Ref. [9] but with another spin 4^+ is also found in this study. See text for details.

A level at 2334 keV was also identified [46] in the (d,p) reaction, although as a 2^+ level.

2437.2 and 2445.9 keV. The angular distributions clearly indicate a 0^+ assignment for these states. This result was obtained for the first time in the present work.

2632.7 and 2643.1 keV. We think that the 2532.7 keV level (also confirmed by the YMKB result), according to the spectra correspondence discussed above, may correspond to the one at 2643.4(8) keV identified as a 0^+ excitation in Ref. [9]. A state with a close energy, 2644.18 keV, was observed in the $(n,n'\gamma)$ reaction [36]. The 2564.73 keV γ ray as the transition from this state to the first 2^+ state and its excitation function could be considered as confirmation of the above assignment. However, the angular distribution of the γ ray of 2564.73 keV is not isotropic. Therefore, the confident 0^+ assignment was not confirmed [36]. As seen from Fig. 5, the angular distribution for the 2632.7 keV level corresponds to the 4^+ spin assignment, also supported by the three-angle angular distribution of YMKB. For the 2643.1 keV level seen in our study we have to assign 4^+ too (Fig. 5). It is likely that this state can be identified with the 2644.18 keV one, for which the 0^+ assignment could not be confidently confirmed in Ref. [36].

2686.8 keV. A level with the energy 2689(7) keV was tentatively identified by Løvhøiden *et al.* [44] as a 0^+ state. A level at 2687.1(3) keV was specified tentatively as 4^+ by Greenwood *et al.* [43]. In Ref. [9] a weak state observed at 2688.8(8) keV was assigned as 0^+. A weak peak has been observed also in the present study at 2686.8(10) keV, for 5°, on the slope of a stronger peak 2679.6 keV, but its intensity for other angles did not allow us to obtain an angular distribution. The correspondence of this not very distinct peak with respect to the level of 2688.8 keV [9] is questionable.

2726.4 and 2757.2 keV. The angular distributions clearly denote 0^+ assignments. They are identified for the first time in the present study.

2888.2 keV. For this level we assign 0^+. According to the spectra correspondence discussed above, we think that this level corresponds to the 2911.2 keV, 0^+ level observed in Ref. [9].

2914.5 keV. The angular distribution indicates a 0^+ assignment for this level. This is a new level with spin 0^+ found in this work. It may be associated with the energy of 2913.4 keV in the spectrum of states excited by the radioactive capture of neutrons [43].

3041.7 and 3079.2 keV. According to our spectra correspondence (see discussion above) we think that these energies correspond to those of the 3076.7 and 3109.9 keV 0^+ states proposed in Ref. [9]. As seen clearly from Fig. 5, our measured angular distributions for these low-intensity peaks correspond to other spins, namely 2^+ and 6^+, respectively. We find other 0^+ states but at higher energies (see discussion below). It is clear that, in the absence of details about the energy calibration procedure used in Ref. [9], it becomes increasingly difficult to make correspondences with our results in this higher energy region.

We suggest that this mismatch between the results of Ref. [9] and those of the present experiment may indicate a different energy calibration used in Ref. [9] in the region of their higher energies (see the discussion of the 1957.1 keV state). Unfortunately, Ref. [9] does not give details about the energy calibration procedure.

In the higher energy interval from 3200 to 4300 keV we found 20 new 0^+ states. This energy region was not investigated before in (p,t) reactions. The total number of 0^+ excited states detected in one nucleus equals now 36, which is the largest number of such states observed so far. For five of them, the 0^+ assignment is tentative. For the states of 1936.5 and 3388.6 keV the reason is a low statistical accuracy. The tentative assignment for the state of 1952.4 keV is based on the γ transitions to the 1^- and 2^+ states, observed in the radioactive capture, and it is not based on the angular distribution from the (p,t) reaction.

3344.5 and 3819.2 keV. For these states the reason for tentative assignment is the absence of a deep minimum at an angle of about 17°. An overlap of another level with a very close energy could be a possible reason. At the same time the calculated angular distribution has such a form at the transfer of a pair of $i_{13/2}$ neutrons, if calculated for a low excitation energy (shown by dashed lines in Fig. 3). However, it is not possible to fit well the experimental angular distributions by using the reaction energies. Calculations for transfer of other angular momenta do not allow us to describe the experimental angular distributions and thus rule out other spin assignments. The perfect fitting for these two energies is questionable and, therefore, the 0^+ assignments for them are tentative.

For some of these states, their energies observed in the (n,γ) reaction [43] were found to be close within the error limits. Apart from the energies, there is no other information about these states. Therefore, one cannot be sure that these states and the ones observed in the (p,t) reaction are the same, although the close proximity of the energies obtained in the two independent experiments supports the validity of our calibration.

As already mentioned, theoretical models have relatively modest results for describing the spectra of multiple 0^+ excitations. The quantitative comparison of the calculated individual collective 0^+ states with accurate experimental data is still questionable. The point of the calculations was rather to see a number of 0^+ excitations in the energy range up to about 3 MeV, and a general trend in the cumulative cross section with increasing energy. Such calculations were performed within the frameworks of both the QPM and the spdf-IBM, in particular, for ^{158}Gd [10,11].

The IBM calculations yields a number of 0^+ states close to the experimental one below 3 MeV, and many of the 0^+ states are of a two-phonon octupole character, as seen from Fig. 6. However, the spdf-IBM fails to reproduce the increasing density of 0^+ states above 3 MeV. In addition, several other 0^+ states at higher excitation energy are calculated in Ref. [10], amounting to 23 excited 0^+ states below 4 MeV. The cross sections were not calculated in this publication since only the use of an extended Hamiltonian allows one to perform such calculations [47]. Therefore, the spdf-IBM reproduces the experimental level energies, at least for low excitation energies.

The cross sections were calculated [11] in the framework of the semimicroscopic QPM, using a reaction model that does not fully account for the dynamical dependence on the single-particle level. Therefore, these QPM results for 0^+ states are compared only qualitatively with their experimental spectra, as shown in Fig. 7. The QPM predicts a number of 0^+ states which is close to the one observed below 3 MeV. However, this very simplified model fails in the cross section calculation for the first excited state. This state is excited very weakly, which may indicate its β-vibrational nature. A large cross section [33% of the cross section for the ground state (g.s.)] is observed for the second excited 0^+ state, which is evidence of the similarity of its structure to the structure of the g.s.. In contrast to this, according to the QPM [11], one should expect a strong excitation just for the first excited 0^+ state, that shows its resemblance to the g.s., and very weak excitations for all other 0^+ states. Six of the QPM 0^+ states (mostly the lowest) have a clear one-phonon character.

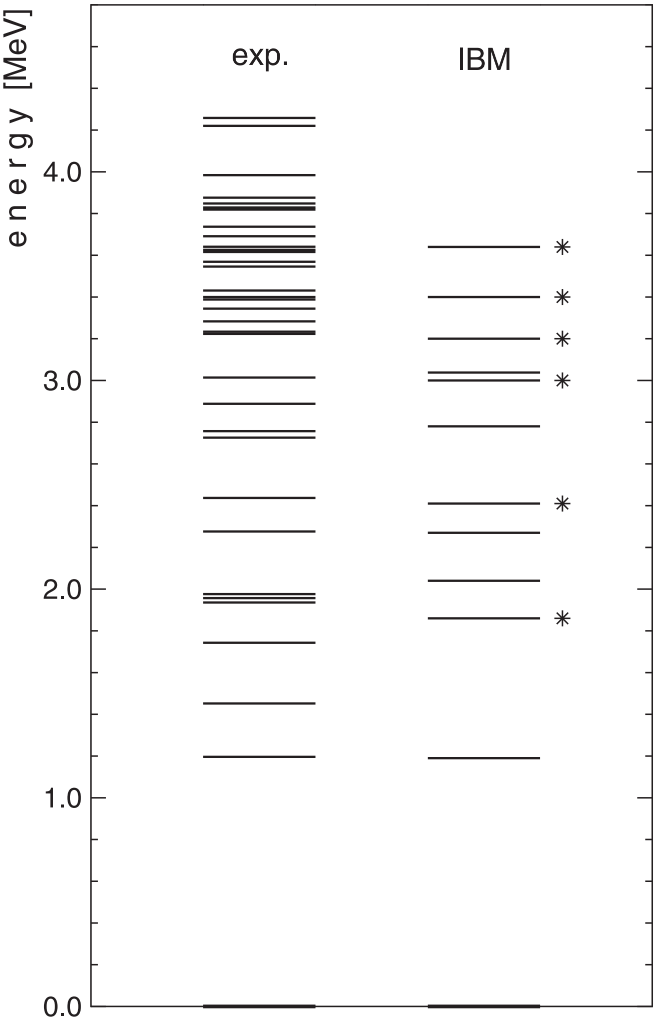

FIG. 6. The experimental 0^+ excitation energies compared with the calculations within the spdf-IBM. Stars on the calculated 0^+ states indicate levels with doubly octupole character.

Other states at higher excitation energy contain large, and, in many cases, dominant two-phonon components. They are built on the collective octupole phonons almost in all cases, in qualitative agreement with the IBM calculation [10,11,15].

There is one additional aspect of such studies. The QPM predicts an increase of the number of 0^+ states and a decrease of their excitation cross sections in the (p,t) reaction with increasing excitation energy [15]. Their structure becomes more complicated and octupole components in the wave function play an increasing role. The experimental spectrum of 0^+ states presented in Fig. 7 demonstrates a somewhat different picture. An increased density of states is observed in the region between 3.2 and 4.0 MeV and, if there is no termination of the spectrum, a drop in the magnitude of the density of 0^+ states is then seen in experimental data. New experimental data in the extended energy region are an excellent opportunity to test and develop the QPM calculations toward the quantitative level of the microscopic description of the collective 0^+ states, as well as other theoretical nuclear models.

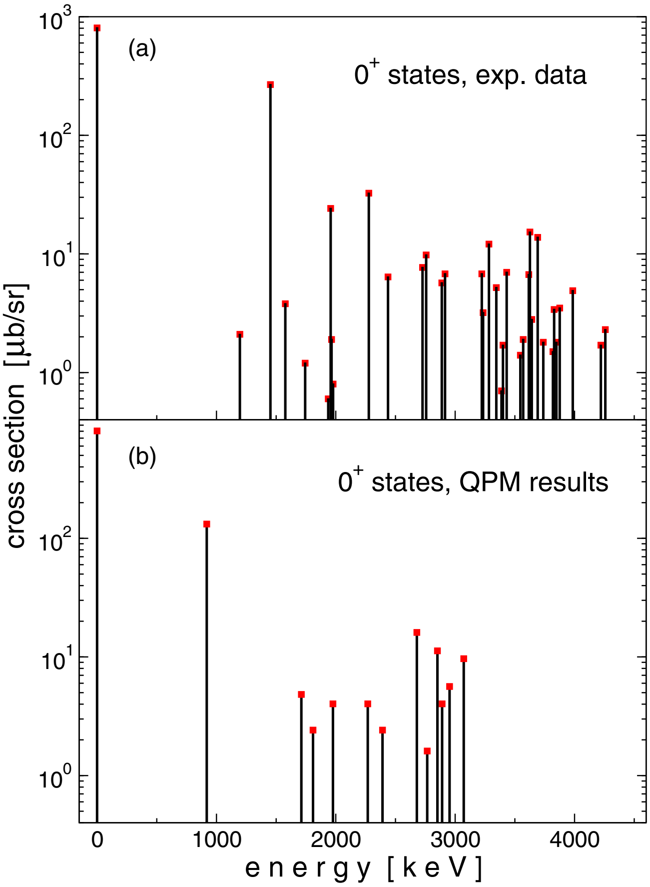

FIG. 7. The (p,t) cross sections at the angle 5° for 0^+ states in ^{158}Gd: experimental data (a) and calculated in the framework of the QPM (b).

III. CONCLUSIONS

We carried out a new high-precision (p,t) reaction on an isotopically enriched target of ^{160}Gd which allowed us to identify 32 excited 0^+ states below 4.3 MeV in the spectrum of ^{158}Gd (28 with firm assignment). Our experimental results and their analysis are advanced also in the accuracy of the obtained new 0^+ states and in improving the information for several known levels. Thus, the total number of 0^+ excited states in this nucleus is increased now to 36. Such abundance of 0^+ states was not previously observed in any nucleus investigated so far. The new information may be interesting, especially among theoreticians, because several models were already applied in an attempt to understand the nature of these states. Much richer new information should attract the attention of both theoreticians and experimentalists since the observation of 36 excited 0^+ states (including tentative assignments) in one nucleus is the strongest challenge to our understanding of these excitations. In a forthcoming analysis of the obtained experimental data, the 2^+ and 4^+ states and possible other levels with positive and negative parity will be assigned. As in our previous publications this can allow building collective bands with the 0^+ states as bandheads, which result in further support for the collectivity of some of these states. The data from the (p,t) reaction are interesting in one more aspect. As noted above, complete or almost complete sequences of states of collective nature with a definite J^π are available from this reaction. This allows one to carry out statistical analyses of these spectra with the aim of clarifying the measure of order and chaos in nuclear spectra [48,49]. Moreover, such studies are helpful in the formation of sequences of states which can be interpreted as collective bands based on 0^+ and other states. Collective bands with different K for the 2^+ and 4^+ bandheads can be formed, and this opens up a new possibility to investigate K-symmetry breaking [49].

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[1] V. G. Soloviev, *Theory of Atomic Nuclei: Quasiparticles and Phonons* (IOP, Bristol, 1992).

[2] R. F. Casten and D. D. Warner, Rev. Mod. Phys. **60**, 389 (1988), and references therein.

[3] V. G. Soloviev, A. V. Sushkov, and N. Yu. Shirikova, Nucl. Phys. **568**, 244 (1994); J. Phys. G: Nucl. Part. Phys. **20**, 113 (1994); Phys. Rev. C **51**, 551 (1995); Phys. At. Nucl. **59**, 51 (1996); **60**, 1599 (1997).

[4] R. E. Griffin, A. D. Jackson, and A. B. Volkov, Phys. Lett. B **36**, 281 (1971).

[5] W. I. van Rij and S. H. Kahana, Phys. Rev. Lett. **28**, 50 (1972).

[6] D. R. Bess, R. A. Broglia, and B. Nilsson, Phys. Lett. B **40**, 338 (1972).

[7] P. E. Garrett, J. Phys. G: Nucl. Part. Phys. **27**, R1 (2001).

[8] A. Bohr and B. R. Mottelson, *Nuclear Structure* (World Scientific, Singapore, 1998), Vol. 2.

[9] S. R. Lesher, A. Aprahamian, L. Trache, A. Oros-Peusquens, S. Deyliz, A. Gollwitzer, R. Hertenberger, B. D. Valnion, and G. Graw, Phys. Rev. C **66**, 051305(R) (2002).

[10] N. V. Zamfir, J.-Y. Zhang, and R. F. Casten, Phys. Rev. C **66**, 057303 (2002).

[11] N. Lo Iudice, A. V. Sushkov, and N. Yu. Shirikova, Phys. Rev. C **70**, 064316 (2004).

[12] Murat Gerceklioglu, Phys. Rev. C **82**, 024306 (2010).

[13] N. V. Zamfir and D. Kusnezov, Phys. Rev. C **63**, 054306 (2001).

[14] N. V. Zamfir and D. Kusnezov, Phys. Rev. C **67**, 014305 (2003).

[15] N. Lo Iudice, A. V. Sushkov, and N. Yu. Shirikova, Phys. Rev. C **72**, 034303 (2005).

[16] J. Lebert, J.-P. Delaoche, M. Girod, H. Coutte, S. Hillaire, S. Peru, N. Pillet, and S. F. Bertsch, J. Phys.: Conf. Ser. **205**, 012007 (2010).

[17] J. P. Delaroche, M. Girod, J. Libert, H. Goutte, S. Hilaire, S. Peru, N. Pillet, and G. F. Bertsch, Phys. Rev. C **81**, 014303 (2010).

[18] L. M. Robledo and G. F. Bertsch, Phys. Rev. C **84**, 054302 (2011).

[19] R. Rodriguez-Guzman, L. M. Robledo, and P. Sarriguren, Phys. Rev. C **86**, 034336 (2012).

[20] H. Baltzer, J. de Boer, A. Gollwitzer, G. Graw, C. Günther, A. I. Levon, M. Loewe, H. J. Maier, J. Manns, U. Müller, B. D. Valnion, T. Weber, and M. Würkner, Z. Phys. A **356**, 13 (1996).

[21] A. I. Levon, J. de Boer, G. Graw, R. Hertenberger, D. Hofer, J. Kvasil, A. Lösch, E. Müller-Zanotti, M. Würkner, H. Baltzer, V. Grafen, and C. Günther, Nucl. Phys. A **576**, 267 (1994).

[22] A. M. Oros, P. von Brentano, R. V. Jolos, L. Trache, G. Graw, G. Cata-Danil, B. D. Valnion, A. Gollwitzer, and K. Heyde, Nucl. Phys. A **613**, 209 (1997).

[23] H.-F. Wirth, G. Graw, S. Christen, D. Cutoiu, Y. Eisermann, C. Günther, R. Hertenberger, J. Jolie, A. I. Levon, O. Möller, G. Thiamova, P. Thirolf, D. Tonev, and N. V. Zamfir, Phys. Rev. C **69**, 044310 (2004).

[24] A. I. Levon, G. Graw, Y. Eisermann, R. Hertenberger, J. Jolie, N. Yu. Shirikova, A. E. Stuchbery, A. V. Sushkov, P. G. Thirolf, H.-F. Wirth, and N. V. Zamfir, Phys. Rev. C **79**, 014318 (2009).

[25] A. I. Levon, G. Graw, R. Hertenberger, S. Pascu, P. G. Thirolf, H.-F. Wirth, and P. Alexa, Phys. Rev. C **88**, 014310 (2013).

[26] A. I. Levon, P. Alexa, G. Graw, R. Hertenberger, S. Pascu, P. G. Thirolf, and H.-F. Wirth, Phys. Rev. C **92**, 064319 (2015).

[27] M. Spieker, D. Bucurescu, J. Endres, T. Faestermann, R. Hertenberger, S. Pascu, S. Skalacki, S. Weber, H.-F. Wirth, N. V. Zamfir, and A. Zilges, Phys. Rev. C **88**, 041303(R) (2013).

[28] M. Spieker, S. Pascu, D. Bucurescu, T. M. Shneidman, T. Faestermann, R. Hertenberger, H.-F. Wirth, N. V. Zamfir, and A. Zilges, Phys. Rev. C **97**, 064319 (2018).

[29] D. A. Meyer, V. Wood, R. F. Casten, C. R. Fitzpatrick, G. Graw, D. Bucurescu, J. Jolie, P. von Brentano, R. Hertenberger, H.-F. Wirth, N. Braun, T. Faestermann, S. Heinze, J. L. Jerke, R. Krücken, M. Mahgoub, O. Möller, D. Mücher, and C. Scholl, Phys. Rev. C **74**, 044309 (2006); J. Phys. G **31**, S1399 (2005); Phys. Lett. B **638**, 44 (2006).

[30] D. Bucurescu, G. Graw, R. Hertenberger, H.-F. Wirth, N. Lo Iudice, A. V. Sushkov, N. Yu. Shirikova, Y. Sun, T. Faestermann, R. Krücken, M. Mahgoub, J. Jolie, P. von Brentano, N. Braun, S. Heinze, O. Möller, D. Mücher, C. Scholl, R. F. Casten, and D. A. Meyer, Phys. Rev. C **73**, 064309 (2006).

[31] L. Bettermann, S. Heinze, J. Jolie, D. Mücher, O. Möller, C. Scholl, R. F. Casten, D. A. Meyer, G. Graw, R. Hertenberger, H.-F. Wirth, and D. Bucurescu, Phys. Rev. C **80**, 044333 (2009).

[32] G. Ilie, R. F. Casten, P. von Brentano, D. Bucurescu, T. Faestermann, G. Graw, S. Heinze, R. Hertenberger, J. Jolie, R. Krücken, D. A. Meyer, D. Mücher, C. Scholl, V. Werner, R. Winkler, and H.-F. Wirth, Phys. Rev. C **82**, 024303 (2010).

[33] C. Bernards, R. F. Casten, V. Werner, P. von Brentano, D. Bucurescu, G. Graw, S. Heinze, R. Hertenberger, J. Jolie, S. Lalkovski, D. A. Meyer, D. Mücher, P. Pejovic, C. Scholl, and H.-F. Wirth, Phys. Rev. C **87**, 024318 (2013).

[34] H.-F. Wirth, Ph.D. thesis, Technische Universität München, 2001 (unpublished), https://mediatum.ub.tum.de/602907.

[35] L. I. Govor, A. M. Demidov, and I. V. Mikhailov, Phys. At. Nucl. **64**, 1254 (2001).

[36] S. R. Lesher, J. N. Orce, Z. Ammar, C. D. Hannant, M. Merrick, N. Warr, T. B. Brown, N. Boukharouba, C. Fransen, M. Scheck, M. T. McEllistrem, and S. W. Yates, Phys. Rev. C **76**, 034318 (2007).

[37] F. Riess, Beschleunigerlaboratorium München, Annual Report, 1991 (unpublished), p. 168.

[38] P. D. Kunz, computer code CHUCK3, University of Colorado (unpublished).

[39] F. D. Becchetti and G. W. Greenlees, Phys. Rev. **182**, 1190 (1969).

[40] E. R. Flynn, D. D. Amstrong, J. G. Beery, and A. G. Blair, Phys. Rev. **182**, 1113 (1969).

[41] N. Nica, Nucl. Data Sheets **141**, 1 (2017).

[42] D. G. Fleming, C. Günther, G. Hagemann, B. Herskind, and P. O. Tjøm, Phys. Rev. C **8**, 806 (1973).

[43] R. C. Greenwood, C. W. Reich, H. A. Baader, H. R. Koch, D. Breitig, O. W. B. Schult, B. Fogelberg, A. Backlin, W. Mampe, T. von Egidy, and E. Schreckenbach, Nucl. Phys. A **304**, 327 (1978).

[44] G. Løvhøiden, T. F. Thorsteinsen, E. Andersen, M. F. Kiziltan, and D. G. Burke, Nucl. Phys. A **494**, 157 (1989).

[45] R. C. Greenwood, M. H. Putnam, and K. D. Watts, Nucl. Instrum. Methods Phys. Res. A **378**, 312 (1996).

[46] W. N. Shelton and R. K. Sheline, Z. Phys. **242**, 368 (1971).

[47] S. Pascu, N. V. Zamfir, Gh. Cata-Danil, and N. Marginean, Phys. Rev. C **81**, 054321 (2010).

[48] A. I. Levon, A. G. Magner, and S. V. Radionov, Phys. Rev. C **97**, 044305 (2018).

[49] A. G. Magner, A. I. Levon, and S. V. Radionov, Eur. Phys. J. A **54**, 214 (2019).