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Particle-γ coincidence spectroscopy of the N = 90 nucleus ^{154}Gd by $(\mathrm{p}, \mathrm{t}\gamma)$

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Abstract. A segmented Si-telescope and HPGe array, STARS-LIBERACE, was used to study the ^{156}Gd(p, tγ)^{154}Gd direct reaction by particle-γ coincidence spectroscopy. New cross sections with a 25 MeV proton beam are reported and compared to previous (p, t) and (t, p) studies. Furthermore, additional evidence for coexisting $K^\pi = 0_1^+, 2_1^+$ and 0_2^+, 2_2^+ configurations at $N = 90$ is presented. Direct and indirect population patterns of the low-lying states are also explored. Review of the new and existing evidence favors an interpretation based on a configuration-dependent pairing interaction. The weakening of monopole pairing strength and an increase in quadrupole pairing strength could bring 2p-2h 0^+ states below 2Δ. This may account for a large number of the low-lying 0^+ states observed in two-nucleon transfer reactions. A hypothesis for the origin of the 0_2^+ and 0_3^+ states is provided.

1 Introduction

The $N = 90$ region has long been the subject of considerable interest due to a rapid change from "vibrational" to "rotational" character [1], revealed by the $E(4_1^+)/E(2_1^+)$ energy ratio in fig. 1, and rich display of excited states below 2 MeV [2]. Traditional interpretations of these excited states have been largely based on collective rotations and vibrations about the average β and γ quadrupole shape parameters. Early descriptions were based on the adiabatic Bohr model [3] which assumed narrow and steep-sided β and γ potentials; this resulted in a simple description due to the decoupling of the vibrations and rotations and it provided a simple language for labeling and systematizing nuclear data. However, recent advances in the solution of the Bohr model within the Algebraic Collective Model (ACM) [4] have demonstrated that rotational bands exhibit unrealistically large mixing (centrifugal) effects when β or γ vibrations occur at low excitation energies, suggesting that the dominant character of the low-lying states may be more triaxial or non-collective in nature with the vibrational excitations at higher energies (see also page 220 of ref. [5]). Nevertheless, the nature of the excited states in these nuclei near $N = 90$ remains contested and elusive.

Over the past 15 years, there have been several studies [6–14] questioning the traditional interpretation of the excited states of $N \sim 90$ nuclei in terms of collective rotations and vibrations about the average β and γ quadrupole shape parameters. In particular, these experimental studies have suggested that the low-lying $K^\pi = 0^+, 4^+$ band heads may be predominantly two-quasiparticle in nature. Even before these studies, alternative explanations of the excited states (*e.g.*, 0^+ states) were offered [15–24], often

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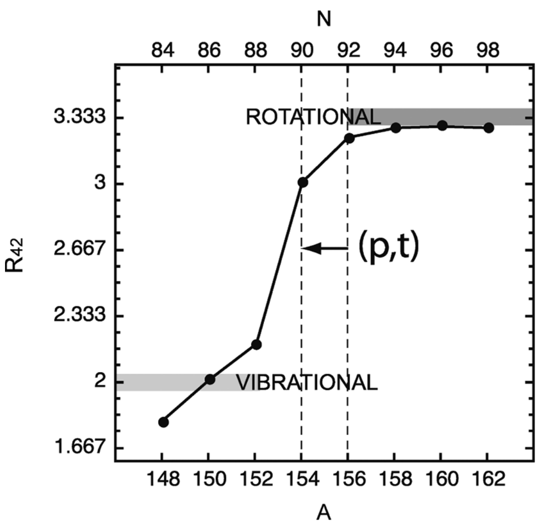

Fig. 1. $R_{42} = E(4_1^+)/E(2_1^+)$ systematics for Gd isotopes [2].

relying on microscopic concepts such as quadrupole pairing; a concept explored and adopted more widely for actinide nuclei [25–27].

The $(\mathrm{p,t})$ and $(\mathrm{t,p})$ two-neutron transfer reactions have been used extensively in populating low-spin, *e.g.*, 0^+ and 2^+, states. Several of these studies have been reported for the Gd and Sm isotopes [28–37] using magnetic spectrometers. In fact, the large cross sections to excited 0^+ states (*e.g.*, $\sim 15\%$ of the ground state) in the actinide region, lead to many of the original interpretations based on low-lying pair excitations, resulting from a weakening of the pairing force between oblate and prolate orbitals near the Fermi surface [25–27]. One of the leading original arguments for such an interpretation in the $N = 90$ region was made by Maher *et al.* [20] and Kolata and Oothoudt [21, 22] through the analysis of $(\mathrm{p,t})$ cross-section data but the final interpretation remained inconclusive.

During the 1990s, Chu *et al.* [23] demonstrated that relatively low-lying 0^+ states in the $N = 90$ region could be considered consistent with a configuration-dependent pairing interaction (*e.g.*, quadrupole pairing). In particular, they employed the Hamiltonian [38,23]

$$H = H_{\mathrm{SP}} + H_{\mathrm{gm}} + H_{\mathrm{gq}} + H_{\mathrm{rot}}, \tag{1}$$

where the components correspond to the single-particle energy, monopole pairing interaction, quadrupole pairing interaction, and rotational energy; the H_{gm} and H_{gq} terms are proportional to monopole and quadrupole pairing strengths, G_m and G_q, respectively. Please see ref. [23] for additional details. The quadrupole pairing interaction weakens the pairing between orbitals with different slopes and strengthens it between those with similar slopes. By using a non-zero quadrupole pairing strength, they were able to reproduce the $K^\pi = 0_2^+$ band in ^{154}Gd and crossing with the $K^\pi = 0_1^+$ ground-state band at $16\hbar$. Unfortunately, $(\mathrm{p,t})$ and $(\mathrm{t,p})$ cross sections with their wavefunctions were never reported. However, this work provided a crucial step in a microscopic understanding of the excited states near $N = 90$.

More recent $(\mathrm{p,t})$ studies of the Gd isotopes [36,37] have revealed a relatively large number of excited 0^+ states below 3 MeV, further challenging simple interpretations based on geometric- or hydrodynamic-based collective models. Early interpretations of these more recent results were largely based on added degrees of freedom within the Interacting Boson Model (IBM) [39], *i.e.*, by using a *spdf* Hamiltonian instead of the more common *sd* Hamiltonian. However, the authors conceded that many of the 0^+ states may be predominantly two-quasiparticle in character. Other early interpretations of the new $(\mathrm{p,t})$ results were made within the framework of the projected shell model [40], which concluded that many of the excited 0^+ states were of mixed nature based on quasiparticle and collective-vibration excitations; these calculations employed a quadrupole plus pairing Hamiltonian with a non-zero quadrupole-pairing term (similar to the work by Chu *et al.* [23]). While there have been other recent theoretical efforts [41–45], new developments are needed that include calculations of both $(\mathrm{p,t})$ and $(\mathrm{t,p})$ cross sections.

In this article, we further investigate the $N = 90$ region by studying ^{154}Gd with the $(\mathrm{p,t})$ reaction; this provides additional evidence to challenge the various interpretations. The present experiment differs from the past $(\mathrm{p,t})$ studies in this region by measuring particle-γ coincidences following the direct reaction. This enables a unique view that would otherwise require combining data from multiple experiments. In particular, we report new cross-section measurements and highlight various direct and indirect population patterns of the low-lying states. This technique has significant advantages over magnetic spectrometer studies when observing higher excitation energies where the level density is large, cf. refs. [46–50] for recent applications of the technique.

2 Experimental setup

The experiment was carried out at the 88-Inch Cyclotron of the Lawrence Berkeley National Laboratory. A 25 MeV proton beam was used to study the $^{156}\mathrm{Gd(p,t}\gamma)^{154}$Gd direct reaction and the particle-γ coincidences were measured with a large-area, double-sided, annular Si-telescope array (segmented into rings, θ, and sectors, ϕ) and an array of 6 Compton-suppressed HPGe clover detectors, STARS-LIBERACE [51]. The ΔE-E telescope covered lab angles of $\theta_{\mathrm{lab}} \approx 33°$–$51°$. The ^{156}Gd target was self-supporting and $825\,\mu\mathrm{g/cm}^2$ thick. The experimental conditions were identical to those described in ref. [46], which reported the $(\mathrm{p,d}\gamma)^{155}$Gd results of the present dataset.

3 Results and discussion

We begin the investigation with a look at the triton projection of the t-γ coincidence matrix, fig. 2. Broad peak-like features are observed for the first couple of MeV in excitation energy, corresponding to ensembles of directly populated states. Beyond this, population and decay of

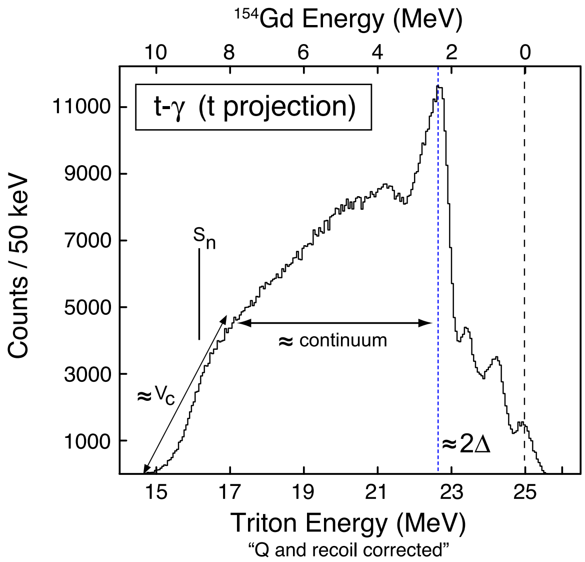

Fig. 2. The triton spectrum from the projection of a t-γ coincidence matrix. The energies have been corrected for the Q value and recoil of the $(\mathrm{p,t})^{154}$Gd reaction.

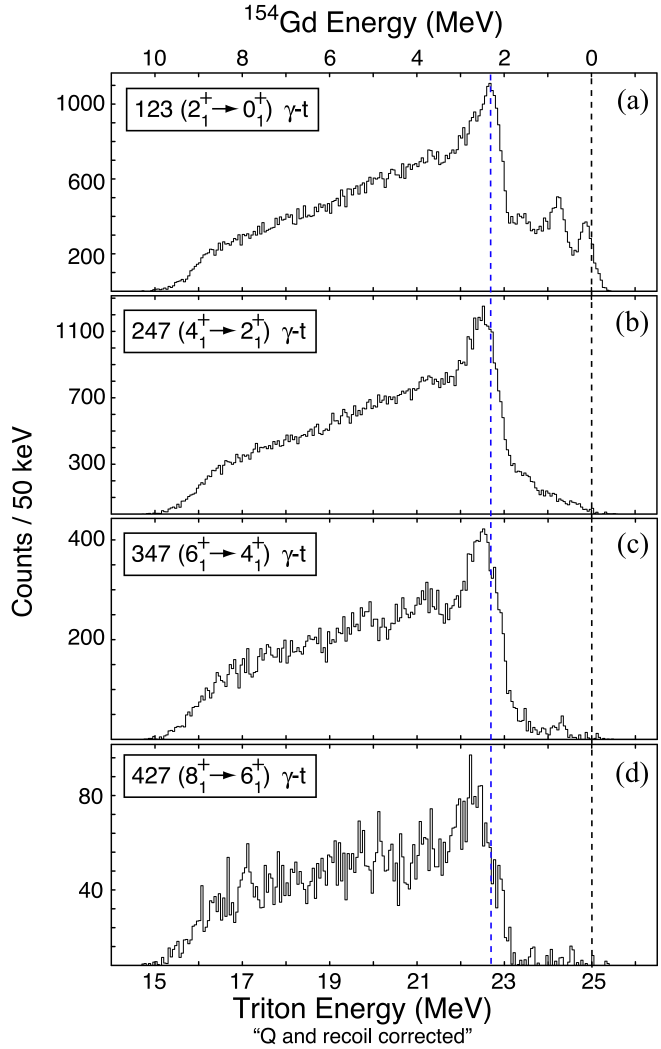

Fig. 3. The triton spectra from yrast γ-ray gates on a γ-t coincidence matrix of $(\mathrm{p,t})^{154}$Gd. A broad peak-like feature, which shifts towards larger energies from (a) to (d), is observed just above 2 MeV, representing an ensemble of states.

the continuum with compound (statistical) character is observed. Triton spectra from γ-ray gates on the yrast transitions are provided in fig. 3. The spectra are dominated by indirect population from higher-lying states, making any direct population of the $K^\pi = 0^+$ yrast states difficult to observe with the present resolution of $FWHM \sim 380$ keV. Interestingly, the broad "peak-like" feature just above 2 MeV remains and even shifts towards larger excitation energies with each successive yrast transition gate. This feature corresponds to several directly populated states with spins up to $7\,\hbar$, including the 7^- isomer (68 ns) at 2137 keV which is believed to be dominated by a $\nu\frac{3}{2}^+[651]+\nu\frac{11}{2}^-[505]$ component [2]. Curiously, no directly populated 0^+ states were observed within this broad feature, consistent with the observation made by Riezebos *et al.* [34] who reported an absence of monopole strength above 2 MeV for ^{156}Gd. However, Meyer *et al.* [37] reported 6 0^+ states above 2 MeV. Interestingly, few discrete γ-rays were observed to originate from the broad feature above 2 MeV (at least with the statistics of the present experiment). A similar broad "peak-like" feature was observed for the Sm isotopes [50] and within the $(\mathrm{p,d})^{155}$Gd results of the present data [46].

The first-excited 0^+ state of ^{154}Gd is at 681 keV, which can decay by a 558 keV γ-ray [2]. The triton spectrum in coincidence with the 558 keV γ-ray is shown in fig. 4. Direct population of the excited 0^+ state is observed. In addition, direct population of a state at 1533(9) keV, which then decays to the excited 0^+ state, is also observed. This higher-lying state corresponds to the 2^+ state at 1531 keV [2], confirmed by an 851 keV γ-ray gate. A similar pattern is observed upon placing a gate on the 692 keV γ-ray from the 2^+ member of the $K^\pi = 0_2^+$ band at 815 keV and the 716 keV γ decay from the 2^+ state at 1531 keV, cf. fig. 5. The level assignments are confirmed by the γ-γ coincidence spectra shown in fig. 6. Evidently, there is a strong connection between the $K^\pi = 0_2^+$ band and the 2^+ state at 1531 keV, believed to be a $K^\pi = 2_2^+$ band head. Note that the $K^\pi = 0_1^+, 2_1^+$ and $K^\pi = 0_2^+, 2_2^+$ band heads have similar energy spacings, 996 keV and 851 keV, respectively. A similar conclusion was drawn from a ^{154}Eu decay study by Kulp *et al.* [10]. This is further supported by the observation of an $E0$ transition between the $K = 2_2^+$ and $K^\pi = 2_1^+$ band heads [52]. Note that $E0$ transitions decay by $\Delta K = 0$. Similar $K^\pi = 0_2^+, 2_2^+$ bands were established by Kulp *et al.* [12] in a Coulomb excitation study of ^{152}Sm and by Kolata and Oothoudt [21,22] in a (p, t) study of ^{156,158}Dy. The 851 and 716 keV γ-ray gated triton spectra in fig. 4 and fig. 5, respectively, demonstrate the absence of any further excitations built upon the 2^+ state at 1531 keV. Curiously, Garrett *et al.* [13] reported coexisting $K^\pi = 0_1^+, 0_1^-$ and 0_2^+, 0_2^- bands in ^{152}Sm. The emerging picture is that the 0_2^+ state at 681 keV may be a non-collective excitation

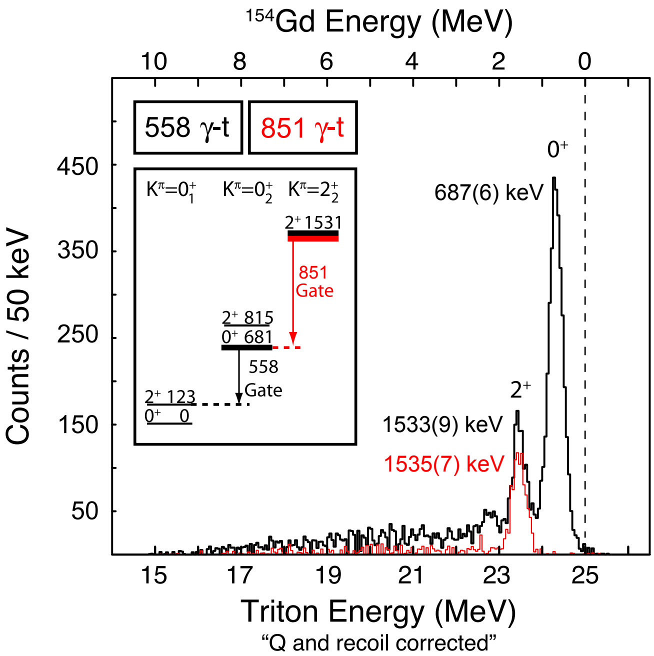

Fig. 4. The triton spectra in coincidence with the 558 keV (black) and 851 keV (red) γ-rays, revealing a link between the 0^+ state at 681 keV and 2^+ state at 1531 keV.

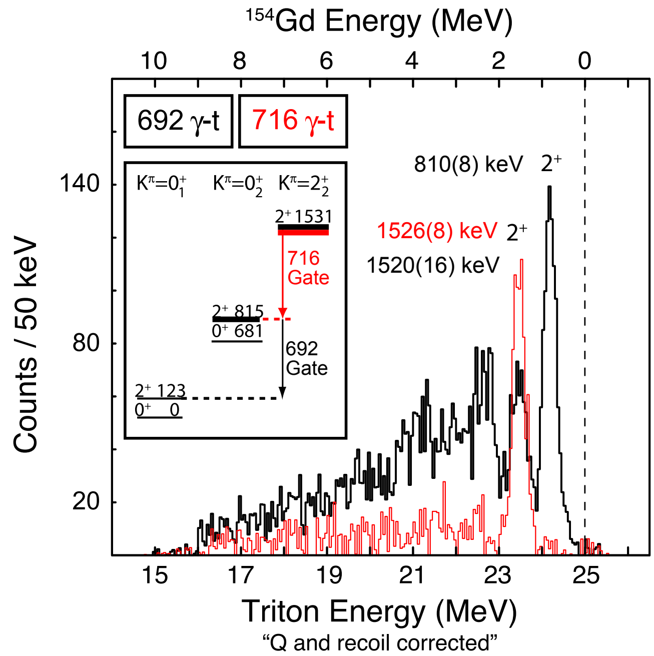

Fig. 5. The triton spectra in coincidence with the 692 keV (black) and 716 keV (red) γ-rays, revealing a link between the 2^+ state at 815 keV and 2^+ state at 1531 keV.

from which the collectivity built on the ground state is repeated. While a β vibration can provide a reasonable approximation to a $K^\pi = 0_2^+$ band, success of such a model is insufficient to necessitate the vibrational feature of the model. Even though the $B(E2; 0_2^+ \rightarrow 2_1^+)$ transition is relatively large, *i.e.*, 52(8) W.u. [2], strong configuration mixing provides an equally plausible explanation [53].

The only other excited 0^+ state observed in the present study resides at 1650 keV. Direct population of this state is demonstrated in fig. 7 through γ-ray gates on the 654 and 1527 keV decay branches. The population pattern of this excited 0^+ state is noticeably different than the first-excited 0^+ state at 681 keV. In particular, there is no observed higher-lying 2^+ state connected to it; this could be due to a difference in the average γ deformation from the ground state. The 654 keV decay branch has only been observed once before, which was reported in the thesis of Kulp [8]. The relative γ-ray branches for the 0^+ state at 1650 keV are $I_\gamma(654) = 146(16)$ to the 2^+ at 996 keV, $I_\gamma(835) = 23(9)$ to the 2^+ at 815 keV, and $I_\gamma(1527) = 100(17)$ to the 2^+ at 123 keV. The relative 835 and 1527 keV decay branches are in agreement with ENSDF [2]. The relative $B(E2)$ for the 654 keV decay to the $K^\pi = 2_1^+$ band head is the largest; this fact in combination with the existence of a $K^\pi = 4_1^+$ band head at 1646 keV is consistent with the expectation of a $\gamma\gamma$ vibration. However, a γ-ray gate on the 650 keV decay from the $K^\pi = 4_1^+$ band head, cf. fig. 8, reveals no direct population but feeding from two or more higher-lying states just above 2 MeV. Figure 9 reveals the γ-rays in coincidence with the 873 keV transition out of the $K^\pi = 2_1^+$ band head.

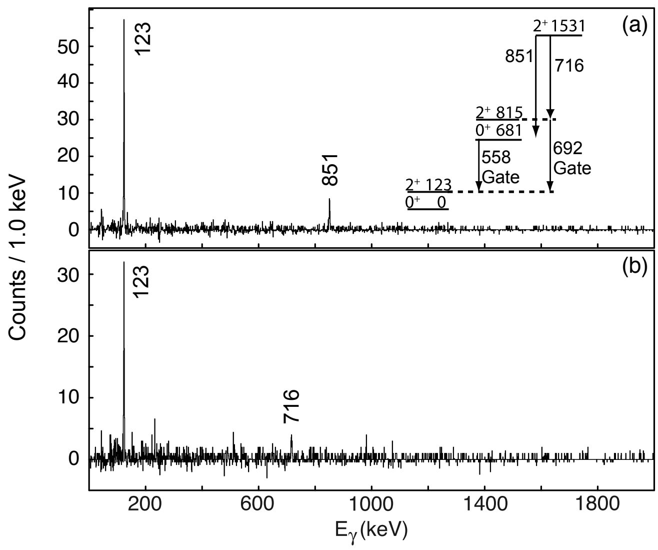

Fig. 6. The γ-ray spectra in coincidence with the (a) 558 keV and (b) 692 keV γ-rays. Only feeding transitions from the 2^+ state at 1531 keV are observed.

Burke *et al.* [6,7] argued against a $\gamma\gamma$-vibration interpretation of the $K^\pi = 4_1^+$ band head at 1646 keV in ^{154}Gd based on strong population following the ^{153}Eu(^{3}He, d) and (α, t) reactions. The state was determined to carry a $\pi\frac{5}{2}^+[413] + \pi\frac{3}{2}^+[411]$ admixture of 80%, explaining the lack of direct population in (p, t). Burke *et al.* concluded that many $K^\pi = 4^+$ $\gamma\gamma$ candidates are likely hexadecapole bands with large two-quasiparticle admixtures, which can have $B(E2)$ patterns that are similar to $\gamma\gamma$ vibrations.

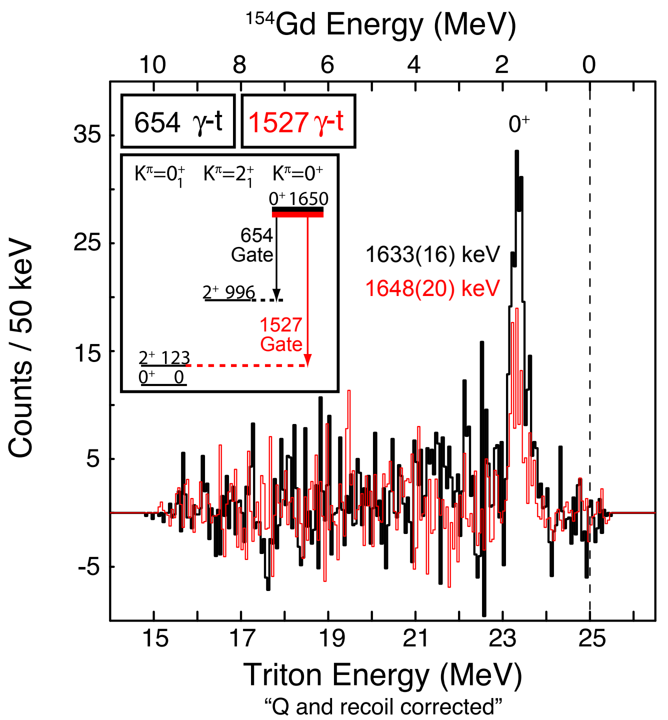

Fig. 7. The triton spectra in coincidence with the 654 keV (black) and 1527 keV (red) γ-rays. Only direct population of the 0^+ state at 1650 keV is observed, conspicuously different from the 558 keV gate in fig. 4.

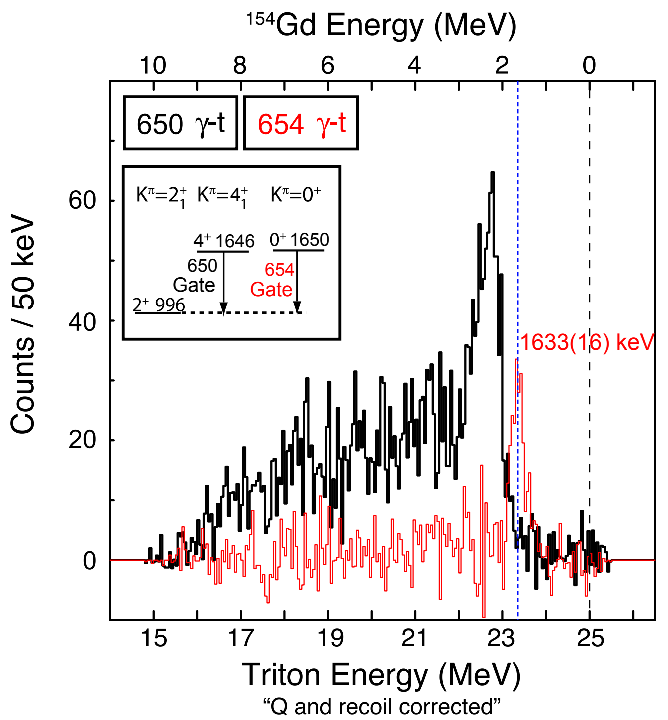

Fig. 8. The triton spectra in coincidence with the 650 keV (black) and 654 keV (red) γ-rays, revealing indirect population of the 4^+ state at 1646 keV and direct population of the 0^+ state at 1650 keV.

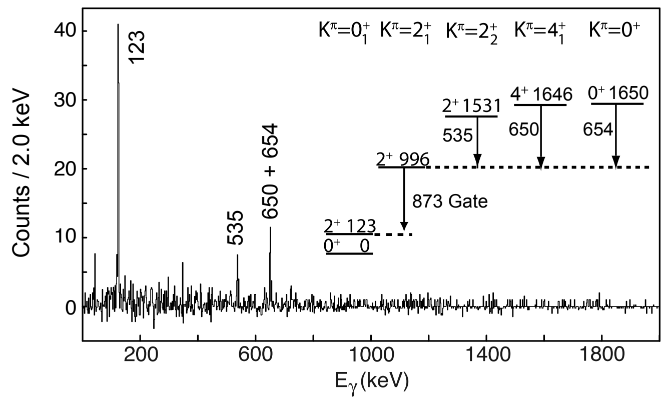

Fig. 9. The γ-ray spectra in coincidence with the 873 keV γ-ray transition, revealing decays from the 2^+, 4^+, and 0^+ states at 1531, 1646, and 1650 keV, respectively.

If the $K^\pi = 4_1^+$ band head at 1646 keV is not a $\gamma\gamma$ vibration, doubt would be cast on whether or not the 0^+ state at 1650 keV is either. It is important to note that the existence of a $\gamma\gamma$ vibration necessitates the existence of an excited $K^\pi = 0^+, 4^+$ pair (not necessarily at the same energy). Either way, the 0^+ state at 1650 keV appears strongly connected to the $K^\pi = 2_1^+$ band head.

Triton angular distributions for the states strongly populated in the (p, t) reaction were extracted in the same manner as reported for the recent $(p, d\gamma)^{155}$Gd study [46]. The 0^+ state at 681 keV and 2^+ states at 815, 996, and 1531 keV were all confirmed to agree with the adopted assignments [2]; a few examples are provided in fig. 10. The theoretical curves were calculated with the distorted-wave Born approximation (DWBA) code DWUCK4 [54] using the optical potential of ref. [32]. The calculations were renormalized to 100 at the largest value. There were insufficient statistics for a definitive 0^+ spin assignment for the state at 1650 keV.

The relative (p, t) cross sections for states directly populated in the present study are provided in table 1 and they are compared to the previous $(p, t)^{154}$Gd results by Fleming *et al.* [32] and Meyer *et al.* [37] and (t, p) results by Shahabuddin *et al.* [33]. A partial level scheme is given in fig. 11 which highlights the states directly populated in the present study; note that only states with similar deformation are strongly populated. The most striking feature is the large (p, t) and (t, p) cross sections and asymmetries to excited 0^+ and 2^+ states. While the first-excited 0^+ state is populated with 16% of the ground state and 31% of the 2_1^+ state (84% in the present study) in the (p, t) reaction [32], it is populated with less than 0.2% of the ground and 2_1^+ states in inelastic scattering [55]. Fleming *et al.* [32] were mostly limited to the lower lying states and Meyer *et al.* [37] only reported 0^+ candidate states. The strongly populated states in the present (p, t) study show qualitative agreement with the previous studies. However, there is a substantial quantitative difference in the population strength of the 2^+ states at 123 and 1531 keV. Based on DWBA calculations with the code DWUCK4 [54], the 2^+ state at 1531 keV may be smaller in the 18 MeV beam

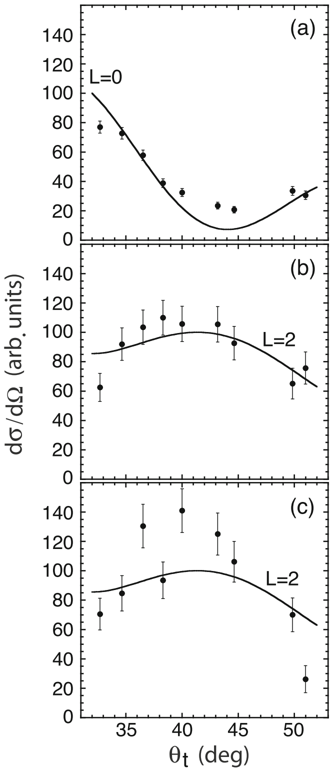

Fig. 10. Triton angular distributions for populating the (a) 0^+ state at 681 keV, (b) 2^+ state at 996 keV, and (c) 2^+ state at 1531 keV.

Table 1. Summary of $(\mathrm{p,t})$ and $(\mathrm{t,p})^{154}$Gd cross sections normalized to the ground state. The present results are normalized to the 681 keV level of ref. [32]. The beam energies were 25 MeV for the present study and ref. [37], 18 MeV for ref. [32], and 15 MeV for ref. [33].

E (keV)	I^π	$\sigma_{\mathrm{p,t}}^{33-51^\circ}$	$\mathrm{d}\sigma_{\mathrm{p,t}}^{30^\circ}$ [32]	$\mathrm{d}\sigma_{\mathrm{p,t}}^{30^\circ}$ [37]	$\mathrm{d}\sigma_{\mathrm{t,p}}^{30^\circ}$ [33]
0	0^+		100	100.0(6)	100
123	2^+	19(2)	51		6
371	4^+		3		1
681	0^+	16(1)*	16	13.9(1)	61
815	2^+	8.7(6)	7		3
996	2^+	15(1)	12		
1048	4^+	1.6(1)	< 1		< 1
1182	0^+			0.02(2)	52
1241	1^-	1.0(1)	< 1		
1252	3^-	4.4(3)	< 1		8
1264	4^+	1.2(1)	< 1		
1353	0^+			0.06(2)	
1404	5^-	0.9(1)			
1418	2^+		< 1		7
1498	0^+			0.02(2)	
1531	2^+	12(1)	4		
1574	0^+			0.29(2)	9
1650	0^+	2.4(3)		0.15(2)	
2137	7^-	3.4(2)			

data due a 40% drop in the $L = 2$ cross section from the ground to excited state; for the present 25 MeV beam data, the cross section actually increases by a few percent. It is not clear why there's a discrepancy in the 2_1^+ state at 123 keV, which is larger in the 18 MeV beam data. The situation is complicated by the fact that the local maxima in the angular distributions shift with beam energy and, unlike the magnetic spectrometer data, the present results are integrated over a larger range of angles, reducing the ability for a direct quantitative comparison. It is difficult to compare the cross sections more rigorously with the present calculations due to the assumption of a single-step reaction; coupled-channel and sequential-transfer effects may be important, particularly for yrast states. These effects must be factored out of the experimental cross sections for further comparison.

Within the detection efficiency and resolution of the present experimental setup, no population of the 0^+ states at 1182 or 1574 keV [2] was observed; they were weakly populated with 0.02(2)% and 0.29(2)% of the ground state in ref. [37]. By comparison, these states are populated with 52% and 9% strength of the ground state in the $(\mathrm{t,p})$ reaction [33], consistent with a recent assignment of the 1182 keV state as the band head of a weakly deformed "pairing isomer" [9]. The new 0^+ states at 1353 and 1498 keV reported in the recent $(\mathrm{p,t})$ study by Meyer *et al.* [37] were not observed either. Another $(\mathrm{p,t}\gamma)$ experiment with higher statistics and γ-γ detection efficiency is needed. One advantage in using γ-ray detection is that possible target contaminants can be more easily identified. Further $(\mathrm{p,t}\gamma)$ studies of odd-mass nuclei are also needed to pinpoint the underlying microscopic components of the wavefunctions. Fusion-evaporation studies of neighboring odd-mass nuclei would also be useful in surveying blocked excitations [14].

The large $(\mathrm{p,t})$ and $(\mathrm{t,p})$ cross sections and asymmetries to excited 0^+ and 2^+ states have traditionally provided the leading arguments for the involvement of pairing degrees of freedom in the nature of the excited states. However, due to the lack of robust quantitative theory predictions for the cross sections, we will limit the remaining discussion to a few simple observations and a qualitative interpretation of the results, particularly with respect to the nature of the excited 0^+ states.

A decay study of ^{154}Gd study by Kulp *et al.* [9] reported the existence of a more weakly deformed band built on the 0_3^+ state at 1182 keV (cf. fig. 11). Based on their results and the large asymmetries in the $(\mathrm{p,t})$ and $(\mathrm{t,p})$ cross sections, they concluded that the 0_3^+ state was a "pairing isomer" built on the fully occupied oblate driving $\nu\frac{11}{2}^-[505]$ orbital (associated with a reduced pairing strength). In a more recent fusion-evaporation study of ^{155}Gd by Sharpey-Schafer *et al.* [14], the existence of $0_2^+\otimes\nu\frac{3}{2}^-[521]$ and $0_2^+\otimes\nu\frac{3}{2}^+[651]$ excitations and a blocked $0_2^+\otimes\nu\frac{11}{2}^-[505]$ excitation was reported. Their conclusion

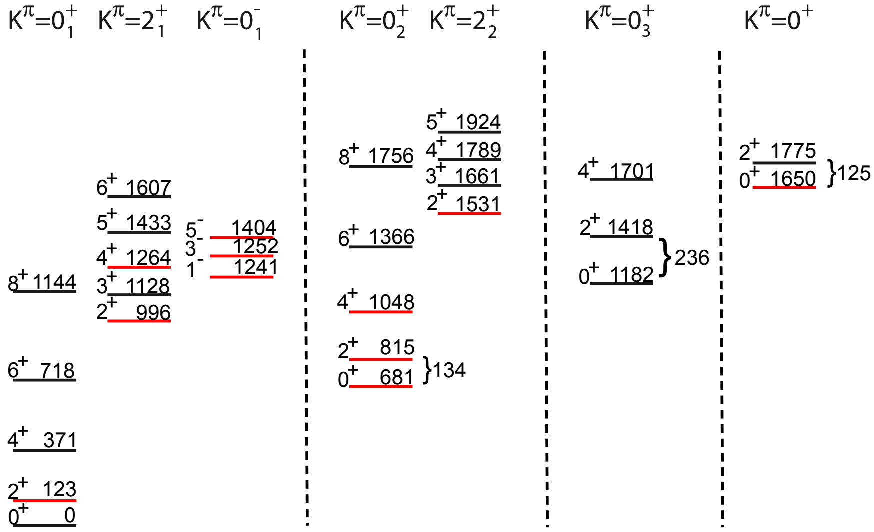

Fig. 11. A partial level scheme of ^{154}Gd, which highlights (red) the directly populated states measured in the present study. The vertical dashed lines separate the individual subspaces, assuming the excited 0^+ states are band heads of two-quasiparticle excitations; Note that only states with similar deformation are strongly populated. The 7^- band head at 2137 keV has been excluded.

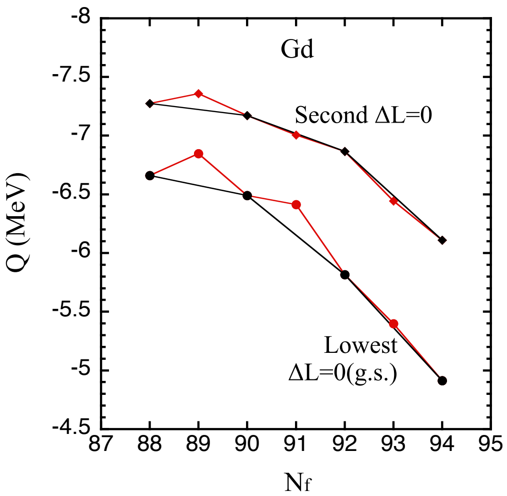

Fig. 12. The Q-value systematics for the first two $L = 0$ transfers of the (p, t)Gd$_{N_f}$ reactions. The difference in staggering between $N_f = 90$ and 92 suggests a configuration-dependent pairing interaction, cf. ref. [27].

was that the 0_2^+ state was built on the fully occupied $\nu\frac{11}{2}^-[505]$ orbital. On the surface, it appears that there is a conflict in these two recent interpretations. However, it may be possible that they are both correct. In particular, only the occupation of the $\nu\frac{11}{2}^-[505]$ orbital was discussed, *i.e.*, the 2p of the 2p-2h configuration. The difference in the 0_2^+ and 0_3^+ states may rest in the 2h component of the configuration.

A signature for a configuration-dependent pairing interaction that is less recognized resides in the degree of staggering of (p, t) Q values for the first and second $L = 0$ transfers, demonstrated by Friedman *et al.* [27] for the U and Pu isotopes. The (p, t) Q values for the gadolinium isotopes are given in fig. 12 as a function of the final neutron number, N_f. In particular, there is an odd-even staggering between $N_f = 90$ and 92 for the first $L = 0$ but not for the second. To the best of our knowledge, this has never been reported or recognized for the $N = 90$ region. The odd-even staggering of the Q values for the first $L = 0$ transfer is simple to understand in terms of blocking. In particular, the odd $\nu\frac{3}{2}^-[521]$ neutron, which defines the ground state of the odd-mass isotopes, blocks the orbital from contributing to the pair correlation energy. However, the Q value for the second $L = 0$ transfer, which corresponds to population of the $0_2^+ \otimes \nu\frac{3}{2}^-[521]$ state, does not reveal any blocking effect. The first conclusion is that the odd neutron, $\nu\frac{3}{2}^-[521]$, has no role in the 0_2^+ excitation. If it did, the $0_2^+ \otimes \nu\frac{3}{2}^-[521]$ state would be blocked. Ultimately, the lack of any odd-even staggering in the second $L = 0$ Q value supports the idea that there exists a neutron orbital with a reduced pairing strength. What remains is the identification of the leading 2p-2h configuration that results in the 0_2^+ excitation.

Other than the ground state $\nu\frac{3}{2}^-[521]$ orbital, which has no role in the 0_2^+ excitation (see above), the two orbitals closest to the Fermi surface are $\nu\frac{11}{2}^-[505]$ and $\nu\frac{3}{2}^+[651]$. Because the $0_2^+ \otimes \nu\frac{3}{2}^+[651]$ excitation was observed [14], the $\nu\frac{3}{2}^+[651]$ orbital must have no role in the 0_2^+ excitation either. According to our recent results on the (p, d)^{155}Gd reaction [46], the largest cross section is to the up-sloping $\nu\frac{1}{2}^+[400]$ orbital. Now consider the following: 1) $\nu\frac{11}{2}^-[505]^{+2}$ would decrease the deformation, and 2) $\nu\frac{1}{2}^+[400]^{-2}$ would increase the deformation. Therefore, we conclude that the leading configuration of the 0_2^+ excitation may be based on $\nu\frac{11}{2}^-[505]^{+2}$-$\nu\frac{1}{2}^+[400]^{-2}$, which could preserve the deformation close to the ground-state value. The leading configuration of the 0_3^+ excitation may be based on $\nu\frac{11}{2}^-[505]^{+2}$-$(X)^{-2}$, where X is likely a more shallow sloped orbital that is weakly populated in the (p,d) reaction [46]. More evidence is needed before speculating any further. Additional two-nucleon and fusion-evaporation studies of the odd-mass isotopes would be useful to further investigate the 0_3^+ excitation, which could support or disprove some of the present ideas.

4 Summary

In summary, the $^{156}\mathrm{Gd}(\mathrm{p},\mathrm{t}\gamma)^{154}\mathrm{Gd}$ direct reaction was studied by particle-γ coincidence measurements. New (p,t) cross sections are reported and additional evidence for coexisting $K^\pi = 0_1^+, 2_1^+$ and $0_2^+, 2_2^+$ bands at $N = 90$ is presented based on (p,t) Q values and population and decay patterns. Furthermore, a possible $K^\pi = 0^+$ band head at 1650 keV was observed with a different direct and indirect population pattern from that of the $K^\pi = 0_2^+$ band head; possibly the result of a different average γ deformation. Review of the new and existing evidence favors an interpretation based on a configuration-dependent pairing interaction. The weakening of monopole pairing strength and an increase in quadrupole pairing strength could bring 2p-2h 0^+ states below 2Δ. This may account for a large number of the low-lying 0^+ states. Based on the (p,t) Q values and blocking arguments, a new hypothesis is given on the origin of the 0_2^+ and 0_3^+ excitations. It is our hope that this work stimulates much needed microscopic-based theory development that can consistently describe the excitation energies, transition probabilities, and (p,t) and (t,p) cross sections to enable a more definitive conclusion on the nature of low-lying states at $N = 90$.

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