Triplet energy differences and the low lying structure of ^{62}Ga

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(Dated: May 19, 2015)

The systematic behavior of triplet energy differences (TED) of $T = 1$, $J^\pi = 2^+$ states is examined. The $A = 62$ isobar is identified as deviating significantly from an otherwise very consistent trend. This deviation can be attributed to the tentative assignments of the pertinent states in ^{62}Ga and ^{62}Ge. An in-beam γ-ray spectroscopy experiment was performed to identify excited states in ^{62}Ga using GRETINA with the S800 spectrometer at NSCL. Cross-section calculations indicate that the relevant $T = 1$, 2^+ state should be one of the states directly populated in this reaction. Using the systematics as a guide, a candidate for the transition from the $T = 1$, 2^+ state is identified. However, previous work has identified similar states with different J^π assignments. As spins and parities were not measurable, it is concluded that an unambiguous identification of the first $T = 1$, 2^+ state is required to reconcile our understanding of TED systematics.

PACS numbers: 21.10.Hw, 21.10.Sf, 29.30.Kv, 29.38.Db

The concept of charge independence in nuclear structure physics implies that nucleon-nucleon interactions are the same for neutron-neutron (V_{nn}), proton-proton (V_{pp}) and neutron-proton (V_{np}) pairs. Isospin was introduced [1] to facilitate this concept by treating the proton and neutron as fermions of the same isospin, t, distinguished by the isospin projection, t_z. The assumption of an isoscalar ($V_{nn} = V_{pp} = V_{np}$) interaction is only approximate due to small charge-dependent components of the nuclear interaction. In addition, electromagnetic contributions such as the (electromagnetic) spin-orbit interaction and the Coulomb force also break charge symmetry. To account for charge-symmetry breaking and charge-dependent effects one can introduce isovector ($V_{pp} - V_{nn}$) and isotensor ($V_{pp} + V_{nn} - 2V_{np}$) terms into an effective nuclear interaction.

Understanding the occurrence and origin of these isospin-breaking terms in the shell model and how they manifest in nuclei is of great contemporary interest, e.g. [2–15]. These studies can be undertaken by examining energy differences between isobaric analog states (IAS). These are defined as states of the same spin and parity J^π, and isospin, T, in a multiplet of isobaric nuclei. This work deals with $T = 1$ states in triplets of nuclei with $T_z = -1, 0, 1$. Examining differences between IAS in $T_z = -1$ and $T_z = +1$ nuclei reveals isovector effects, whereas triplet energy differences, or TED reveal isotensor effects. TED are defined as

$$TED_J = E^*_{J,T,T_z=-1} + E^*_{J,T,T_z=+1} - 2E^*_{J,T,T_z=0} \quad (1)$$

where E^*_J is the excitation energy of an IAS of isospin T measured relative to the lowest state of the same isospin in that nucleus. In odd-odd $N = Z$ nuclei, the $T = 0$ and $T = 1$ structures are very close in energy, often leading to a $T = 1$ ground state. TED can provide very sensitive information on isotensor two-body interactions - i.e. the degree to which the np interaction is different from the average of the pp and nn interactions. For example, it is well known from nucleon scattering data [16] that the np-interaction is about 2.5% stronger than the average of nn and pp. Isotensor effects of this kind, if translated into the nuclear medium, may be expected to be measureable via TED. Identification of the $T = 1$ states in the odd-odd $N = Z$ system, among the sea of

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$T = 0$ states, can be very challenging, but is essential for this analysis. In some cases, even in well-studied nuclei, the first $T = 1$, 2^+ state can be elusive. One such example is ^{62}Ga, which is the topic of this paper. We present new data on ^{62}Ga employing a reaction methodology not previously used for this purpose – two-neutron knockout.

Previous experiments to perform detailed spectroscopy of excited states in ^{62}Ga have used fusion-evaporation reactions and β decay as the population mechanism. In Ref. [17], Vincent *et al.* used the ^{40}Ca(^{28}Si,αpn)^{62}Ga reaction to populate states up to 6.846 MeV, which were primarily yrast in nature. These states all appear to be $T = 0$ as no obvious analogs exist in the $|T_z| = 1$ systems. A further experiment performed by Rudolph *et al.* used the ^{40}Ca(^{24}Mg,pn)^{62}Ga reaction channel at 55 MeV and 60 MeV [18] to populate many non-yrast states. A γ-ray transition with an energy of 446 keV was identified as a dipole transition decaying to the 1^+ state at 571 keV. This was interpreted as decaying from a state at 1017 keV, which was suggested as the $T = 1$, 2^+ state due to its similar energy to the analog state in ^{62}Zn. Gamma decay to the ground state (via a 1017 keV transition) was not identified in that work.

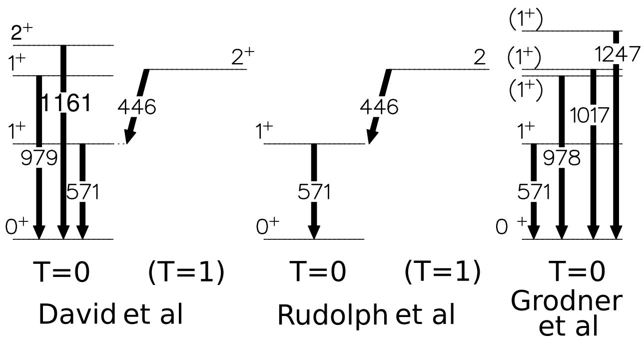

FIG. 1. Low lying 1^+ and 2^+ states in ^{62}Ga observed in three previous experiments [18, 19, 21].

Two other works have recently appeared in the literature, and the observed low lying 1^+ and 2^+ states are shown in Fig. 1. David *et al.* [19] used the ^{24}Mg(^{40}Ca,pn)^{62}Ga reaction performed at 103 MeV, with states in ^{62}Ga identified using a recoil-beta-tagging method [20]. The spectrum of states below 1.5 MeV reported is the same as those of Rudolph *et al.* [18], with the addition of (presumed $T = 0$) states at 1161 keV and 979 keV, assigned as 2^+ and 1^+ respectively. In both of these works, the authors suggest that the state at 1017 keV, decaying by a dipole transition to the 1^+_1 first excited state, is the $T = 1$ analog of the 2^+_1 states in the even-even neighbors ^{62}Ge and ^{62}Zn. In Ref. [21] Grodner *et al.* observed γ-ray transitions of 978 keV and 1017 keV in the β-decay of ^{62}Ge. These were tentatively assigned as decays from (1^+) states to the 0^+ ground state, and the authors suggest that this state is different from the 1017 keV state suggested to be the $T = 1$, 2^+ state.

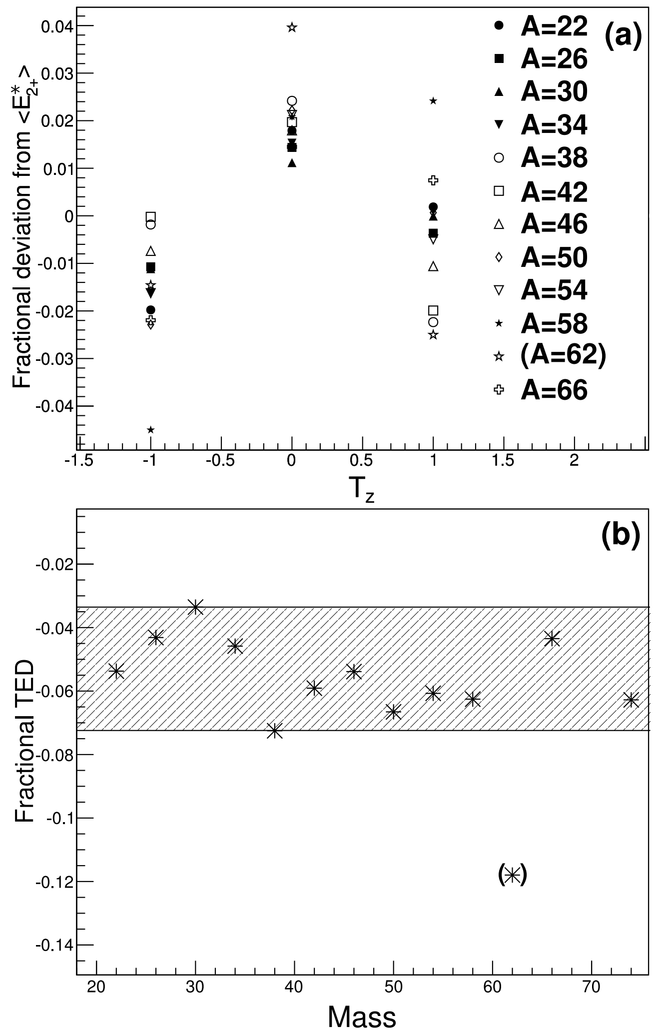

FIG. 2. Panel (a) shows the fractional deviation from the average energy, defined as: $(E^*_{2^+} - \langle E^*_{2^+}\rangle)/\langle E^*_{2^+}\rangle$, where $\langle E^*_{2^+}\rangle$ is the average $E^*_{2^+}$ calculated individually for each triplet. Panel (b) shows the TED for the $T = 1$, 2^+ states divided by the average energy of the states for each triplet. The shaded region covers the entire range of the data not including $A = 62$ and is used later in the analysis. The currently assigned datum for the $A = 62$ triplet is bracketed.

To try to shed some light on the likely location of the $T = 1$, 2^+ state, it is worth considering systematics of $T = 1$ triplets, which show a remarkably consistent behavior. In general it is found that the energy of the $T = 1$, 2^+ state in the $N = Z$, $T_z = 0$ nucleus is always larger than the average energy of the state across the triplet. This is shown in the upper panel of Fig. 2 where the fractional deviation from the average excitation energy of the three $T = 1$, 2^+ states is shown for all published triplets from the *sd*-shell to the *fp*-shell. In essence, this is an isotensor effect related to the angular-momentum coupling of *np*, *pp* and *nn* pairs among the triplet, and how the angular momentum recouples with increasing excitation energy. This was first described by

Lenzi *et al.* [22] and O'Leary *et al.* [23] who showed that the pairs that re-couple are predominantly np pairs in the odd-odd $N = Z$ system, and like-nucleon pairs in the even-even neighbours. The higher excitation energy in the odd-odd system can then be explained by the different changes in Coulomb energy, with respect to the ground state, among the triplet. Importantly, however, it has also been found that, especially for higher spin states, the Coulomb isotensor interaction is insufficient to fully account for the effect, and an additional isospin non-conserving isotensor interaction is needed to fully account for the data [7, 8, 11, 24, 25]. Hence, a systematic study is required to examine this effect.

The consistent behavior of the TED is rooted in these isotensor effects. Experimentally, we find that the magnitude of the TED is approximately a constant fraction of the component state excitation energy. This relationship is demonstrated in Fig. 2(b), which shows the TED normalized to the average energy of the $T = 1$ states. A simple empirical observation is that all the published data on TED lie in a narrow range, as demonstrated by the shaded region. The exception is the $A = 62$ system, where the tentatively assigned $T = 1$, 2^+ states in ^{62}Ge and ^{62}Ga, at 964keV and 1017keV respectively, have been used [18, 26]. The stark difference in this case suggests that at least one of the hitherto tentative assignments of the ^{62}Ga or ^{62}Ge $T = 1$, 2^+ states may be wrong.

In this paper, an experiment to identify the $T = 1$, 2^+ state in ^{62}Ga is reported using an alternative production mechanism to previous studies: two-neutron (2n) knockout from ^{64}Ga. Previous studies of 2n knockout have typically strongly populated low-lying low-spin states [10, 27–29]. However, during the analysis it was observed that a significant fraction of the ^{64}Ga secondary beam is in the low lying 42.9 keV $T = 1$, 2^+ isomeric state, which will be discussed later. The isomeric ratio is not measureable here, however we expect to see knockout from both the ground state and the isomer. A two-nucleon knockout cross-section calculation along the lines of Ref. [30, 31] has been performed with two-nucleon amplitudes calculated using NuShellX [32] in a truncated-basis shell-model calculation. Excitation of up to three protons and three neutrons outside of the $f_{\frac{7}{2}}$ orbital were allowed, using the GXPF1A interaction [33], and three states of each J^π were calculated.

Knockout cross sections were calculated from both the ground state and the isomeric state of ^{64}Ga. The knockout strength is spread widely among ≈ 15 states below about 2 MeV in ^{62}Ga. The limitations imposed by the truncation means that a detailed numerical analysis of the cross sections is not appropriate, but the calculations nevertheless suggest that the $T = 1$, 2^+ state in ^{62}Ga should be directly populated from both initial states of the beam. From the ground state of ^{64}Ga, the direct population of the $T = 1$, 2^+ state in ^{62}Ga is about 12% of the total, with all other strongly populated states ($> 5\%$) having even J. For knockout from the isomeric state of the beam, the population of the $T = 1$, 2^+ state is larger, at around 17%, with most of the the other strongly-populated states having odd-J.

The experiment was performed at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University. A primary beam of ^{78}Kr provided by the Coupled Cyclotron Facility was accelerated to 150 A.MeV and fragmented on a 650 mg/cm^2 ^{9}Be target to produce a cocktail of secondary beams including ^{65}Ge and ^{64}Ga. Secondary beam particles were identified on an event-by-event basis by their time-of-flight (TOF) through the A1900 separator [34]. The A1900 was set such that ^{66}As nuclei were at the center of the momentum acceptance range. Secondary beams were incident on a 96 mg/cm^2 beryllium foil at the target position of the S800 spectrograph [35] . Reaction products in the S800 were identified using TOF and energy loss detectors at the S800 focal plane [36]. Positions in the S800 were measured using two Cathode Readout Drift Chambers (CRDCs) and used both to determine position and angle at the target from trajectory reconstruction, and to correct time-of-flight measurements for flight path and momentum.

Gamma rays were detected using the Gamma-Ray Energy Tracking In-Beam Nuclear Array (GRETINA [37]), which consists of 28, coaxial, HPGe crystals. The crystals pack tightly and cover $\sim 1\pi$ of the solid angle in the laboratory frame. The outer contacts of each detector are segmented with six longitudinal segments and six lateral segments. Signals from all 36 segments and the core are digitized and signal decomposition localizes the interaction points of γ rays with sub-segment resolution. Signal decomposition was performed in real time during the experiment. In the offline analysis all γ-ray interaction points associated with an event were spatially clustered, and Compton-tracked to determine the first interaction point and reject scattered γ rays which contribute to the Compton background. γ-ray first-hit interaction points, in combination with the path of particles through the S800, determined the angle for event-by-event Doppler correction.

In addition to the 2n knockout data, the 1p2n reaction channel (from the ^{65}Ge beam) was also present in the data and was used in the analysis. As well as providing additional data, this allowed for a γ-ray coincidence analysis by construction of a 2D γ-ray energy coincidence matrix. The resulting γ-ray spectra from these two reactions are shown in Fig. 3(a) and (b). Peak energies were assigned from fits, with errors assigned from both the fits and the Doppler correction used. β values used for the Doppler correction were ascertained by iteratively Doppler reconstructing known peaks in the data with different β values until they were at the correct energies and the peak width had been minimized. Assigned peaks in Fig. 3 are labeled with literature values where known [17, 18].

Three previously known transitions, which are observed [17–19] to decay between, or into, the main low-lying odd-J yrast structure, are observed: the 571-keV

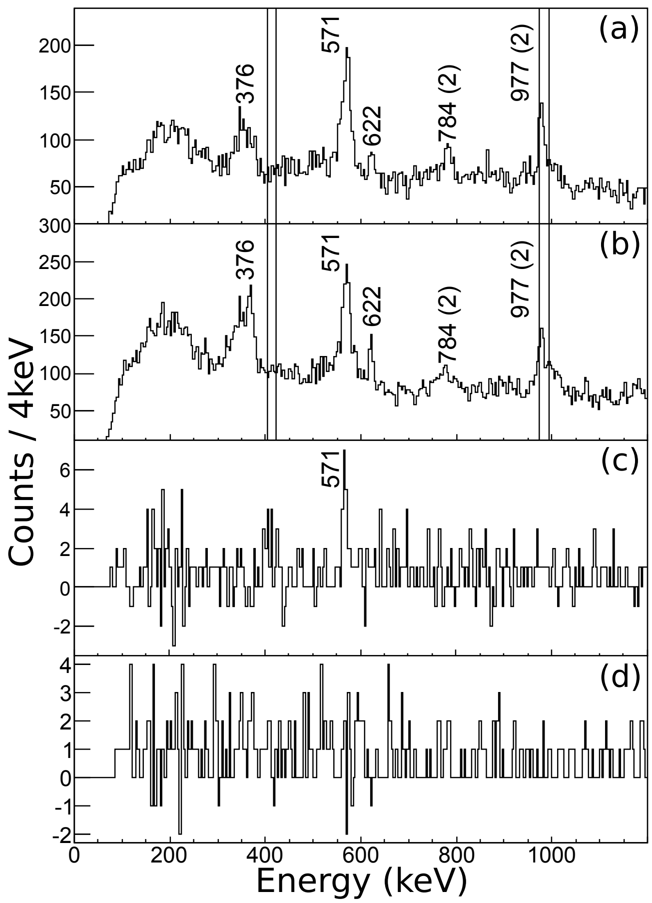

FIG. 3. Panel (a) shows a Doppler-corrected γ-ray spectrum in coincidence with ^{62}Ga recoils populated by direct 2n knockout from ^{64}Ga. The vertical lines show the expected positions of the $E2$ and $M1$ decays from the $T = 1$, 2^+ state based on the systematics shown by the hashed area in Fig. 2(b) - see text for details. Panel (b) shows a γ-ray spectrum of ^{62}Ga created by 1p2n removal from ^{65}Ge. Panels (c) and (d) are from γ-γ coincidence analysis in the 1p2n channel: panel (c) shows a (local-background-subtracted) spectrum of γ-rays in coincidence with the 784 keV peak, Panel (d) shows a (local-background-subtracted) spectrum of γ rays in coincidence with the 977 keV peak. The peak at 784(2) keV is new to this work.

transition from the 1^+ to the 0^+ ground state, the 376-keV transition from the 5^+ at 1193 keV to the 3^+ at 817 keV and the 622-keV transition that also feeds the 3^+ state. The 3^+ state itself has a half life that was previously measured to be 3.4 ns, so with the beam velocity of $\beta = 0.296$ it is not expected that the transition between the 3^+ and 1^+ states will be easily observable. This lifetime corresponds to γ-decay occurring on average around 0.5 m outside the target, and the angles relevant for the Doppler correction cannot be determined.

The transition assigned as the 376-keV transition between the 5^+ and 3^+ states has a wide peak shape and is shifted to a lower energy, which would be the expected behaviour of a transition half life of a few hundred picoseconds. This low-energy $E2$ transition is in-

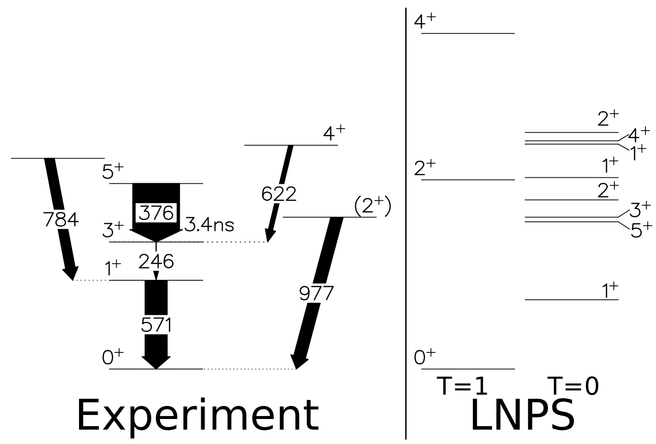

FIG. 4. The left side shows the populated levels and observed γ rays in ^{62}Ga, along with their efficiency-corrected relative intensities, measured in the 2n-knockout spectrum, indicated by the widths of the arrows. States, apart from the 977-keV state, have been labeled with assignments from previous work [19]. The 977-keV state is labelled as (2^+) as it is considered here as a candidate for the $T = 1$, 2^+ state. The right hand side shows shell model predictions of low lying $T = 0$ (right band) and $T = 1$ (left band) states using ANTOINE [39] and the LNPS interaction [40].

deed expected to be long lived - shell-model predictions by Rudolph *et al.* [18] and Srivastava *et al.* [38] predict half lives of around 350 ps and 560 ps, respectively. The transitions observed in this experiment are shown in the left hand side of Fig. 4. The 246 keV transition is given a minimum intensity in this figure as it is not observed due to the lifetime of the 3^+ state, and it is assumed that all the structure at around 360 keV indeed corresponds to the 376-keV transition. A new transition with an energy of 784(2) keV is also observed in both spectra.

The analysis has shown strong evidence that a significant fraction of the ^{64}Ga beam is in the low-lying 43 keV 2^+ 22 μs isomeric state rather than the 0^+ ground state (both states have $T = 1$). There are supporting arguments for this: (i) Examination of the 1n knockout channel shows that one of the states strongly directly populated in ^{63}Ga is the $\frac{9}{2}^-_1$ state, which can only be populated from the isomeric state in the beam. (ii) The observed relatively strong population of the odd-spin yrast states in ^{62}Ga: the calculations indicate that the most strongly populated states in ^{62}Ga, populated directly from the 0^+ ground state, have even spins and the largest population of the odd spin yrast states comes from knockout from the 2^+ isomer. (iii) Population of the 5^+ state from the ground state is only possible via removal of an $f_{\frac{7}{2}}$ neutron, which is expected to be weak. Given that the 5^+ appears to be one of the most strongly populated states, this supports the presence of the isomer in the beam.

In addition to known transitions, in both direct 2n knockout from ^{64}Ga and 1p2n knockout from ^{65}Ge, a 977(2)-keV transition is observed which we consider here as a candidate for the decay of the $T = 1$, 2^+ state. Fig. 3(c) and (d) show spectra measured in coincidence with the 784(2)-keV and 977(2)-keV transitions. Panel (c) of Fig. 3 shows that the transition at 784(2) keV is in coincidence with the 571-keV transition from the 1^+ to the ground state, suggesting a new state with an energy of 1350(2) keV. Given that the significantly smaller peak at 784(2) keV has a clear coincidence, the lack of coincident γ-rays with the more intense 977(2)-keV transition, see Fig. 3(d), implies it is decaying directly to the ground state. We see no evidence of a 446-keV γ-ray as would be expected if the previously suggested [18] $T = 1$, 2^+ state at 1017 keV was populated.

Panels (a) and (b) of Fig. 3 have regions of interest indicated, by the vertical lines, which are deduced from the normalized TED data shown in Fig. 2(b). The regions of interest show where the centroid of the decay of the $T = 1$, 2^+ state in ^{62}Ga would lie assuming that the TED lies in the same shaded region as all other nuclei so-far observed (and of course assumes that the assignment of the analog state in ^{62}Ge is correct). The higher-energy region applies to an $E2$ transition decaying directly to the ground state and the lower energy region corresponds to an isovector $M1$ transition to the 571 keV 1^+ state. The only observed peak with a centroid energy within (or even close to) these regions is the 977(2)-keV transition which, based on these data alone, would make it a strong candidate for the decay of the $T = 1$, 2^+ state.

In Fig. 4, the observed states are compared with shell-model calculations performed in ANTOINE [39] using the LNPS interaction [40] in the fp-space. The truncation allows a total of five excitations from $f_{\frac{7}{2}}$ to the higher-lying fp orbits. The shell model gives a reasonable description of the observed states. We have used this model to calculate the $B(E2)$ and $B(M1)$ for the two possible decays of the 977-keV state (to the ground state and 571-keV $T = 0$, 1^+ state) under the assumption of this being the $T = 1$, 2^+ state. The calculations predict that the transition from the $T = 1$, 2^+ state will be about 7 times stronger to the ground state than to the $T = 0$, 1^+ state if we assume the experimental energies presented here. This calculation is consistent with that of Rudolph *et al.* in suggesting that the dominant decay of the $T = 1$, 2^+ state is expected to be to the ground state and not to the $T = 0$, 1^+ state. This decay pattern is different from that found in odd-odd $N = Z$ nuclei in the $f_{\frac{7}{2}}$ shell, where strong isovector $M1$ transitions have been observed to compete with the isoscalar $E2$. This has been interpreted in a *quasi-deuteron* picture involving orbitals with $j = l + \frac{1}{2}$ [41, 42]. In the $f_{\frac{7}{2}}$ shell, wavefunctions are dominated by this single $j = l + \frac{1}{2}$ orbital, and hence strong isovector $M1$ transitions are observed. However, all the calculations presented here suggest that this simple picture does not apply in the mixed valence space around ^{62}Ga. In addition, Srivastava *et al.* [38] recently published shell-model calculations in the full $f_{\frac{5}{2}}pg_{\frac{9}{2}}$ model space for ^{62}Ga and deformed shell-model calculations based on Hartree-Fock intrinsic states in the same model space. The spherical shell-model calculations show that the $T = 1$, 2^+ state $E2$ decay to the ground state is about a factor of two stronger than the isovector $M1$ to the $T = 0$, 1^+ state, and the deformed calculations show that the $E2$ decay completely dominates.

As noted earlier, David *et al.* [19] and Grodner *et al.* [21] both identify a transition with the same energy (within error) as the 977(2) keV peak observed here, with David *et al.* making an assignment of 1^+ based on angular distribution. Here, we are not in a position to measure the spin/parity of our observed transition at 977(2) keV. However, the reactions presented in the current work are likely to directly populate the $T = 1$, 2^+ state, as well as other low-lying states, as shown by the cross-section calculations performed here. No other peaks in either reaction presented here are plausible candidates for the transition. Given the density of states it is possible that the $T = 0$, 1^+ and $T = 1$, 2^+ states lie closer in energy than can be resolved in this study.

In conclusion, the systematics of TED for the known $T = 1$, 2^+ states were reviewed, highlighting the anomalous behavior of the $A = 62$ triplet. An experiment was performed populating excited states in ^{62}Ga using knockout from the ground state and 2^+ isomeric state in ^{64}Ga. Calculations indicate that this reaction should directly populate the $T = 1$, 2^+ state, along with the other low-lying yrast states. Using the TED systematics as a guide a state has been identified as a candidate for the $T = 1$, 2^+ state, however spins or parities could not be measured, and previous work has already identified a state at a very similar energy as $T = 0$, 1^+. It is possible, therefore, that there is doublet of transitions that cannot resolved in this study. The question of the $A = 62$ TED then remains open until a definitive identification can be made for the $T = 1$ states in ^{62}Ga.

ACKNOWLEDGMENTS

The authors want to thank T. Ginter and J. Pereira for their effort during the experiment, and D. Rudolph and H. David for helpful discussions. This work was supported by the UK Science and Technology Facilities Council (STFC). GRETINA was funded by the DOE, Office of Science. Operation of the array at NSCL was supported by NSF under Cooperative Agreement No. PHY-1102511 (NSCL) and DOE under Grant No. DE-AC02-05CH11231 (LBNL).M.P. acknowledges support from the Helmholtz International Center for FAIR within the framework of the LOEWE program (Landesoffensive zur Entwicklung Wissenschaftlich-Ökonomischer Exzellenz) launched by the State of Hesse.

[1] E. Wigner, Phys. Rev. 51, **106** (1937).
[2] M. A Bentley and S.M. Lenzi, Prog. Part. Nucl. Phys. **59**, 497 (2007).
[3] D. D. Warner, M. A. Bentley, P. Van Isacker, Nature Phys. **2**, 311 (2006).
[4] D. G. Jenkins *et al.*, Phys. Rev. C **87**, 064301 (2013).
[5] Y. H. Lam, N.A. Smirnova, and E. Caurier, Phys. Rev. C **87**, 054304 (2013).
[6] B. S. Nara Singh *et al.*, Phys. Rev. C **75**, 061301 (2007).
[7] A. Gadea *et al.*, Phys. Rev. Lett. **97**, 152501 (2006).
[8] K. Kaneko, Y. Sun, T. Mizusaki and S. Tazaki. Phys. Rev. C **89**, 031302(R) (2014).
[9] K. Kaneko, Y. Sun, T. Mizusaki, and S. Tazaki. Phys. Rev. Lett. **110**, 172505 (2013).
[10] P. J. Davies *et al.*, Phys. Rev. Lett. **111**, 072501 (2013).
[11] A. P. Zuker, S. M. Lenzi, G. Martinez-Pinedo, and A. Poves, Phys. Rev. Lett. **89**, 142502 (2002)
[12] S. J. Williams *et al.*, Phys. Rev. C **68**, 011301(R) (2003)
[13] J. Ekman, C. Fahlander and D. Rudolph, Mod. Phys. Lett. **A20**, 2977 (2005).
[14] J. Ekman et al., Phys. Rev. Lett. **92**, 132502 (2004).
[15] R. du Rietz et al.,Phys. Rev. Lett. **93**, 222501 (2004).
[16] G. Q. Li and R. Machleidt, Phys. Rev. C **58**, 3153 (1998).
[17] S. M. Vincent *et al.*, Phys. Lett. B**437**, 264 (1998).
[18] D. Rudolph *et al.*, Phys. Rev. C **69**, 034309 (2004).
[19] H. M. David *et al.*, Phys. Lett. B**726**, 665 (2013).
[20] A. N. Steer *et. al.*. Nucl. Instrum. Meth. A **565**, 630 (2006)
[21] E. Grodner *et al.*, Phys. Rev. Lett. **113**, 092501 (2014).
[22] S. M. Lenzi *et al.*, Phys. Rev. C **60**, 021303 (1999).
[23] C. D. O'Leary *et al.*, Phys. Lett. B**525**, 49 (2002).
[24] P. Ruotsalainen *et. al.*, Phys. Rev. C **88**, 041308(R) (2013).
[25] J. Henderson *et. al.*, Phys. Rev. C **90**, 051303(R) (2014).
[26] D. Rudolph, E. K. Johansson, L.-L. Andersson, J. Ekman, C. Fahlander, and R. du Rietz, Nucl. Phys. A **752**, 241c (2005).
[27] K. Yoneda *et al.*, Phys. Rev. C **74**, 021303(R) (2006).
[28] F. Recchia *et al.*, Phys. Rev. C **88**, 041302(R) (2013).
[29] A. J. Nichols *et al.* Phys. Lett. B**733**, 52 (2014).
[30] J. A. Tostevin and B. A. Brown. Phys. Rev. C **74**, 064604 (2006)
[31] E. C. Simpson, J. A. Tostevin, D. Bazin, B. A. Brown, and A. Gade. Phys. Rev. Lett. **102**, 132502 (2009).
[32] B. A. Brown, W. D. M. Rae, E. McDonald and M. Horoi, http://www.nscl.msu.edu/ brown/resources/resources.html.
[33] M. Honma, T. Otsuka, B. A. Brown, and T. Mizusaki, Eur. Phys. J. A **25**, 499 (2005); Phys. Rev. C **69**, 034335 (2004).
[34] D. J. Morrissey *et al.*, Nucl. Instrum. Methods Phys. Res. B **204**, 90 (2003).
[35] D. Bazin *et al.*, Nucl. Instrum. Methods Phys. Res. B **204**, 629 (2003).
[36] J. Yurkon *et al.*, Nucl. Instrum. Methods Phys. Res. A **422**, 291 (1999).
[37] S. Paschalis *et al.*, Nucl. Instrum. Methods Phys. Res. A **709**, 44 (2013).
[38] P. C. Srivastava, R. Sahu, and V.K.B. Kota, Eur. Phys. J. A **51**, 3 (2015).
[39] E. Caurier, and F. Nowacki, Acta Phys. Pol. B **30**, 705 (1999).
[40] S. M. Lenzi, F. Nowacki, A. Poves, and K. Sieja, Phys. Rev. C **82**, 054301 (2010).
[41] A. F. Lisetskiy, R.V. Jolos, N. Pietralla and P. von Brentano. Phys. Rev. C **60**, 064310 (1999).
[42] A. F. Lisetskiy *et al.*, Phys. Lett. B**512**, 290 (2001).