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

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

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Background: Triplet energy differences (TED) can be studied to yield information on isospin-non-conserving interactions in nuclei.

Purpose: The systematic behavior of triplet energy differences (TED) of $T = 1$, $J^\pi = 2^+$ states is examined. The $A = 62$ isobar is identified as having a TED value that deviates 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.

Methods: An in-beam γ-ray spectroscopy experiment was performed to identify excited states in ^{62}Ga using GRETINA with the S800 spectrometer at NSCL using a two-nucleon knockout approach. Cross-section calculations for the knockout process and shell-model calculations have been performed to interpret the population and decay properties observed.

Results: 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. Cross-section calculations indicate that the relevant $T = 1$, 2^+ state should be one of the states directly populated in this reaction.

Conclusions: 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.

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The concept of charge independence in nuclear structure physics comes from the observation that the strong nucleon-nucleon interactions are virtualy identical for neutron-neutron (V_{nn}), proton-proton (V_{pp}) and neutron-proton (V_{np}) pairs. The assumption of charge independence allows us to treat, thoeretically, the nucleus as a system of two types of fermions, interacting identically. The isospin concept was introduced [1] to facilitate this idea by treating the proton and neutron as fermions of the same isospin quantum number $t = \frac{1}{2}$, distinguished by the isospin projection, t_z. Isobaric analogue states in nuclei are then classified by their total isospin quantum number T in a multiplet of nuclei of the same mass number and with $T_z = \sum t_z = (N - Z)/2$. Isospin symmetry dictates that in the absence of electromagnetic effects, isobaric analogue states will be degenerate. In reality, electromagnetic effects, and other isospin-symmetry-breaking interactions of nuclear origin, will break isospin symmetry and lift this degeneracy, although the underlying symmetry of the wavefunctions of the analogue states is expected to be largely unaffected. Accounting for isospin non-conserving effects in a model calculation mandates the intoduction of isovector $(V_{pp} - V_{nn})$ and isotensor $(V_{pp} + V_{nn} - 2V_{np})$ components into effective nuclear interaction – see e.g. Ref [2] for a more complete discussion.

Understanding the occurrence and origin of these isospin-breaking terms, and how they manifest in nuclei, is of great contemporary interest. This is especially true in relation to the shell model, where significant work has been done in understanding how isospin non-conserving interactions of both isovector and isotensor origin need to be incuded in the effective interaction to explain, numerically, the differences between isobaric analogue

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states – e.g. [2–15]. These studies are undertaken by examining excitation energy differences between states of the same spin and parity J^π, and isospin, T, in an isobaric muliplet, and reproducing those energy dfferences in a shell-model approach including isovector and isotensor terms. This work deals with $T = 1$ states in isobaric triplets of nuclei with $T_z = -1, 0, 1$. Examining differences between the mirror pair with $T_z = -1$ and $T_z = +1$ gives specific information on isovector phenomena, whereas triplet energy differences (TED) – the subject of this paper – relate to 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 $T = 0$ 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 in the odd-odd $N = Z$ member of the triplet 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. A partial scheme from reference [18] is shown in Fig. 1(a).

Two other works have recently appeared in the literature, and the observed low lying 1^+ and 2^+ states for these are also 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

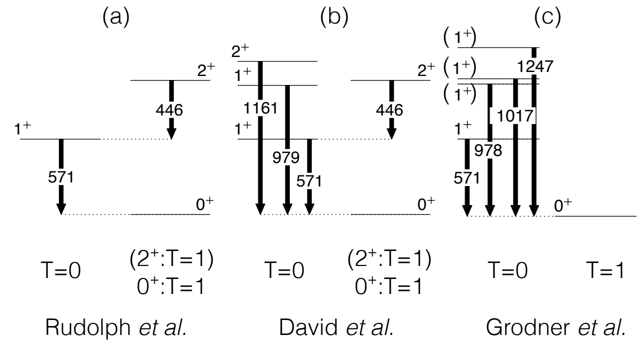

FIG. 1. Low lying 1^+ and 2^+ states in ^{62}Ga observed in three previous experiments: (a) Rudolph *et. al.* [18], (b) David *et. al.* [19] and (c) Grodner *et. al.* [21]. The T=1 assignment of the 2^+ states is placed in parentheses here as it has been made on the basis of energy systematics.

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 – see Fig. 1(b). 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 – see Fig. 1(c). 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.

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. This is now possible for nuclei across the whole fpg shell due to spectroscopic studies in the last decade that have allowed observation of the $T = 1$ excited states in the difficult-to-access $T_z = 0$ $N = Z$ nuclei and the proton rich nuclei with $T_z = -1$ [7, 18, 22, 24, 26–34]. The pattern of excitation energies for the $T = 1$, 2^+ states among the triplet show a remarkably consistent behavior as a function of mass number. Specifically 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 within a triplet 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. For the $T = 1$ ground state, $J = 0$ couplings for $T = 1$ pairs (in the same shell-model level) are expected to dominate. With increasing excitation energy and total angular momentum, some re-coupling of pairs to higher J occurs which, for protons, will cause a change in the Coulomb

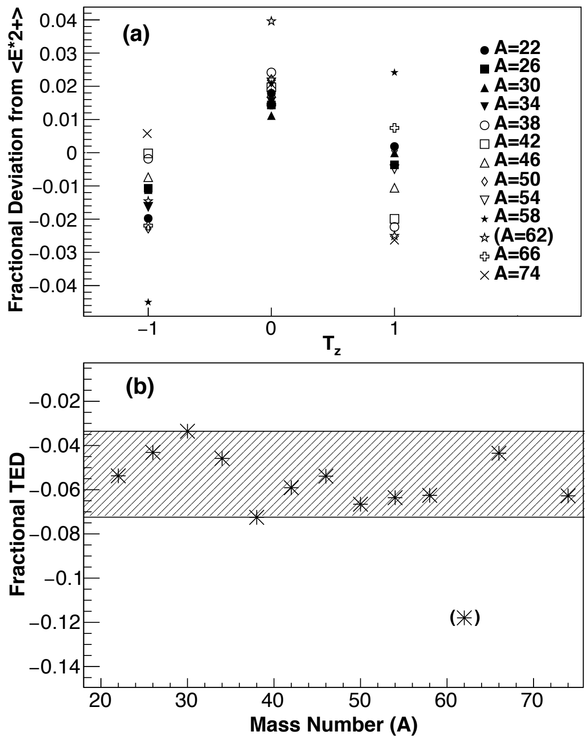

FIG. 2. Panel (a) shows the fractional deviation from the average energy, defined as: $(E^*_{2+} - \langle E^*_{2+} \rangle)/\langle E^*_{2+} \rangle$, where $\langle E^*_{2+} \rangle$ is the average E^*_{2+} calculated individually for each triplet. Panel (b) shows the fractional TED, defined as the TED for the $T = 1$, 2^+ states divided by $\langle E^*_{2+} \rangle$ for that 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. The data for the fpg shell, which are generally the most recent, can be found in the following references: A=42 [23], A=46 [22, 24], A=50 [26, 27], A=54 [7], A=58 [28, 29], A=62 [18, 34], A=66 [30, 31], A=74 [32, 33].

energy. Lenzi *et al.* [22] and O'Leary *et al.* [25] examined this in a shell-model calculation and showed that the pairs that re-couple their angular momentum this way 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 interaction alone is insufficient to fully account for the effect in a shell-model calculation, and an additional isospin non-conserving isotensor interaction is needed to fully account for the data [7, 8, 11, 31, 33]. Hence, a systematic study is required to examine this effect.

The consistent pattern of excitation energies among triplets is seen also in the TED. This is highlighted in Fig. 2(b), which shows the TED divided by the average energy of the three $T = 1$ states in that triplet. 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, 34]. 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, 35–37]. 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. [38, 39] has been performed with two-nucleon amplitudes calculated using NuShellX [40] 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 [41], 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 [42]. 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 [43]. Reaction products in the S800 were identified using TOF and energy loss detectors at the S800 focal plane [44]. 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 [45]), 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 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 from a state with a half life of a few hundred picoseconds. The low gamma-ray energy of this $E2$ transition is indeed expected to result in the state being long lived – shell-model predictions by Rudolph *et al.* [18] and Srivastava *et al.* [46] both predict half lives of around 350 ps. The transitions observed in this experiment are shown in Fig. 4(a). The 246 keV

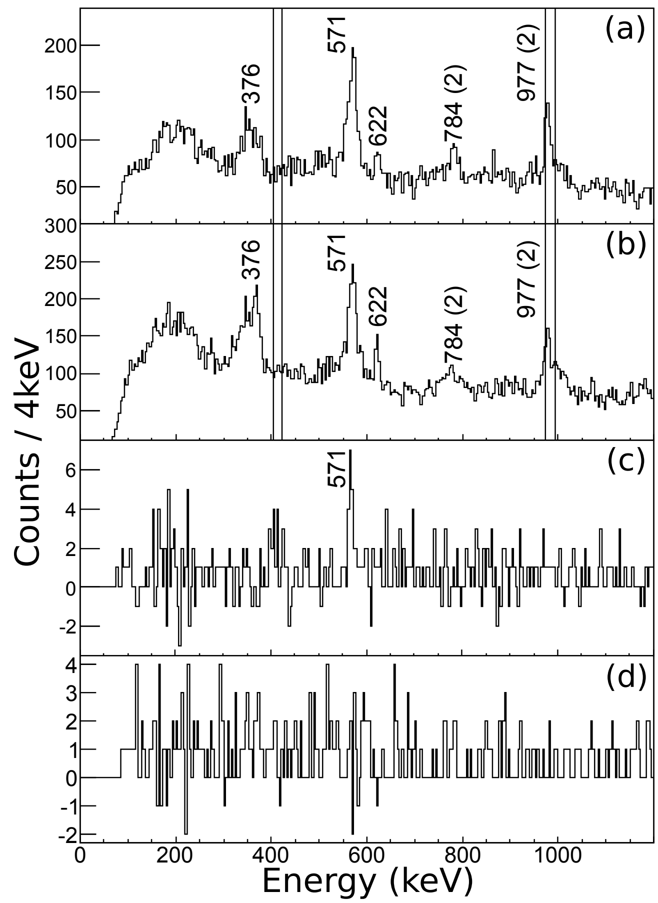

FIG. 3. Panel (a) shows a Doppler-corrected γ-ray spectrum in coincidence with ^{62}Ga recoils populated by direct 2n knockout from ^{64}Ga. The vertical lines show the expected positions of the $E2$ and $M1$ decays from the $T = 1$, 2^+ state based on the systematics shown by the hashed area in Fig. 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 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 in Fig. 3(a) 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

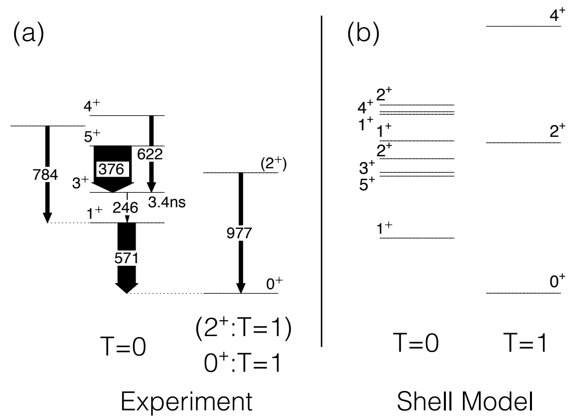

FIG. 4. (a) The populated levels and observed γ rays in ^{62}Ga, along with their efficiency-corrected relative intensities, measured in the 2n-knockout spectrum, indicated by the widths of the arrows. States, apart from the 977-keV state, have been labeled with assignments from previous work [19]. The 977-keV state is labelled as (2^+: $T = 1$) as it is considered here as a candidate for the $T = 1$, 2^+ state. (b) Shell model predictions of low lying $T = 0$ (right band) and $T = 1$ (left band) states using ANTOINE [47] and the LNPS interaction [48].

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 1355(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 [47] using the LNPS interaction [48] 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 $j = l + \frac{1}{2}$ [49, 50]. 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.* [46] 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 four stronger than the isovector $M1$ to the $T = 0$, 1^+ state, again using our experimental energies, 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 TED for the $A = 62$ triplet when compared with the systematics of TED as a function of mass number. An experiment was performed populating excited states in ^{62}Ga utilising two-neutron knockout from a ^{64}Ga beam. Knockout from both the ground state and 2^+ isomeric state in the beam have been considered. Reaction cross-section calculations, incorporating information from shell-model wavefunctions, indicate that this reaction should directly populate the $T = 1$, 2^+ state, along with the other low-lying yrast states in ^{62}Ga. Using the TED systematics as a guide a state has been identified as a candidate for the $T = 1$, 2^+ state. However an angular momentum/parity assignment could not be made for the state observed, and previous work has already identified a state at a very similar excitation energy as a $T = 0$, 1^+ state. It is possible, therefore, that there is doublet of transitions that cannot be experimentally 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.

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