Title
Onset of high-spin rotational bands in the N=Z nucleus Ga 62

Permalink
https://escholarship.org/uc/item/1x57p49t

Journal
Physical Review C, 102(1)

ISSN
2469-9985

Authors
Rudolph, D
Ragnarsson, I
Åberg, S
et al.

Publication Date
2020-07-01

DOI
10.1103/PhysRevC.102.014313

Peer reviewed
Onset of high-spin rotational bands in the $N = Z$ nucleus $^{62}$Ga

D. Rudolph, I. Ragnarsson, S. Åberg, C. Andreoiu, M. P. Carpenter, R. M. Clark, J. Ekman, C. Fahlander, R. V. F. Janssens, F. G. Kondev, T. Lauritsen, D. G. Sarantites, D. Seweryniak, and C. E. Svensson

$^1$Department of Physics, Lund University, S-22100 Lund, Sweden
$^2$Chemistry Department, Simon Fraser University, Burnaby, British Columbia, V5A 1S6, Canada
$^3$Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA
$^4$Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
$^5$Department of Material Science and Applied Mathematics, Malmö University, S-20506 Malmö, Sweden
$^6$Department of Physics and Astronomy, University of North Carolina, Chapel Hill, North Carolina 27599, USA
$^7$Chemistry Department, Washington University, St. Louis, Missouri 63130, USA
$^8$Department of Physics, University of Guelph, Guelph, Ontario, N1G 2W1, USA

(Received 17 May 2020; accepted 25 June 2020; published 15 July 2020)

The fusion-evaporation reaction $^{28}$Si + $^{40}$Ca at 122 MeV beam energy was used to populate high-spin states in the odd-odd $N = Z$ nucleus $^{62}$Ga. With the combination of the Gammasphere spectrometer and the Microball CsI(Tl) charged-particle detector array the decay scheme of $^{62}$Ga was extended beyond 10 MeV excitation energy. The onset of band structures was observed. These high-spin rotational states are interpreted and classified by means of cranked Nilsson-Strutinsky calculations.

DOI: 10.1103/PhysRevC.102.014313

I. INTRODUCTION

Due to inherent symmetries, nuclei at or near the $N = Z$ line continue to be at the forefront of nuclear structure research. This includes, for instance, superallowed $\beta$ decays, isobaric analog states identified by means of $\beta$-delayed proton emission, breaking of charge independence and charge symmetry in isospin $T = 1$ triplets or $T = 1/2$ mirror nuclei, or studying the influence of isovector $T = 1$ or isoscalar $T = 0$ pairing correlations on rotational behavior at high angular momenta. Beyond $N = Z = 28$ $^{56}$Ni, the proton drip line is close to the $N = Z$ line, which often adds nuclear astrophysics aspects into mostly decay studies of $N \lesssim Z$ nuclei.

The odd-odd $N = Z$ nucleus $^{62}$Ga is a well-studied example: a lot of effort has been put into precise measurements of details of the superallowed $\beta$ decay of its $T = 1, I^\pi = 0^+$ ground state (see Refs. [1–3] and references therein). Triplet energy differences along the mass $A = 62$ isobars $^{62}$Ge, $^{62}$Ga, and $^{62}$Zn have been studied, most recently by two-nucleon knockout [4]. This study provided evidence for the relevant $T = 1, I^\pi = 2^+$ state at 977 keV in $^{62}$Ga, improving upon the results of Ref. [5], while both refine an earlier suggestion [6]. A $\beta$-decay study of $^{62}$Ge reported a number of low-spin states in $^{62}$Ga, all with tentative $1^+$ assignments, including a state at 978 keV [7], while targeting the influence of $T = 0$ pairing correlations through weak Gamow-Teller decay branches. Similarly, $^{62}$Ga is close to the borderline where odd-odd $N = Z$ nuclei change ground state from $T = 0$ to $T = 1$. This competition results in a crossing of the $T = 1, I^\pi = 0^+$ ground-state band by a $T = 0$ band already at spin $I = 2\hbar$.

The first medium- to high-spin states in $^{62}$Ga were reported in Refs. [8–10]. These were extended based on studies employing multi-coincidence $\gamma$-ray spectrometers [5,6], identifying the odd-spin yrast sequence up to a terminating $I^\pi = 17^+$ state near 10 MeV excitation energy. For more complete experimental information we point to Ref. [11]. The possible rotational behavior of these states was subject of a dedicated theoretical study, discussing also $T = 0$ and $T = 1$ aspects [12]. However, different from most neighboring $A \approx 60$ nuclei [13,14], well- or superdeformed rotational bands have not yet been identified in $^{62}$Ga. In particular, the odd-odd $N = Z$ neighbor $^{58}$Cu enabled a case study, both experimentally [15–17] and theoretically [18–21]. There, comparisons with the ‘doubly-magic superdeformed band’ in $^{60}$Zn [13] as well as possible influences of neutron-proton pairing correlations in the isospin $T = 0$ or $T = 1$ channels were investigated.

Revisiting existing data from experiments briefly described in Sec. II, we present an analysis devoted to high-spin states in $^{62}$Ga as outlined in Sec. III. The experimental results are presented in Sec. IV. The newly observed structures, indicating the onset of the long-sought well-deformed rotational bands in $^{62}$Ga, are discussed in Sec. V and compared with results from cranked Nilsson-Strutinsky calculations. The paper concludes with a brief summary.

II. EXPERIMENT

The experiment was conducted at the Argonne Tandem Linac Accelerator System (ATLAS). The fusion-evaporation

Published by the American Physical Society under the terms of the Creative Commons Attribution 4.0 International license. Further distribution of this work must maintain attribution to the author(s) and the published article’s title, journal citation, and DOI. Funded by Bibsam.

Published by the American Physical Society
reaction $^{28}$Si+$^{40}$Ca, at a beam energy of 122 MeV, was used to populate high-spin states in neutron-deficient, mass $A \approx 60$ nuclei near the $N = Z$ line. Excited states in $^{62}$Ga were reached following the evaporation of one $\alpha$ particle, one proton, and one neutron, i.e., the $\alpha_1p1n$ reaction channel. An experimental relative production cross section of $\sigma_{rel} \approx 0.2\%$ could be estimated. The $^{40}$Ca target was enriched to 99.975% and 0.5 mg/cm$^2$ thin. It was enclosed by two thin gold layers and transported to the target chamber in argon atmosphere to prevent oxidation.

The experimental setup combined the Gammasphere array [22] surrounding the target chamber with the nearly 4$\pi$ 95-CsI(Tl)-element charged-particle detector system Microball [23] inside. At the time of the experiment, Gammasphere comprised 101 germanium detector elements. The heavy-metal collimators were removed from the detector elements to allow charged particles measured with Microball, this information is useful for reaction channel selection [25]. Events were recorded when at least four Compton-suppressed $\gamma$ rays were detected.

### III. DATA ANALYSIS

The data analysis follows procedures established and described earlier a number of times in extensive studies of neighboring nuclei for this and similar experiments in the mass $A \approx 60$ region [26–30]. In brief, based on momenta of evaporated charged particles measured with Microball, this information is useful for more accurate Doppler-shift corrections and thus significantly improved this allows for more accurate Doppler-shift corrections and γ-ray sum-energy measurements [24]. In conjunction with the summed energies of the evaporated charged particles measured with Microball, this information is useful for reaction channel selection [25]. Events were recorded when at least four Compton-suppressed $\gamma$ rays were detected.

The widths of the arrows correspond to the relative intensities of the $\gamma$ rays. In the figure, $X = 11$ MeV.

contaminating reaction channels, including $^{62}$Zn (1$\alpha2p$, [30]), $^{61}$Cu (1$\alpha3p$, [27]), $^{61}$Zn (1$\alpha2p1n$, [28]), $^{55}$Cu (2$\alpha1p$, [26]), or $^{58}$Ni (2$\alpha2p$, [29]), are all very well known, likewise the 1$\alpha1p$ channel $^{63}$Ga [31]. The $\gamma$-ray spectra in coincidence with any combination of the three low-lying transitions in $^{62}$Ga reveal almost exclusively lines associated with $^{62}$Ga (see Sec. IV). In an iterative process, this fact was used to optimize the conditions on event-by-event $\gamma$-ray multiplicity as well as $\gamma$-ray sum-energy and total-energy measurements [24,25] to obtain the best possible signal-to-contamination ratio for the analysis of excited states in $^{62}$Ga in the preselected 1$\alpha1p$ data set.

With the 1$\alpha1p$ coincidence, and the mentioned optimized conditions, the subsequent $\gamma$-ray analysis steps involved $E_\gamma$ projections, $E_\gamma$-$E_\gamma$ matrices, and an $E_\gamma$-$E_\gamma$-$E_\gamma$ cube. These were inspected by means of the RADWARE software package [32] and the spectrum-analysis code TV [33]. $E_\gamma$ projections and $E_\gamma$-$E_\gamma$ matrices required a coincidence with at least one of the three low-energy $\gamma$-ray transitions at 246, 377, or 571 keV. The inspection of the $E_\gamma$-$E_\gamma$-$E_\gamma$ cube engaged almost always one or more of these two transitions as well. The analysis resulted in the experimental high-spin level scheme of $^{63}$Ga shown in Fig. 1. The selectivity for $^{62}$Ga can be judged by the $\gamma$-ray spectrum displayed in Fig. 2(a).

Well-deformed rotational bands in the $A \approx 60$ region involve typically $\gamma$-ray transitions between some 1.5 and 4.0 MeV. The lifetimes of the corresponding states are usually so short that the residual nuclei emit these $\gamma$ rays while the nucleus is still inside the thin target layer, i.e. moving with slightly higher velocities than used for standard Doppler
FIG. 1. The yrast sequence up to the 1746-keV 15+ state were used to select the nucleus of interest. Obviously, prompt proton emission is unlikely because all well- or superdeformed high-spin bands observed in the daughter nucleus 61Zn could be connected into low-spin states of 61Zn [28]. Similarly, in the decay scheme of 58Cu, no indication of any prompt α emission from states in 62Ga could be identified.

The collaboration conducted also a series of high-spin experiments with Gammasphere producing the compound nucleus 64Ge, populating 62Ga in the 1p1n channel. If one were to discriminate 62Ga events in these data sets, one might expect to populate very high spin states. Though such an approach worked out nicely for the 2p channel 62Zn [34] (and, similarly in yet another data set, for 58Ni populated via 2p evaporation [35]), it did not yield any results for 62Ga. The explanation can be found in the low absolute and relative production cross-section for the 1p1n vs 2p reaction channel.

IV. EXPERIMENTAL RESULTS

The level scheme derived from the present study is shown in Fig. 1. The yrast sequence up to the 17+ state at 9976 keV and the off-yrast part between 2 and 5 MeV excitation energy was reported previously [4–6,9,10], the latter in fact more comprehensively. This is readily understood in terms of anticipated entry-state distributions, which are shifted to on average higher excitation energies and larger angular momenta for the present data set. The only minor inconsistency with previous work is the γ-ray energy reported for the 17+ → 15+ transition, being 1390 keV in Ref. [5] but 1387.9(10) keV in Ref. [9] and here found to be 1387.4(7) keV. All states beyond an excitation energy of 10 MeV and the γ rays connected to them were observed for the first time.

Energies and spin-parity assignments of the levels in the decay scheme of Fig. 1 as well as energies, relative intensities, and DCO ratios of the transitions are summarized in Table I. The intensities are normalized to the 1241-keV, 758 state at 83◦ and here found to be 1387.4(7) keV. All states beyond an excitation energy of 10 MeV and the γ rays connected to them were observed for the first time.

Energies and spin-parity assignments of the levels in the decay scheme of Fig. 1 as well as energies, relative intensities, and DCO ratios of the transitions are summarized in Table I. The intensities are normalized to the 1241-keV, 758 state at 83◦ and here found to be 1387.4(7) keV. All states beyond an excitation energy of 10 MeV and the γ rays connected to them were observed for the first time.
The $\gamma$-ray spectra in Fig. 2 provide the low-energy reference spectrum for $^{62}$Ga in panel (a) and the confirmation of the 1387-keV line concluding the yrast sequence up to the 17$^+$ state at 9976 keV in panel (b). The yrast sequence includes the bypass via the 3922-keV 8$^+$ state, while panel (a) reveals also several of the $\gamma$ rays known to belong to the low-spin nonyrast structure of $^{62}$Ga. The one, and only notable contamination, in the spectrum in Fig. 2(a), marked “C”, is at 1310 keV, which corresponds to the energy of the most intense transition in $^{61}$Cu [27]. The DCO ratios of the 1387-1746-1107-946-2355-1241-keV sequence are all in agreement with stretched $E2$ multipolarity, which in combination with yrast arguments allows for firm spin and parity assignments of the concerned states. The DCO ratio of the 1487-keV transition points to a $\Delta I = 1$ assignment, while the DCO value for the 867-keV transition is clearly below 0.6, i.e., it has a finite $E2/M1$ mixing ratio, i.e., the spin $I = 8$ state at 3922 keV must have positive parity. Due to yrast arguments, the state at 4945 is likely to be the yrare 9$^+$ state, while technically a 10$^+$ assignment cannot be excluded. Due to two $\gamma$ rays bridging three units of angular momentum between the 5735- and 3922-keV states, the parity of the 4945-keV state must be positive though. Spin-parity assignments of the 2373-3492-4657-keV side structure were taken from Refs. [5,6].

The $\gamma$-ray spectrum in Fig. 3 is the basis for the newly observed high-spin part of the level scheme in Fig. 1. It shows...
the relevant high-energy part of the sum of all spectra taken in coincidence with any combination of the three low-energy transitions (246, 377, or 571 keV) and all those spectra in coincidence with any of these three transitions and with any of the other transitions in the yrast sequence (867, 946, 1107, 1241, 1387, 1487, 1746, or 2355 keV). The binning is 4 keV per channel. Transitions marked with 246, 377, 571, 867, 946, 1107, 1241, 1387, 1487, 1746, or 2355 keV transitions are consistent with stretched dipole assignment. The cube analysis indicates that the weak 2759-keV line should be placed on top of the 12701-keV state. These two sequences do not indicate well-deformed rotational bands. Finally, three more high-energy γ-rays at 3662, 3802, and 3957 keV are found to feed the 13+, 15+, and 17+ yrast states, respectively. Whether or not they represent links to deformed rotational bands remains open at the present level of available statistics.

Clearly, the level scheme in Fig. 1 runs out at some 16 MeV excitation energy and an angular momentum of some 20 h. This is comparable to the high-spin studies of neighboring odd-odd N = Z nuclei populated through similar fusion-evaporation reactions. The high-spin scheme of 58Cu extends to somewhat larger values of excitation energy and spin, probably due to the presence of one dominating rotational band [15,16]. The interpretation of 58Co at high spins implies that the γ-ray flux is spread out over many possible deformed bands [37]. The high-spin region in 66As remains to be settled [38,39].

V. DISCUSSION

The cranked Nilsson-Strutinsky (CNS) calculations are based on the modified oscillator potential, which is cranked around a principal axis [40–42]. Here, we consider both the standard parameters [40] and the prescriptions and new Nilsson parameters for the mass A ≈ 60 region derived more recently [43].

Active j shells comprise the complete N = 3 oscillator shell as well as 1g9/2 in the N = 4 oscillator shell. CNS configurations are classified by the number of holes in the 1f7/2 orbital and particles in either the upper f p or 1g9/2 orbitals. Note, however, that in CNS, we do not refer to the pure j shells but rather to the orbitals in the deformed rotating potential which have their dominant amplitudes in these j shells. The CNS notation [(p1)p2p3; (n1)n2n3] is used where p1 (n1) represents the number of proton (neutron) holes in orbitals of f7/2 character, p2 (n2) the number of protons (neutrons) of f p character, and p3 (n3) the number of g9/2 protons (neutrons). Labels in parentheses are omitted when equal to zero. For an odd number of particles, signature might be specified as subscript index ‘+’ or ‘−’, for example, [21+, 21−].

For an extensive study of 62Ga up to the 9976-keV 17+ state, including isospin aspects within shell-model and CNS approaches, we refer to Ref. [12]. Here, we focus on the hitherto unobserved states at high spin, which indicate the onset of well-deformed rotational structures in 62Ga.

The CNS description started with a scan for the yrast states for the four combinations of parity, π = +, −, and signature, α = 0, 1 for angular momenta up to spin l = 30h. These results are shown in Fig. 4. At low spin, the yrast states are expected, and found to have, all valence particles in the f p orbitals, corresponding to CNS configurations of the type [30;30]. For a brief spin interval, 9− and 11− negative-parity, α = 1 states form the yrast line, i.e., with only one particle in the lowest g9/2 Nilsson orbital, [21+, 31−]. The CNS description started with a scan for the yrast states for the four combinations of parity, π = +, −, and signature, α = 0, 1 for angular momenta up to spin l = 30h. These results are shown in Fig. 4. At low spin, the yrast states are expected, and found to have, all valence particles in the f p orbitals, corresponding to CNS configurations of the type [30;30]. For a brief spin interval, 9− and 11− negative-parity, α = 1 states form the yrast line, i.e., with only one particle in the lowest g9/2 Nilsson orbital, [21+, 31−]. The CNS description started with a scan for the yrast states for the four combinations of parity, π = +, −, and signature, α = 0, 1 for angular momenta up to spin l = 30h. These results are shown in Fig. 4. At low spin, the yrast states are expected, and found to have, all valence particles in the f p orbitals, corresponding to CNS configurations of the type [30;30].
FIG. 4. (a) shows typical examples for different classes of predicted bands. They are obtained from a scan for yrast configurations for the four combinations of parity and signature for spins up to $I = 30\hbar$ in $^{62}\text{Ga}$, using standard CNS parameters [40]. They are plotted relative to a rotating liquid drop energy, $E_{\text{rd}}$, calculated according to Ref. [44]. Positive (negative) parity is indicated by straight (dashed) lines. Signature $\alpha = 0 (\alpha = 1)$ is indicated by filled (open) symbols. Large open circles indicate noncollective states, i.e., where the spin is built from ‘rotation around the symmetry axis’. Large squares are used for states which have reached their $I_{\text{max}}$ values though still more or less collective. (b) shows proton-neutron symmetric configurations of $^{62}\text{Ga}$ of types $[3^+; 0^_+], [3^-; 0^-], [21^+; 2^+_1], [1^+; 2^+_1], [1^+; 2^-], [03^+; 03^-]$, i.e., without considering holes in $f_{7/2}$ orbitals. These CNS calculations use the new parameters [43].

The lowest $g_{9/2}$ orbital is so large that for signature $\alpha = 0$, i.e., even spin values, it is more favorable to let either the two $fp$ protons or the two $fp$ neutrons have the same signature (cf. $[2^+_1; 2^+_1]$ or $[2^-; 2^-]$ in Fig. 4) than converting one $g_{9/2}$ from signature $\alpha = +1/2$ into signature $\alpha = -1/2$, corresponding to, e.g., the $[21^-; 21^+]$ configuration.

To obtain spin values in excess of $I = 17\hbar$ it is possible to stay in the valence space and lift a third particle from the $fp$ into the $g_{9/2}$ orbitals. Two such negative-parity configurations, $[1^-; 2^+], [1^-; 2^+], [1^+_2; 2^+_1]$ show a favored termination close to $(18^-)$ or at yrast $(19^-)$, respectively. More interesting, however, are configurations that involve an additional hole in $f_{7/2}$, i.e., of type $[1; 3]1$ or $[2; 1]3$, respectively. Two bands of this type are shown in Fig. 4(a), which terminate at spins $I = 20$ and $21\hbar$, respectively. One can note that the termination at $I = 21\hbar$ is very much unfavored compared with the band terminating at spin $20\hbar$. In line with investigations in $^{62}\text{Zn}$ (cf. discussion of the bands TB1 and TB2 in Ref. [30]), it is known that the signature change of a hole in $f_{7/2}$ (e.g., from $[21^+; 1^-; 3^+; 1^+]$ to $[21^+; 1^+; 3^-; 1^+]$) is costly in excitation energy.

For the sake of the observed states displayed in Fig. 1, one could stop here. Nevertheless, we note that the next predicted excitation is to switch to negative parity bands by lifting a third $fp$ particle into a $g_{9/2}$ orbital before configurations with four holes in $f_{7/2}$ and four or five particles in $g_{9/2}$ orbitals dominate the yrast line at $I \approx 30\hbar$. In fact, the configuration $(2; 3)2$ relate $^{62}\text{Ga}$ at high spins to the anticipated $(2; 3)2$ configuration of the superdeformed band observed in $^{60}\text{Zn}$ [13,18,20].
FIG. 5. (a) shows energies relative to the rotating liquid drop energy [44] of the observed ‘bands’ in $^{62}$Ga They are compared with the assigned calculated CNS configurations using standard parameters [40] in (b). The difference between experiment and theoretical interpretation is shown in (c). The label ‘gb’ represents the $\pi (fp)^3\sigma (fp)^3$ ground band up to spin $9^+$, denoted $[3,0;3,0]$ in the CNS description. Moving one proton and one neutron into the lowest $g_{9/2}$ orbitals leads to the $[21;21]_\alpha$ band labeled ‘gb’. High-spin bands Q1, Q2, and Q3 are interpreted to involve the excitation of either one proton or one neutron across the shell gap at particle number 28. Connections of experiment-related data points of Q3 are dotted due to the unknown excitation energy (X $\approx$ 11 MeV in Fig. 1). The data point at spin $I = 21\hbar$ in Q1 is tentative, hence put in parentheses.

It is instructive to consider the proton-neutron symmetric configurations in $^{62}$Ga with an increasing number of $g_{9/2}$ particles, which are shown in Fig. 4(b). As already noticed in Fig. 4(a), the configurations with no or one such proton and neutron are calculated yrast, and the latter turns out to be particularly favored. Also the configurations with two $g_{9/2}$ particles approach the yrast line for their terminating states at $I = 20$ and $21\hbar$, respectively. However, the band with all valence particles in $g_{9/2}$ orbitals lies high above yrast over its full spin range. This is different from the $I = 21\hbar$ state in $^{94}$Ag with all six valence holes in $g_{9/2}$ orbitals, which appears to be particularly favored in energy [45]. The difference is, of course, that with particles outside the $N = Z = 28$ gap there is a competition to put the valence particles in either the $fp$ orbitals or the $g_{9/2}$ orbitals while holes in the $N = Z = 50$ core are naturally put in the $g_{9/2}$ orbitals because the competing $N' = 3$ shells are much lower in energy.

Figures 5 and 6 provide the comparison of the experimental bands and CNS calculations with standard [40] and new $A \approx 60$ [43] parameters. Following up on the discussion in Ref. [12], it is obvious that the experimental signature $\alpha = 1, 9^+$ through 17$^+$ sequence (4945- through 9976-keV levels) to the $[21;21]_\alpha$ CNS configuration is also apparent [12]. Looking at details, the kink in the experimental data at spin $I = 13\hbar$ suggests a switch from a $p_{9/2}^2$ $g_{9/2}$ occupation for both protons and neutrons ($I_{\text{max}} = 13\hbar$) to a different $(fp)^3$ $g_{9/2}$ occupation for both protons and neutrons ($I_{\text{max}} = 17\hbar$). In fact, the $8^+ \rightarrow 6^+ \rightarrow 4^+ \rightarrow 2^+ \rightarrow 0^+$ cascade in the even-even core $^{60}$Zn reveals an almost identical behavior [13]. In a seniority coupling scheme, the proton and neutron in the $g_{9/2}$ orbital can be viewed as an aligned spectator contributing with $I = 9\hbar$ with seniority $\nu = 2$. Seniority $\nu = 4$ states reach a maximum of $I = (9 + 4)\hbar = 13\hbar$ (for this $\alpha = 1$ band). Breaking an additional pair, i.e., switching to seniority $\nu = 6$, provides the remaining states with $I_{\text{max}} = (9 + 4 + 4)\hbar = 17\hbar$. In this picture, the change in seniority explains the kink in energy observed experimentally in Fig. 5(a) [12].

For the predicted negative-parity yrast $9^-$ and $11^-$ states there are neither candidates in the present data nor reported in earlier medium-spin studies [5,6]. At lower spins, the corresponding structures are quickly becoming nonyrast. Population from the top, i.e., via the signature $\alpha = 1$ positive parity yrast sequence, is very unlikely, because it would require $M2$ transitions between, for instance, the observed 13$^+$ and the predicted 11$^-$ yrast states. Note that the negative-parity states with signature $\alpha = 0$ never turn yrast in this spin region due to too large a signature splitting even in the $fp$ orbitals (cf. Fig. 4).

Moving beyond spin $I = 17\hbar$, another excitation from an $fp$ into a $g_{9/2}$ orbital invokes rotational bands concluding in favored termination. The experimental level at 12701 keV with a tentative spin 18 assignment is a good candidate to match the predicted 18$^-$ terminating state of the $[21;21]_\alpha$ configuration. An experimental candidate for the predicted terminating 19$^-$ state of the $[1;2;21]_\alpha$ configuration might be the level at 13610 keV. Here, the strength of a high-energy 3634-keV line could account for the intrinsically required $g_{9/2} \rightarrow f_{5/2}$ M2 recoupling to reach the terminating 17$^-$ state of the $[21;21]_\alpha$ configuration.

The rather short bands observed above $I = 17\hbar$, labeled Q1, Q2, and Q3 in Fig. 1, are in good agreement with the CNS configurations involving either a proton or neutron excitation from a $f_{7/2}$ orbital into a $fp$ orbital, i.e., one hole in the $f_{7/2}$ shell. These bands are of the same type as the first smoothly terminating bands which were identified in the $A = 60$ region, namely bands with one hole in the $f_{7/2}$ in $^{64}$Zn [46] and $^{62}$Zn [47]. For $^{62}$Ga, if one assumes that the Q3 band is similar to the Q2 band (but slightly lower in energy than plotted in Fig. 1), the difference between experiment and calculations in Figs. 5(c) and 6(c) is essentially constant as a function of spin and close to zero. The only deviation is found for the tentative $21^+ \rightarrow 19^+$ transition, for which experiment suggests a less unfavored termination as the predictions. As discussed above, the unfavored energy is caused by a large signature splitting at termination for configurations with one hole in the $f_{7/2}$ shell which in turn is understood from the high energy cost to make

its counterpart in a corresponding $\alpha = 0$ configuration. It lies above the spin 1 to 9 sequence in both experiment and calculations.

The assignment of the experimental signature $\alpha = 1, 9^+$ through 17$^+$ sequence (4945- through 9976-keV levels) to the $[21;21]_\alpha$ CNS configuration is also apparent [12]. Looking at details, the kink in the experimental data at spin $I = 13\hbar$ suggests a switch from a $p_{9/2}^2$ $g_{9/2}$ occupation for both protons and neutrons ($I_{\text{max}} = 13\hbar$) to a different $(fp)^3$ $g_{9/2}$ occupation for both protons and neutrons ($I_{\text{max}} = 17\hbar$). In fact, the $8^+ \rightarrow 6^+ \rightarrow 4^+ \rightarrow 2^+ \rightarrow 0^+$ cascade in the even-even core $^{60}$Zn reveals an almost identical behavior [13]. In a seniority coupling scheme, the proton and neutron in the $g_{9/2}$ orbital can be viewed as an aligned spectator contributing with $I = 9\hbar$ with seniority $\nu = 2$. Seniority $\nu = 4$ states reach a maximum of $I = (9 + 4)\hbar = 13\hbar$ (for this $\alpha = 1$ band). Breaking an additional pair, i.e., switching to seniority $\nu = 6$, provides the remaining states with $I_{\text{max}} = (9 + 4 + 4)\hbar = 17\hbar$. In this picture, the change in seniority explains the kink in energy observed experimentally in Fig. 5(a) [12].

For the predicted negative-parity yrast $9^-$ and $11^-$ states there are neither candidates in the present data nor reported in earlier medium-spin studies [5,6]. At lower spins, the corresponding structures are quickly becoming nonyrast. Population from the top, i.e., via the signature $\alpha = 1$ positive parity yrast sequence, is very unlikely, because it would require $M2$ transitions between, for instance, the observed 13$^+$ and the predicted 11$^-$ yrast states. Note that the negative-parity states with signature $\alpha = 0$ never turn yrast in this spin region due to too large a signature splitting even in the $fp$ orbitals (cf. Fig. 4).

Moving beyond spin $I = 17\hbar$, another excitation from an $fp$ into a $g_{9/2}$ orbital invokes rotational bands concluding in favored termination. The experimental level at 12701 keV with a tentative spin 18 assignment is a good candidate to match the predicted 18$^-$ terminating state of the $[21;21]_\alpha$ configuration. An experimental candidate for the predicted terminating 19$^-$ state of the $[1;2;21]_\alpha$ configuration might be the level at 13610 keV. Here, the strength of a high-energy 3634-keV line could account for the intrinsically required $g_{9/2} \rightarrow f_{5/2}$ M2 recoupling to reach the terminating 17$^-$ state of the $[21;21]_\alpha$ configuration.

The rather short bands observed above $I = 17\hbar$, labeled Q1, Q2, and Q3 in Fig. 1, are in good agreement with the CNS configurations involving either a proton or neutron excitation from a $f_{7/2}$ orbital into a $fp$ orbital, i.e., one hole in the $f_{7/2}$ shell. These bands are of the same type as the first smoothly terminating bands which were identified in the $A = 60$ region, namely bands with one hole in the $f_{7/2}$ in $^{64}$Zn [46] and $^{62}$Zn [47]. For $^{62}$Ga, if one assumes that the Q3 band is similar to the Q2 band (but slightly lower in energy than plotted in Fig. 1), the difference between experiment and calculations in Figs. 5(c) and 6(c) is essentially constant as a function of spin and close to zero. The only deviation is found for the tentative $21^+ \rightarrow 19^+$ transition, for which experiment suggests a less unfavored termination as the predictions. As discussed above, the unfavored energy is caused by a large signature splitting at termination for configurations with one hole in the $f_{7/2}$ shell which in turn is understood from the high energy cost to make
FIG. 6. Same as Fig. 5 but using new parameters \[43\] for the CNS calculations.

a hole in the low-lying \[303\] /2 Nilsson orbital at large oblate deformation.

The general features of the yrast states with standard and new parameters are very similar, where the low spin bands are formed with all valence particles in the \(fp\) orbitals followed by configurations where at first, valence particles are excited to the \(g9/2\) orbitals before excitations from the \(f7/2\) shell of the \(N = Z = 28\) core become competitive in energy. Such an evolution is seen most clearly in \(62\)Zn, highlighted in Fig. 21 of Ref. [30]. Considering that pairing is not included, the difference between experiment and theory should have a spin dependence reflecting some kind of average pairing energy, i.e., of the type \(c_1 \exp(-c_2 I)\) (\(c_1, c_2\) constants), for instance, as calculated in \(^{138}\)Nd in Ref. [48] and for \(^{167}\)Lu in Ref. [49]. It appears that the differences using standard parameters follows such a trend somewhat better than those where the new parameters are used.

The shape evolution of the calculated \([21^+_1; (1^-)3^+_1, 2^+_1]\) configuration associated with band Q1 is shown in Fig. 7. It starts out at similarly small values of \(\gamma \approx 20^\circ\) but somewhat larger prolate deformation \(\varepsilon_2 \approx 0.27\) than the \([21^+_1; 21^+_1]\) yrast structure (cf. Fig. 5 in Ref. [12]). Both structures are predicted to terminate at about the same shape at \(\gamma \approx 60^\circ\), but with reversed \(\varepsilon_2 \approx 0.23\) \(([21^+_1; (1^-)3^+_1, 2^+_1])\) and \(\varepsilon_2 \approx 0.27\) \(([21^+_1; 21^+_1])\) quadrupole deformation. The difference in shape evolution of these two configurations can be understood from the polarizing effects of the hole in the \(m = \Omega = 7/2\) or \(5/2\) \(f7/2\) orbital. On the prolate side, a hole in the up-sloping orbitals leads to a larger deformation, while it leads to a smaller deformation on the oblate side.

VI. SUMMARY AND CONCLUSIONS

The experimental level scheme of \(^{62}\)Ga has been extended from 10 MeV up to 17 MeV excitation energy. The onset of well-deformed rotational bands could be established in that excitation energy region reaching spin \(I \gtrsim 20h\). While the yrast states up to \(I = 17h\) are formed from the valence particles outside the \(^{56}\)Ni core, the explanation of the higher spin states suggests one hole in the \(f7/2\) shell. CNS calculations with standard and new parameters provide comparable results, though details point toward a somewhat better description with the standard parameters. Any profound discussion of \(T = 0\) pairing effects at high spins in \(^{62}\)Ga calls for the identification of well-deformed \([2)32; (2)32]\) structures. However, a corresponding experiment will be challenging due to counteracting limitations of the required excitation energy and angular momentum versus finite absolute and sufficient relative production cross section to populate and observe \(^{62}\)Ga at such high-lying entry states. A properly designed experiment with the next generation of \(\gamma\)-ray tracking arrays will be capable of handling the task [50,51].

ACKNOWLEDGMENTS

We would like to thank the accelerator crews and the Gammasphere support staff at Argonne and for their supreme efforts. This research used resources of ANL’s ATLAS facility, which is a DOE Office of Science User Facility. This work is supported in part by the Swedish Research Council (Vetenskapsrådet, VR 2016-3969) and the U.S. Department of Energy under Grants No. DE-AC02-06CH11357 (ANL), No. DE-AC03-76SF00098 (BNL), and No. DE-FG05-88ER-40406 (WU).
