Identification of the $g_{9/2}$-proton bands in the neutron-rich ^{71,73,75,77}Ga nuclei

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Excited states in the odd-A ^{71,73,75,77}Ga nuclei have been populated in deep-inelastic reactions of a ^{76}Ge beam at 530 MeV with a thick ^{238}U target. High-spin sequences built upon the $9/2^+$, $5/2^-$, and $3/2^-$ states were identified in all four isotopes. A comparison of the observed structures with the yrast positive-parity states in the neighboring even-even Zn cores indicates that the newly identified levels may be regarded as arising from the relatively weak coupling of the odd proton to the core states. However, significant contributions from broken pairs are expected to be present in this region of excitation energy. The present data set also provides clarification of previously reported decay paths of the low-energy levels in ^{71,73,75,77}Ga.

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I. INTRODUCTION

Recent studies of the structure of odd-mass Cu nuclei made it possible to follow the evolution of single-particle states around the $Z = 28$ closed shell and also to study the onset of collective effects for a single proton coupled to the changing Ni core structures [1]. The discovery by Franchoo *et al.* [2,3] of a sharp downward shift in the excitation energy of the $5/2^-$ states arising from the $f_{5/2}$ proton orbital in ^{71,73}Cu (see top panel of Fig. 1) provided strong support for the development of a model showing the critical role of the tensor interaction between the $g_{9/2}$ neutrons and $f_{5/2}$ protons [4,5]. Shell-model calculations with a realistic effective interaction derived from the G-matrix and modified further for the monopole correction [4,6–8], as well as calculations with a tensor force included in the NN interaction [5], reproduced the decrease in excitation energy of the effective single-particle strengths, in particular for the $5/2^-$ level, with increasing neutron number. However, the calculated energy shift turned out to be smaller than that observed experimentally. A recent Coulomb excitation experiment with radioactive beams led to the identification of the yrast $1/2^-$ levels in ^{71,73}Cu [1]. The sharp decline in the position of this level was found to follow that of the $5/2^-$ state. Furthermore, the large $B(E2; 1/2^- \rightarrow 3/2^-_{\rm g.s.})$ value determined experimentally indicated that the low-lying $1/2^-$ level has a structure that is more collective than predicted by shell-model calculations.

With three protons beyond the $Z = 28$ closed shell, the structure of the odd-mass Ga isotopes is expected to be even more complex, owing to the inclusion of a broken proton pair in collective effects. Low-energy levels in these nuclei have been determined in both proton stripping and pickup reactions [9–12] as well as through radioactive decay studies [13–15]. The stable ^{69,71}Ga isotopes have also been investigated in Coulomb excitation and scattering experiments [16,17]. High-spin level structures for ^{69}Ga and lighter Ga isotopes have been obtained from various heavy-ion reactions [18,19]. The $N = 38$ nucleus ^{69}Ga has been the upper limit for such studies with stable beam and target combinations.

II. PREVIOUS STUDIES

Previous studies of the structure of the odd-A Ga nuclei indicated that their level schemes below ∼2 MeV involve negative-parity states arising from single-particle and core-coupled configurations dominated by the $p_{3/2}$, $f_{5/2}$, $p_{1/2}$, and $f_{7/2}$ proton orbitals. Results of (^{3}He, d) reactions on ^{64,66,68,70}Zn stable targets provided evidence for significant shifts in transition strengths and excitation energies for the low-lying states in ^{71}Ga, when compared to ^{65,67,69}Ga [9]. In particular, the $\ell = 1$ transition strength to the first excited state in ^{71}Ga was found to be an order of magnitude smaller than the corresponding values in the lighter Ga isotopes. In addition, the excitation energies of the $\ell = 3$ $(5/2^-)$ and $\ell = 4$ $(9/2^+)$ levels were found to decrease in ^{71}Ga. The observed discontinuities at $N = 40$ were attributed to an increased proton-neutron interaction between particles occupying the same orbital [9]. The deviation from the systematics observed in ^{71}Ga was confirmed by the results of a (d, ^{3}He) transfer reaction [10]. In that work, the spectroscopic factors measured in the ^{69,71,73,75}Ga isotopes indicated an abrupt change in the proton configurations between $N = 40$ and 42. Although the $p_{1/2}$, $f_{5/2}$, $p_{3/2}$, and $g_{9/2}$ single-particle strengths were found to be carried by a single level for each proton orbital involved, the position of these orbits turned out to be very different in the Ga isotopes below and

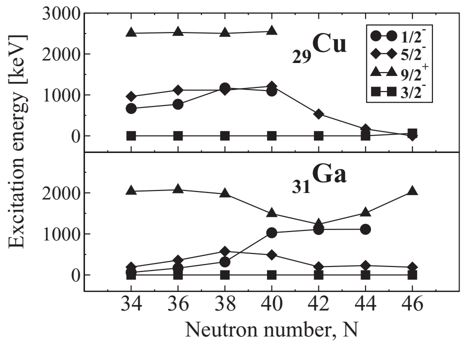

FIG. 1. Systematics of the single-particle states $3/2^-$ (squares), $5/2^-$ (diamonds), $1/2^-$ (circles), and $9/2^+$ (triangles) in the odd-A Cu (top) and Ga (bottom) isotopes with $N = 34$–46. Evidence for the single-particle character of the states included in these systematics has been obtained in previous transfer reactions and Coulomb excitation experiments.

above $N = 40$, as demonstrated in the bottom panel of Fig. 1. For instance, the excitation energy of the $1/2^-$ state, containing an important component from the $p_{1/2}$ proton orbital (in terms of the measured spectroscopic factors), appears to display a sharp rise from 320 keV in ^{69}Ga to 1109 keV in ^{71}Ga. Results from a (t, p) reaction on stable Ga targets have been used to firmly assign spin $3/2^-$ to the low-lying states in ^{71,73}Ga, for which the angular distribution of the protons were consistent with $\ell = 0$ transitions [20]. The splitting of the $\ell = 0$ strength in three approximately equal components observed in ^{73}Ga was interpreted as a clear sign for a change in nuclear deformation between $N = 40$ and 42 [20]. The proposed change in the nuclear shape was also supported by the behavior observed for the $9/2^+$ level arising from the $\pi g_{9/2}$ orbital. The position of the latter was found to decrease from ~2.0 MeV in ^{65,67,69}Ga to ~1.5 MeV in ^{71}Ga and ~1.2 MeV in ^{73}Ga and then rise again to 1.5 MeV in ^{75}Ga and finally back to 2 MeV in ^{77}Ga (see Fig. 1 and Ref. [10]). This trend resembles that exhibited by the corresponding level in the odd-A As and Br isotopes [21]. In all three isotopic chains, the minimum position of the $9/2^+$ level was observed at $N = 42$. Calculations in the framework of the deformed model plus Coriolis coupling and pairing interaction associated the change in the position of the $9/2^+$ state with an increase in deformation as the neutron number reaches the $N = 28$–50 midshell [22]. The deformation is predicted to be at a maximum of $\beta_2 \approx 0.2$ at $N = 42$, which will correspond to a minimum in excitation energy for the $9/2^+$ proton state. However, further calculations and discussions concerning the shapes of these odd-A nuclei have been limited by the lack of high-spin data, as well as by ambiguous spin assignments for a number of the proposed levels.

Results of previous β-decay studies [13–15] in all four nuclei indicated that the $9/2^+$ state cascades to the $3/2^-$ ground state via $E1$ transitions through lower energy $7/2^-$, $9/2^-$, and/or $11/2^-$ levels. In contrast, in the neighboring $Z = 29$ nuclei ^{67,69}Cu, direct $E3$ population of the $3/2^-$ ground state has been observed [23,24]. From the measured half-life of the $9/2^+$ state in ^{67}Cu, lower limits of 11 and 1.1×10^{-6} W.u. were determined for the $B(E3; 9/2^+ \to 3/2^-_{\text{g.s.}})$ and $B(E1; 9/2^+ \to 7/2^-)$ transition strengths, respectively [23]. The limit obtained for the $B(E3)$ value in ^{67}Cu was found to be in good agreement with the large $B(E3) \uparrow$ strength in ^{63}Cu, extracted from an electron-scattering measurement [25,26]. The fast $E3$ decay observed experimentally was interpreted to arise from the strong mixing of the $9/2^+$ single-particle level with the state of the same spin belonging to the multiplet arising from the coupling of the odd $p_{3/2}$ proton with the 3^- octupole vibration in the even-even Ni cores [26]. In ^{69}Cu, the observed $B(E3)/B(E1)$ ratio was found to be two orders of magnitude smaller than that determined in ^{67}Cu. As systematics suggest that the 3^- state in ^{68}Ni should be lower in energy than that in ^{66}Ni, the smaller ratio was explained by the mixing of the $9/2^+$ level arising from the $\pi g_{9/2}$ orbital with the $(\pi p_{3/2} \nu g_{9/2} \nu p_{1/2}^{-1})_{9/2^+}$ configuration [27]. In this case, $E3$ transitions between states of this configuration and the $3/2^-$ ground state, dominated by the $\pi p_{3/2}$ orbital, are quite hindered.

So far, no $E3$ decay from the $9/2^+$ level has been observed in the odd-A Ga isotopes beyond $N = 34$. The absence of such a transition might be explained by the fact that, in the Ga isotopic chain, the energy spacing between the $9/2^+$ single-particle levels and 3^- octupole states in the even-even Ge and Zn neighboring cores is ~500 keV larger than that observed experimentally in the Cu-Ni counterparts. The larger energy spacing would then be expected to lead to a smaller mixing between the $9/2^+$ proton state and the $(\pi p_{3/2} \otimes 3^-)_{9/2^+}$ configuration.

Results of fusion-evaporation reactions indicated that, at low excitation energies, the level structures of the lighter ^{65,67,69}Ga isotopes exhibit a typical particle-core coupling pattern [18,19]. This suggests moderate prolate deformations for these nuclei, in agreement with theoretical predictions [22]. Above 1.5–2.0 MeV, two distinct bands were identified in all three isotopes, one of positive parity, based on a $9/2^+$ level, and another of negative parity, based on a $5/2^-$ level. The mean lifetimes measured for most of the observed levels in ^{69}Ga indicated that the two structures decay by rather collective $E2$ transitions [19]. In the heavier ^{71,73,75}Ga isotopes, however, the addition of $g_{9/2}$ neutrons is expected to drive the nuclear shape toward slightly larger deformation, leading to a more pronounced rotational-like pattern for the structures built on the single-particle proton levels.

The aim of the present analysis was to identify high-spin excited-level sequences and clarify some of the spin and parity assignments for lower energy levels in the odd-A Ga isotopes with $N \geqslant 40$.

III. EXPERIMENT

Excited levels in ^{71,73,75,77}Ga were populated in the deep-inelastic reaction of a 530-MeV ^{76}Ge beam with a 55 mg/cm^2, isotopically enriched ^{238}U target. The beam was produced by the ATLAS accelerator at Argonne National Laboratory. The beam energy was chosen to be ~20% above the Coulomb barrier at mid-target.

Gamma rays emitted by the reaction products were detected by the Gammasphere array consisting of 100 Compton-suppressed HPGe detectors [28]. The event trigger was set to require signals from a minimum of three Compton-suppressed Ge detectors.

The data were sorted offline into single-γ spectra, γ-γ coincidence matrices, and γ-γ-γ cubes. As this kind of reaction leads to the population of a wide range of projectile- and target-like fragments, the content of the single-γ spectra and even the γ-γ matrices is very complex. Therefore, in most cases, transitions in the nuclei of interest can only be identified by analyzing triple- or higher fold coincidence data. This requires that at least two coincident γ rays are known from previous studies. In the ^{71,73,75,77}Ga isotopes, the transitions observed in β-decay studies reported in Refs. [13–15] were used to place double gates in the coincidence cube. The results obtained in this analysis are presented in the following section.

IV. EXPERIMENTAL RESULTS

A. ^{71}Ga

The β-decay study reported in Ref. [13] showed that the $9/2^+$ state in ^{71}Ga de-excites via a 386-keV $E1$ transition to the $7/2^-$ state at 1107 keV. The main decay path of this level is through the 620–488 keV cascade defining the $7/2^- \rightarrow 5/2^- \rightarrow 3/2^-_{\mathrm{g.s}}$ spin sequence.

In the present analysis, double coincidence gates placed on the 488–620 keV and 386–620 keV transitions revealed intense peaks at 588 and 859 keV (see Fig. 2 and top panel of Fig. 3). Both transitions also appeared in all combinations of double gates using the 488-, 620-, and 1107-keV γ rays with the 386-keV transition. Based on their observed intensities, the 588- and 859-keV lines were placed in the level scheme of ^{71}Ga as depopulating the states at 2082 and 2941 keV, above the $9/2^+$ level, as shown in Fig. 4. Furthermore, double gates set on any two coincident transitions on the decay path of the newly observed 2941-keV state revealed the γ rays of 1057 and 1087 keV that proved to not be in mutual coincidence. Thus, both transitions were placed in the level scheme of ^{71}Ga as feeding the state at 2941 keV (see the level scheme presented in Fig. 4). An example of a double-gated spectrum showing the presence of these two γ rays is displayed in the middle panel of Fig. 3.

Spins and parities for the levels below the $9/2^+$ state were determined previously in transfer reactions [9], from the observed decay pattern and from experimental log ft values extracted in a β-decay study [13], as well as from angular distributions of γ rays emitted in the ^{71}Ga$(n, n'\gamma)$ reaction

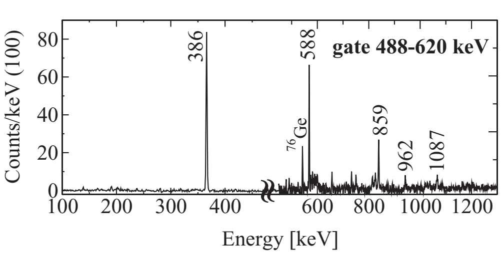

FIG. 2. γ-ray spectrum obtained by setting double coincidence gates on the 488- and 620-keV transitions in ^{71}Ga. Peaks marked by their energies are attributed to ^{71}Ga.

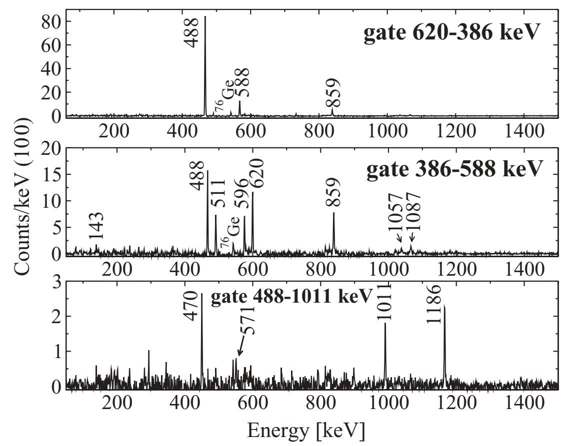

FIG. 3. γ-ray spectra obtained by placing double coincidence gates on transitions in ^{71}Ga. Peaks marked by their energies are attributed to ^{71}Ga.

[17]. The low statistics obtained in the present experiment prevents the extraction of angular distribution and correlation data for the transitions de-exciting the newly observed high-energy levels. Thus, spins and parities are proposed for the new states based on a comparison with the systematics and on nuclear structure considerations. As the energy spacing between the states observed at 2082, 2941, and 4028 keV resembles that of the levels seen above the $9/2^+$ state in ^{69}Ga, $E2$ character was assumed for the 588-, 859-, and 1087-keV transitions in ^{71}Ga. This suggests spin and parity assignments of $13/2^+$, $17/2^+$, and $21/2^+$ for the levels at 2082, 2941, and 4028 keV, respectively.

Once the sequence of positive-parity states on top of the $9/2^+$ level was established, double gates placed on the newly observed transitions were used to investigate the various decay

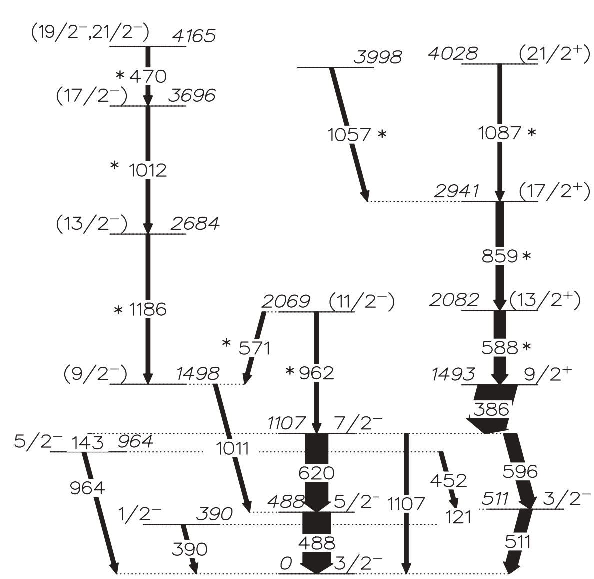

FIG. 4. Level scheme of ^{71}Ga obtained from the present coincidence analysis. The widths of the arrows are proportional to the intensities of the γ rays. Transitions observed for the first time in this work are indicated by a star.

paths of the $9/2^+$ state reported previously [13,17]. In the middle panel of Fig. 3, the spectrum obtained by setting a double gate on the 386- and 588-keV coincident transitions shows strong peaks at 511 and 596 keV. Both transitions were observed previously in the study of the $9/2^+ \beta$-decaying isomer in ^{71}Zn and associated with the secondary decay path of the $7/2^-$ state at 1107 keV [13,17]. The much weaker transitions of 121, 143, 390, 452, and 964 keV, identified in the aforementioned decay studies, were also observed in the present data set.

The investigation of the 488–1011 keV coincidence gate revealed the transitions of 1186, 1012, and 470 keV (see bottom panel of Fig. 3). Based on intensity arguments, the new γ rays were arranged in the level scheme presented in Fig. 4 as belonging to the cascade feeding the level at 1498 keV. This state and its decay path via two transitions of 1011 and 588 keV were identified in the β-decay study reported in Ref. [13]. However, the 588-keV γ ray is not observed in the present data set. According to Ref. [13], this transition should be present in the spectrum at the level of 10% of the decay branching for the 1498-keV level, which is still above the observational limit of the present measurement.

In Ref. [13], spins and parities $5/2^-$ or $7/2^-$ were suggested for the 1498-keV level, based on the observed decay paths to the $5/2^-$ state at 488 keV and to a level at 910 keV. However, the population in a deep-inelastic reaction of a third $5/2^-$ level, located ~1 MeV above the yrast $5/2^-$ state, is rather unlikely. This leaves only the value $7/2^-$ proposed in Ref. [13] as a likely assignment for this 1498-keV level. In the present work, only the decay branch to the level at 488 keV was seen. For the state at 910 keV, results of the $(n, n'\gamma)$ experiment suggested a spin $3/2^-$, based on the observed isotropic angular distribution for the 910-keV γ ray [17]. However, such a spin value, although indicated as likely, could not be confirmed by the analysis of the angular distribution of the protons emitted in the (t, p) reaction [20]. Also, given the discrepancy of the γ branchings observed in this work with those reported in the previous β-decay study [13], the present result opens up the possibility that the level at 1498 keV has $9/2^-$ quantum numbers and corresponds to the state of the same spin observed at an excitation energy of 1765 keV in ^{69}Ga [19]. In fact, the structure consisting of the coincident γ rays of 1186, 1011, and 470 keV, determined in the present work to feed the 1498-keV level, is very similar to the 1478–836–450 keV cascade observed to populate the corresponding level in the lighter ^{69}Ga isotope reported in Ref. [19]. In that work, spins and parities $13/2^-$ and $15/2^-$ were determined from an angular distribution analysis for the levels decaying by the 1478- and 836-keV γ transitions. The result of such an analysis for the 450-keV transition, combined with the yield ratio extracted from an excitation function measurement, suggested possible spin values of $17/2^-$ or $19/2^-$ for the level at 4528 keV [19]. Thus, based on the comparison with the observed level structure of ^{69}Ga, spins and parities $9/2^-$, $13/2^-$, $17/2^-$, and $(19/2^-, 21/2^-)$ are proposed in this work for the levels at 1498, 2684, 3696, and 4165 keV, respectively. These sequences in both nuclei appear to arise from the coupling of the $f_{5/2}$ proton with the levels expected from a broken pair of $g_{9/2}$ neutrons.

TABLE I. Excitation energies, transition energies and intensities, and initial and final spins and parities for the transitions observed in ^{71}Ga as obtained in the present experiment. The intensities are normalized to the 386-keV transition, set to be 100. The experimental errors on the transition energies are 0.2 keV for the intense γ rays and 0.5 keV for the weak ones ($I_\gamma < 5\%$).

E_{level} (keV)	E_γ (keV)	I_γ (%)	$I_i^\pi \rightarrow I_f^\pi$
390.2	390.2	3.2(3)	$1/2^- \rightarrow 3/2^-$
487.5	487.5	72.3(8)	$5/2^- \rightarrow 3/2^-$
511.3	121.1	3.9(5)	$3/2^- \rightarrow 1/2^-$
	511.3	31(5)	$3/2^- \rightarrow 3/2^-$
963.8	452.5	3.4(3)	$5/2^- \rightarrow 3/2^-$
	963.8	3.4(4)	$5/2^- \rightarrow 3/2^-$
1107.2	143.4	4.4(4)	$7/2^- \rightarrow 5/2^-$
	595.9	33.9(5)	$7/2^- \rightarrow 3/2^-$
	619.7	58.9(7)	$7/2^- \rightarrow 5/2^-$
	1107.2	2.7(3)	$7/2^- \rightarrow 3/2^-$
1493.2	386.0	100	$9/2^+ \rightarrow 7/2^-$
1498.4	1010.9[a]	10.8(5)	$(9/2^-) \rightarrow 5/2^-$
2069.1	570.7	1.1(2)	$(11/2^-) \rightarrow (9/2^-)$
	961.9	2.7(2)	$(11/2^-) \rightarrow 7/2^-$
2081.5	588.3	18.2(3)	$(13/2^+) \rightarrow 9/2^+$
2684.0	1185.6	6.4(4)	$(13/2^-) \rightarrow (9/2^-)$
2940.7	859.2	10.2(5)	$(17/2^+) \rightarrow (13/2^+)$
3695.5	1011.5[a]	5.1(3)	$(17/2^-) \rightarrow (13/2^-)$
3998.0	1057.3	4.1(5)	$\rightarrow (17/2^+)$
4027.5	1086.8	5.2(3)	$(21/2^+) \rightarrow (17/2^+)$
4165.2	469.7	4.2(4)	$(19/2^-, 21/2^-) \rightarrow (17/2^-)$

[a]This transition is a doublet in ^{71}Ga. The summed intensity extracted from the present data set is 15(2).

The excitation energies, γ-ray energies, and observed intensities, as well as initial and final spin values for the transitions identified in the present work for ^{71}Ga, are given in Table I. Intensities were determined from the γ-γ matrices for the strongest lines and γ-γ-γ cubes for the remainder of the transitions. All levels below 1 MeV reported in the Nuclear Data Sheets were populated in this experiment, except for the $3/2^-$ level at 910 keV [29].

B. ^{73}Ga

In contrast to ^{71}Ga, the level structure of ^{73}Ga was not well known from previous studies, owing to the low Q value for radioactive decay. Hence, a number of low-lying levels are only known with ±7 keV uncertainties. In particular, the $9/2^+$ level was determined in a $(d, {}^3\mathrm{He})$ reaction to be at 1233(7) keV [10]. Thus, the $9/2^+$ state would be ~250 keV lower than the corresponding level in the neighboring ^{71,75}Ga nuclei. In that work, six lower-lying levels at 198 ($\ell = 3$), 214 ($\ell = 1$), 495 ($\ell = 3$), 912 ($\ell = 1$), 952 ($\ell = 3$), and 1112 keV ($\ell = 1$) were also populated. All these observed states and their angular spins were confirmed in a recent measurement with a polarized beam [12].

In a ^{71}Ga(t, p) reaction study, three low-energy $3/2^-$ states were identified by strong $\ell = 0$ transitions: the levels at 219 and 915 keV, as well as the state thought to be the ground state [17]. However, recent results from collinear laser spectroscopy have revealed the possibility of a $1/2^-$ spin and parity assignment for the ground state [30]. Although the present data neither support nor refute such a possibility, it is interesting to note that the results of a study of the β decay of ^{73}Ga to levels of ^{73}Ge [31] are quite compatible with a $1/2^-$ spin and parity assignment for the ground state of ^{73}Ga. In view of the "certainty" of the $\ell = 0$ assignment in the (t, p) reactions [12,17], there is little doubt that a $3/2^-$ level is either the ground state or an excited level located quite close to the ground state.

The β-decay study reported in Ref. [14] in which levels of ^{73}Ga were populated in the decay of ^{73}Zn revealed the transitions de-exciting the levels at 218 (corresponding to the state at 214 identified in Ref. [10]), 496, and 911 keV, as well as several high-energy γ rays de-exciting states located above an excitation energy of 1.7 MeV. However, no transitions depopulating the $9/2^+$ state at 1233 keV were reported prior to this work. Moreover, the γ-ray branchings and precise energies for the decay of the levels at 198, 952, and 1112 keV, populated in the transfer reaction study described in Ref. [10], had not been previously determined.

As mentioned in the previous section, the systematics of the lighter Ga isotopes indicate that the $9/2^+$ proton state decays via a rather strong $E1$ transition to a nearby $7/2^-$ state. In ^{73}Ga, results of a $(d, {}^3\text{He})$ reaction indicated an $\ell = 3$ character for the levels at 198, 495, and 952 keV [10]. Therefore, spins and parities $5/2^-$ or $7/2^-$ were proposed for these states. The level at 198 keV was found to be strongly populated in an (α, p) reaction and to have an angular distribution similar to that of the $5/2^-$ state at 488 keV in the lighter ^{71}Ga isotope [11]. Thus, a spin and parity assignment of $5/2^-$ was also proposed for the 198-keV level in ^{73}Ga. The small strength observed in the (α, p) reaction for the 952-keV level suggests a $7/2^-$ assignment for this state. Furthermore, based on the comparison with the angular distributions obtained for the $5/2^-$ state at 965 keV in ^{71}Ga, the same spin-parity values were proposed for the 496-keV level in ^{73}Ga [11]. In contrast, recent polarized proton pickup data suggest spin and parity $7/2^-$ for this state [12].

The comparison with the systematics of the lighter Ga isotopes suggests the $7/2^-$ level at 952 keV as a strong candidate for the state expected to be rather strongly fed in the decay of the $9/2^+$ level. The $9/2^+ \to 7/2^-$ transition would then correspond to a γ ray of 280 keV.

The result of a double gate set on the 218-keV transition observed in the β-decay study reported in Ref. [14] and the 280-keV γ ray proposed in the present work to de-excite the $9/2^+$ state in ^{73}Ga is presented in Fig. 5(a). Two peaks at 581 and 734 keV are found to dominate the coincidence spectrum. The 734-keV transition equals the energy difference between the 952- and 218-keV levels, identified previously in transfer and β-decay studies. The second strong γ ray at 581 keV is a good candidate for the transition feeding the $9/2^+$ state.

The spectrum obtained by setting a double gate on the 280- and 581-keV γ transitions is presented in Fig. 5(b). The peak at

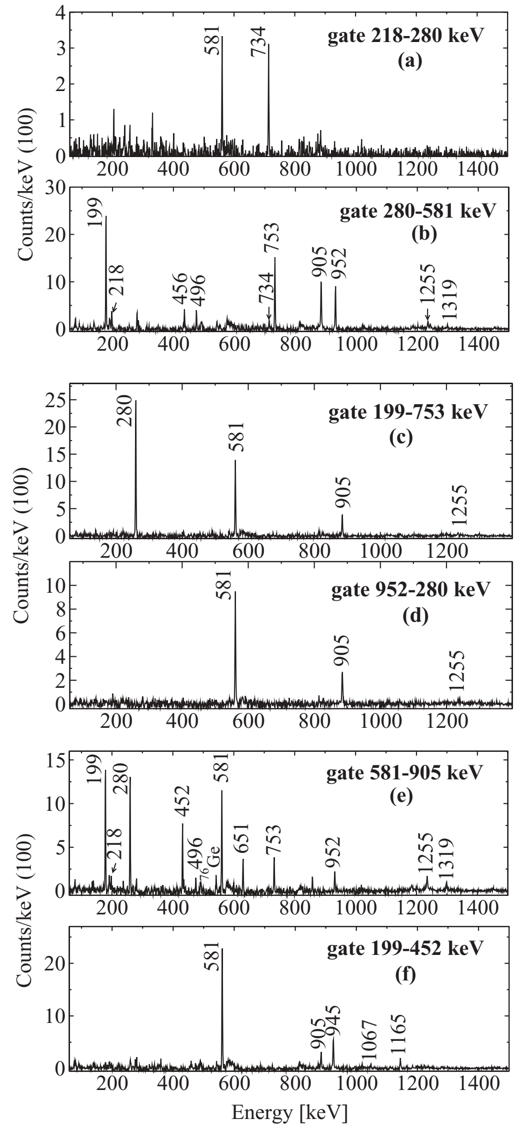

FIG. 5. γ-ray spectra obtained by placing double coincidence gates on transitions in ^{73}Ga. Transitions marked by their energies belong to the ^{73}Ga level scheme.

952 keV is observed along with three pairs of γ rays that sum to 952 keV, including the transitions at 199 and 496 keV that establish the energies of those levels observed in the transfer reaction studies reported in Ref. [11] with an uncertainty of 3 keV. Also observed are three additional transitions, whose mutual coincidences and intensities are used to establish the sequence of levels that populate the $9/2^+$ level. Thus, the present data set confirms the few transitions reported by Runte *et al.* [14] and shows clear evidence for the presence of γ rays connecting most of the low-lying states identified in previous transfer reaction experiments [10,11]. By placing double gates on these transitions, the structure built on top of the $9/2^+$ could be unambiguously identified [see Fig. 5(c)]. This structure is found to consist of mutually coincident transitions of 581, 905, 1255, and 1319 keV [see Figs. 5(d) and 5(e)], proposed to de-excite the states at 1814, 2718, 3974, and 5293 keV,

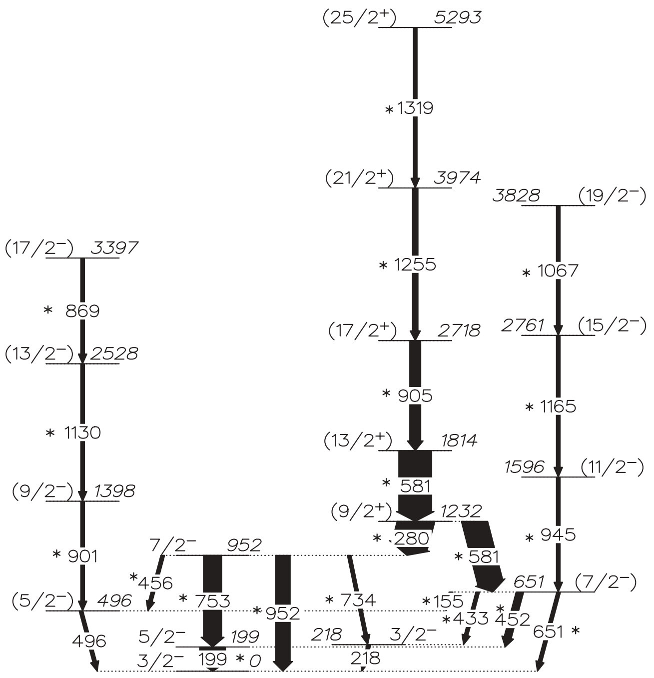

FIG. 6. Level scheme of ^{73}Ga obtained from the present coincidence analysis. The widths of the arrows are proportional to the intensities of the γ rays. Transitions observed for the first time in this work are marked with a star.

respectively. The newly observed states were placed in the level scheme of ^{73}Ga as shown in Fig. 6.

The double gate set on the 581- and 905-keV γ rays, observed for the first time in this work, reveals rather intense peaks at 452, 581, and 651 keV [see Fig. 5(e)]. The 581- and 651-keV γ rays sum to 1232 keV, the excitation energy of the $9/2^+$ state. This suggests the presence of an excited state located either at 581 or 651 keV. The observation of the 452-keV peak in the spectrum displayed in Fig. 5(e) strongly favors a level at an excitation energy of 651 keV; the 452-keV transition would then correspond to a decay branch to the state at 199 keV. Thus, the transition of 581 keV proposed in this work to feed the $9/2^+$ state at 1232 keV is observed to be a self-coincident doublet with a γ ray of the same energy that de-excites the $9/2^+$ state (see Fig. 6).

The spectrum obtained by placing a double gate on the 199- and 452-keV γ rays is presented in Fig. 5(f). Observed is a strong peak at 581 keV, corresponding to the summed intensity of the 581-keV coincident doublet. The 905-keV transition, proposed in the present work to de-excite the state at 2718 keV, is also present in the spectrum. The three peaks at 945, 1165, and 1067 keV are very good candidates for a structure built on top of the newly identified level at 651 keV. Combinations of double gates on any of these three transitions (see Fig. 7), and/or γ rays already assigned to the level scheme of ^{73}Ga, provided strong evidence that the peaks at 945, 1165, and 1067 keV belong to this nucleus.

The results of the (t,p) reaction described in Ref. [20] also indicated the existence of an excited state at 1396(3) keV for which the angular distribution of the outgoing proton was consistent with an $\ell = 4$ transfer. The population

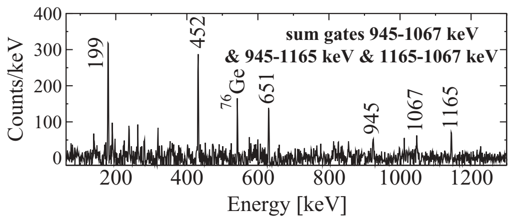

FIG. 7. γ-ray spectrum obtained by summing double coincidence gates set on transitions in ^{73}Ga. Peaks marked by their energies were attributed to ^{73}Ga.

and possible de-excitation paths of this level were investigated in the present work by setting single gates on energies that equal the difference between the 1396-keV level and the low-lying levels at 1232, 952, 651, 496, 218, and 199 keV (see Fig. 6). The gate set on the 901-keV γ ray between the 1396(3)- and 496-keV excited states showed clear evidence for the known ground-state transition of 496 keV, thus fixing the energy of the emitting level to 1398 keV. Furthermore, the spectrum obtained by setting a double gate on the 496-keV γ ray and the newly observed transition of 901 keV showed peaks at 1130 and 869 keV. Based on the observed intensity, the two γ rays were placed in the level scheme of ^{73}Ga as shown in Fig. 6. The coincidence spectrum obtained by setting a double gate on the 496- and 1130-keV transitions is presented in Fig. 8.

The structure identified on top of the $9/2^+$ state exhibits an energy sequence almost identical to that identified in ^{71}Ga. With no side bands or staggered level energies, an $E2$ sequence is also suggested for ^{73}Ga. As the level at 651 keV is found to receive feeding from the $9/2^+$ state and decay to $3/2^-$ and $5/2^-$ states, the most probable negative-parity values are either $5/2^-$ or $7/2^-$.

The energy spacing between the levels identified at 651, 1596, 2761, and 3828 keV is very similar to that observed for the positive-parity yrast band of the ^{72}Zn core [32]. Thus, the structure observed on top of the 651-keV state is proposed to arise from the coupling of the $\pi p_{3/2}$ odd proton-hole to the excited states in the Zn core. This suggests negative parity and spins of $7/2^-$, $11/2^-$, $15/2^-$, and $19/2^-$ for the levels at 651, 1596, 2761, and 3828 keV, respectively.

The sequence of transitions 901–1130–869 keV observed in the present work on top of the proposed $5/2^-$ state at 496 keV is similar to the 1191–1478–836 keV cascade in ^{69}Ga, investigated in a fusion-evaporation reaction [19]. Therefore, spins and parities $9/2^-$, $13/2^-$, and $17/2^-$ are proposed for the levels at 1398, 2528, and 3397 keV in ^{73}Ga. The $9/2^-$

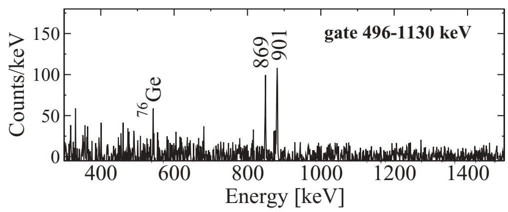

FIG. 8. γ-ray spectrum obtained by placing a double coincidence gate on the 496- and 1130-keV transitions in ^{73}Ga. Peaks marked by their energies were attributed to ^{73}Ga.

TABLE II. Excitation energies, transition energies and intensities, and initial and final spins and parities for the transitions observed in ^{73}Ga as obtained in the present experiment. The intensities are normalized to the 280-keV transition, set to be 100. The experimental errors on the transition energies are 0.2 keV for the intense γ rays and 0.5 keV for the weak ones ($I_\gamma < 5\%$).

E_{level} (keV)	E_γ (keV)	I_γ (%)	$I_i^\pi \rightarrow I_f^\pi$
199.1	199.1	69.2(5)	$5/2^- \rightarrow 3/2^-$
218.2	218.2	6.4(3)	$3/2^- \rightarrow 3/2^-$
496.2	496.2	10.7(4)	$(5/2^-) \rightarrow 3/2^-$
651.2	155.0	1.7(2)	$(7/2^-) \rightarrow 5/2^-$
	433.0	2.2(2)	$(7/2^-) \rightarrow 3/2^-$
	452.1	18.5(7)	$(7/2^-) \rightarrow 5/2^-$
	651.2	10.7(1)	$(7/2^-) \rightarrow 3/2^-$
952.4	456.2	11.4(3)	$7/2^- \rightarrow 5/2^-$
	734.2	5.6(2)	$7/2^- \rightarrow 3/2^-$
	753.3	48.2(8)	$7/2^- \rightarrow 5/2^-$
	952.4	38.4(4)	$7/2^- \rightarrow 3/2^-$
1232.1	279.7	100	$(9/2^+) \rightarrow 7/2^-$
	580.9[a]	72.4(5)	$(9/2^+) \rightarrow (7/2^-)$
1397.6	901.4	7.5(6)	$(9/2^-) \rightarrow (5/2^-)$
1596.4	945.2	9.4(5)	$(11/2^-) \rightarrow (7/2^-)$
1813.5	581.4[a]	87.5(8)	$(13/2^+) \rightarrow (9/2^+)$
2528.0	1130.4	5.1(2)	$(13/2^-) \rightarrow (9/2^-)$
2718.3	904.8	33.3(5)	$(17/2^+) \rightarrow (13/2^+)$
2761.2	1164.8	5.2(4)	$(15/2^-) \rightarrow (11/2^-)$
3397.4	869.4	3.3(5)	$(17/2^-) \rightarrow (13/2^-)$
3828.5	1067.3	4.1(2)	$(19/2^-) \rightarrow (15/2^-)$
3973.5	1255.2	11.5(4)	$(21/2^+) \rightarrow (17/2^+)$
5292.7	1319.2	3.1(2)	$(25/2^+) \rightarrow (21/2^+)$

[a]This transition is a doublet in ^{73}Ga. The summed intensity extracted from the present data set is 158(2).

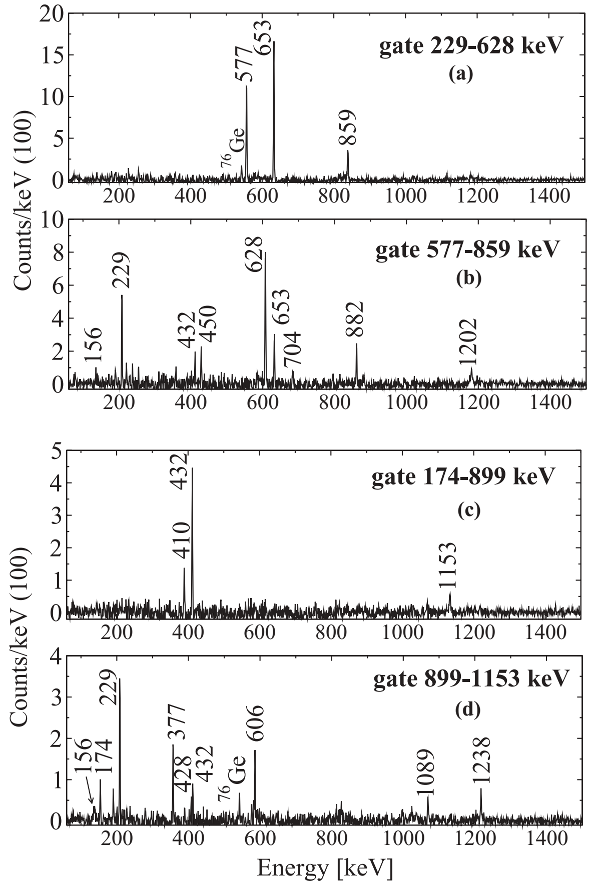

FIG. 9. γ-ray spectra obtained by setting double coincidence gates on transitions in ^{75}Ga. Transitions marked by their energies belong to the ^{75}Ga level scheme.

assignment for the state at 1398 keV is also consistent with the measured $\ell = 4$ transfer in a ^{71}Ga$(t,p)^{73}$Ga reaction from the $3/2^-$ ground state of ^{71}Ga [20].

The spectroscopic information extracted in the present analysis for the levels observed in ^{73}Ga is summarized in Table II. All levels reported in the Nuclear Data Sheets below 1 MeV were populated in this experiment, except for the $3/2^-$ level at 911 keV [33].

C. ^{75}Ga

^{75}Ga is better known experimentally than the lighter ^{73}Ga isotope because of the higher Q value for β decay of the $7/2^+$ ground state of the ^{75}Zn parent nucleus. Hence, it has been possible to identify both a new sequence of negative-parity levels as well as positive-parity states above the $9/2^+$ state [15].

The $9/2^+$ state in ^{75}Ga was proposed at an excitation energy of 1517(7) keV [10], when first identified in a $(d, {}^3\text{He})$ transfer reaction. Later, the results of the study reported in Ref. [15] indicated the presence of two close-lying states at 1507 and 1510 keV, both populated in the β decay of ^{75}Zn. However, no spins and parities were assigned to these two levels. As transfer reaction results indicated that the main part of the $\ell = 4$ strength is located in this energy region [10,12], both states were considered in the present work as candidates for the $9/2^+$ state of dominant $g_{9/2}$ character.

In the β-decay work just mentioned, the 1507-keV state was found to decay to the $5/2^-$ level at 606 keV, whereas the decay of the 1510-keV state proceeds through the excited level at 882 keV. For the 882-keV state, results of the transfer reaction study by Rotbard *et al.* led them to propose spins and parities $5/2^-$ or $7/2^-$ [10]. However, it was recently assigned as $7/2^-$ in Ref. [12]. The systematics of the lighter Ga isotopes indicates that the single-particle $9/2^+$ state predominantly feeds a nearby $7/2^-$ level, which decays further to the ground state either directly or via a cascade of two transitions through the yrast $5/2^-$ level. In ^{75}Ga, such a decay pattern is exhibited by the state at 1510 keV [15].

The double gate placed on the ground-state transition of 229 keV and the γ ray of 628 keV, the candidate proposed in this work for the $9/2^+ \rightarrow 7/2^-$ decay, exhibits strong peaks at 577, 653, and 859 keV [see Fig. 9(a)]. The 653-keV transition was identified previously in β decay and placed in the ^{75}Ga level scheme as connecting the 882- and 229-keV states [15]. The other two peaks are proposed in this work to feed the state at 1510 keV. Both transitions are also present in other double gates placed on pairs of coincident γ rays de-exciting the 882-keV state through the excited states at 22, 178, and 432 keV reported in β decay [15]. Thus, based on

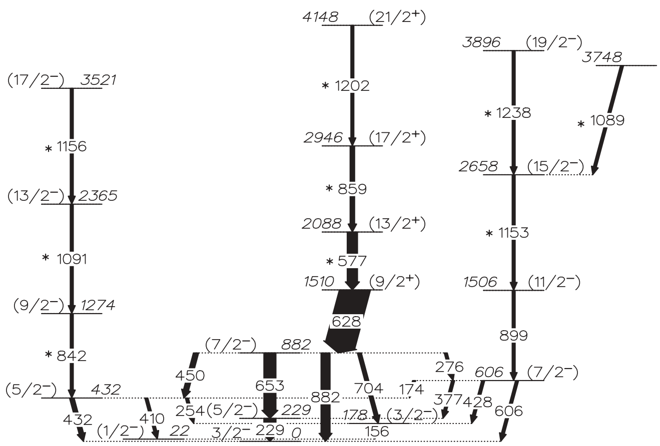

FIG. 10. Level scheme of ^{75}Ga obtained from the present coincidence analysis. The widths of the arrows are proportional to the intensities of the γ rays. Transitions observed for the first time in this work are indicated by a star.

the coincidence relationship and intensity arguments, the 577- and 859-keV transitions were arranged in the level scheme of ^{75}Ga as proposed in Fig. 10.

The coincidence spectrum obtained by setting a double gate on the newly observed 577- and 859-keV γ rays is presented in Fig. 9(b). The resulting spectrum provided evidence for extending the structure built on the 1510-keV level up to an excitation energy of 4148 keV and also confirmed most of the decay paths of the 882-keV state reported in Ref. [15].

An excited state at 606 keV in ^{75}Ga was mentioned for the first time in the β-decay study of ^{75}Zn [34]. However, this state was obscured at forward angles in the ^{76}Ge$(d, {}^3\mathrm{He})^{75}$Ga reaction by the ^{16}O$(d, {}^3\mathrm{He})^{15}N_{g.s.}$ contaminant reaction [10]. In that work, a very weak peak, possibly corresponding to the population of this level, was observed at other angles, but only upper limits of 0.03 and 0.2 for the $\ell = 1$ and $\ell = 3$ spectroscopic factors, respectively, could be extracted. The 606-keV state, however, was found to be rather well populated in the more recent β-decay study by Ekström *et al.* [15]. A spin and parity assignment of $5/2^-$ was proposed for this level, based on the observation of six decaying transitions toward $1/2^-$, $3/2^-$ and $5/2^-$ lower lying states. The level at 606 keV was also observed in the recent polarized-beam measurement but, because of low statistics, no angular distributions of the outgoing ^{3}He particles could be analyzed [12].

In the present work, the presence of the 606-keV level was investigated by setting double gates on the decay branches reported in Ref. [15]. In all cases, the resulting spectrum revealed a strong peak at 899 keV, which might correspond to the 901-keV γ ray, proposed in Ref. [15] to de-excite the level at 1508 keV. Furthermore, the spectra obtained by placing double gates on the 899-keV γ ray and transitions of 174, 377, or 428 keV, reported previously to de-excite the 606-keV state, indicated peaks at 410, 432, 229, and 156 keV. These peaks correspond to γ rays already assigned to the level scheme of ^{75}Ga [15]. An example of such a double-gated spectrum is displayed in Fig. 9(c). The spectrum also reveals a peak at 1153 keV that was placed in the level scheme of ^{75}Ga as de-exciting the level at 2658 keV (see Fig. 10).

The coincidence spectrum obtained by gating on the 899- and 1153-keV γ rays, observed for the first time in the present experiment, is displayed in Fig. 9(d). The spectrum provides clear evidence for the ground-state transitions of 229, 432, and 606 keV as well as for two peaks at 1089 and 1238 keV. The investigation of the coincidence relationships between these two transitions and γ rays already placed in the level scheme of ^{75}Ga indicated that both belong to this nucleus but are not in coincidence with one another. Thus, the present data indicate that the new state at 2658 keV receives population from a level located at 3896 keV, via the 1238-keV transition, and an excited state at 3748 keV, which decays by emitting a γ ray of 1089 keV (see Fig. 10).

In the β-decay work of Ref. [15] an excited level at 1274 keV that has the strongest decay branch to the $5/2^-$ state at 432 keV via a transition of 842 keV was also reported. A double gate set in the present work on the 432–842 keV cascade showed peaks at 1091 and 1156 keV. The presence of the 432- and 410-keV transitions in the spectra obtained by setting double gates on any combination of the γ rays of 842, 1091, and 1156 keV provided the basis for placing the latter two transitions in the level scheme of ^{75}Ga (Fig. 10). The coincidence spectrum obtained by placing a double gate on the 842- and 1091-keV transitions is shown in Fig. 11.

As in the case of the lighter ^{71,73}Ga, spins and parities to the newly observed levels in ^{75}Ga are proposed in this work based on comparisons with systematics. As the decay pattern observed in the present work for the level at 1510 keV resembles closely that determined for the $9/2^+$ states in the lighter ^{71,73}Ga nuclei of Figs. 4 and 6, spin $9/2^+$ is favored for this state, in agreement with the work of Ref. [12]. Furthermore, an $E2$ character is proposed for the transitions de-exciting the structure identified on top of this level, which leads to spin assignments of $13/2^+$, $17/2^+$, and $21/2^+$ for the newly reported states at 2088, 2946, and 4148 keV (see Fig. 10). As the cascade of transitions observed to feed the 606-keV level exhibits a collective bandlike pattern, $E2$ multipolarity is also suggested for the γ rays of 899, 1153, and 1238 keV (see the level scheme of Fig. 10). As already mentioned, the weak branch to the $1/2^-$ state at 22 keV along with the absence of any feeding from the $9/2^+$ level suggested $5/2^-$ quantum numbers for the 606-keV state [15]. In the present analysis, no 584-keV transition to the state at 22 keV could be observed, perhaps owing to the weak branch reported in β decay. In view of the strong resemblance to both the decay and population pattern of the $7/2^-$ state at 651 keV in ^{73}Ga,

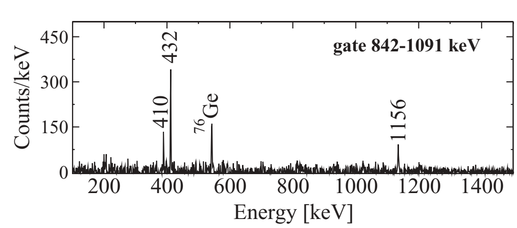

FIG. 11. γ-ray spectrum obtained by placing a double coincidence gate on the 842- and 1091-keV transitions in ^{75}Ga. Peaks marked by their energies were attributed to ^{75}Ga.

TABLE III. Excitation energies, γ energies and intensities, and initial and final spins and parities for the observed transitions in ^{75}Ga obtained in the present experiment. The intensities are normalized to the 628-keV transition, set to be 100. The experimental errors on the transition energies are 0.2 keV for the intense γ rays and 0.5 keV for the weak ones ($I_\gamma < 5\%$).

E_{level} (keV)	E_γ (keV)	I_γ (%)	$I_i^\pi \rightarrow I_f^\pi$
22.2			$(1/2^-) \rightarrow 3/2^-$
178.2	155.8	15.2(4)	$(3/2^-) \rightarrow (1/2^-)$
229.3	229.3	41.4(5)	$(5/2^-) \rightarrow 3/2^-$
432.2	254.0	1.4(2)	$(5/2^-) \rightarrow (3/2^-)$
	409.8	4.4(3)	$(5/2^-) \rightarrow (1/2^-)$
	432.2	15.4(6)	$(5/2^-) \rightarrow 3/2^-$
606.3	174.1	1.7(2)	$(7/2^-) \rightarrow (5/2^-)$
	377.0	2.6(3)	$(7/2^-) \rightarrow (5/2^-)$
	428.1	<1	$(7/2^-) \rightarrow (3/2^-)$
	606.3	4.2(4)	$(7/2^-) \rightarrow 3/2^-$
881.9	275.6	1.4(1)	$(7/2^-) \rightarrow (7/2^-)$
	449.7	16.6(5)	$(7/2^-) \rightarrow (5/2^-)$
	652.6	39.4(6)	$(7/2^-) \rightarrow (5/2^-)$
	703.7	13.5(3)	$(7/2^-) \rightarrow (3/2^-)$
	881.9	32.1(6)	$(7/2^-) \rightarrow 3/2^-$
1273.9	841.7	11.4(3)	$(9/2^-) \rightarrow (5/2^-)$
1505.5	899.2	8.6(7)	$(11/2^-) \rightarrow (7/2^-)$
1510.2	628.3	100	$(9/2^+) \rightarrow (7/2^-)$
2087.5	577.3	34.2(6)	$(13/2^+) \rightarrow (9/2^+)$
2365.1	1091.2	6.7(4)	$(13/2^-) \rightarrow (9/2^-)$
2658.4	1152.9	5.3(4)	$(15/2^-) \rightarrow (11/2^-)$
2946.2	858.7	14.8(3)	$(17/2^+) \rightarrow (13/2^+)$
3520.6	1155.5	4.1(2)	$(17/2^-) \rightarrow (13/2^-)$
3747.5	1089.1	2.1(2)	$\rightarrow (15/2^-)$
3896.3	1237.9	3.4(3)	$(19/2^-) \rightarrow (15/2^-)$
4148.5	1202.3	5.1(4)	$(21/2^+) \rightarrow (17/2^+)$

a spin and parity assignment of $7/2^-$ is proposed for the level at 606 keV in ^{75}Ga.

The excited cascade observed on top of the single-particle $5/2^-$ state at 432 keV is similar to that built on the $5/2^-$ level at 574 keV in ^{69}Ga [19] and on the 496-keV state in ^{73}Ga, reported in the previous section. Based on systematics, spins and parities $9/2^-$, $13/2^-$, and $17/2^-$ are proposed for the excited states at 1274, 2365, and 3521 keV in ^{75}Ga. The $9/2^-$ spin assignment for the level at 1274 keV is also supported by the observed β branch from the $7/2^+$ ground-state of ^{73}Zn [15].

The spectroscopic information extracted in the present analysis for the levels observed in ^{75}Ga can be found in Table III. All levels reported in the Nuclear Data Sheets below 1 MeV were populated in this experiment, including indirect population of the proposed low-spin $1/2^-$ state at 22 keV [35].

D. ^{77}Ga

Because ^{77}Ga is located farther from stability, no transfer data are available for this nucleus. However, an extensive level scheme has been developed from the β-decay study of the $7/2^+$ ground state in ^{77}Zn [15]. In that work, spin and parity values of $9/2^+$ have been assigned to a level at 2029 keV, based on the measured half-life, $T_{1/2} = 4.4$ ns, and shell-model systematics.

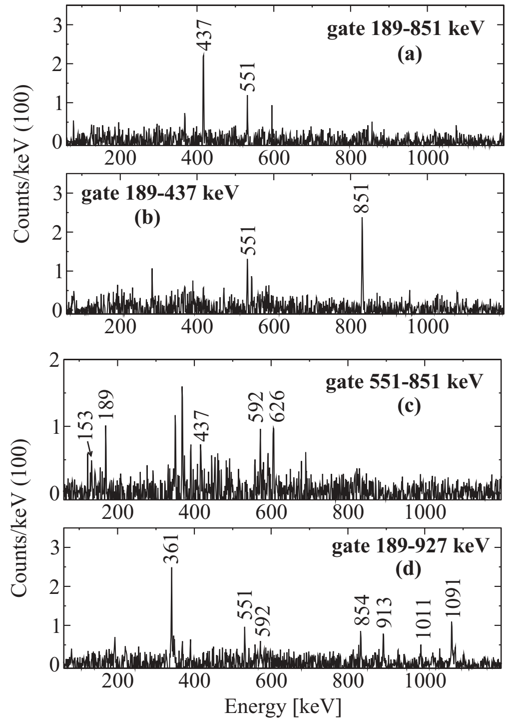

FIG. 12. γ-ray spectra obtained by setting double coincidence gates on transitions in ^{77}Ga. Transitions marked by their energies belong to the ^{77}Ga level scheme.

^{77}Ga was rather weakly populated in the present deep-inelastic reaction. Samples of double gates set on previously known transitions are displayed in Figs. 12(a) and 12(b).

The double gate set on one of the strongest decay paths via γ rays at 551 and 851 keV is provided in Fig. 12(c), where the strong lines expected at 153, 189, 437, and 626 keV are observed, along with a weak transition at 592 keV. A second decay branch to the ground state from the proposed $9/2^+$ level is also available via γ rays at 913, 927, and 189 keV. A double coincidence gate on the latter transitions shows a peak at 592 keV [see Fig. 12(d)]. This transition is tentatively assigned in the present work as the $13/2^+ \rightarrow 9/2^+$ transition. Owing to the high excitation energy of the $9/2^+$ state, most of the yrast strength passes through other transitions, as indicated in the level scheme presented in Fig. 13. The latter is based on that obtained from β decay [15]. All levels observed in the present work below 2 MeV excitation energy were previously reported.

The double coincidence gate placed on the 189- and 927-keV transitions also reveals peaks at 1091 and 1011 keV. Based on the coincidence relationships and the observed intensities, both transitions were placed in the level scheme of ^{77}Ga (see Fig. 13).

Spins and parities assigned in the present work to the previously known levels are consistent with the radioactivity data, except for the proposed alternate assignments $9/2^-$ for the 1116-keV level and $7/2^-$ for the state at 626 keV. A very weak transition of 1116 keV was assigned in Ref. [15]

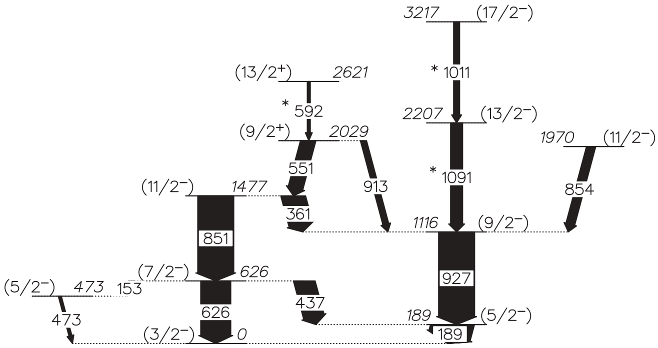

FIG. 13. Level scheme of ^{77}Ga obtained from the present coincidence analysis. The widths of the arrows are proportional to the intensities of the γ rays. Transitions observed for the first time in this work are indicated by a star.

as a transition to the $3/2^-$ ground state of ^{77}Ga. Such an assignment would limit the spin of this state to $7/2^-$. However, the 1116-keV transition was not observed in the present work. This branch was reported previously to be only 3% of the intensity of the main branch and the subsequent γ ray was placed in the level scheme of ^{77}Ga without any coincidence evidence. The newly observed levels at 2207 and 3217 keV were proposed to decay via $E2$ transitions. Therefore, spins and parities $13/2^-$ and $17/2^-$ were assigned to these states.

In the present work, spins $7/2^-$ and $11/2^-$ are proposed for the states at 626 and 1477 keV. This assignment is based on the observed energy spacings, which are similar to those of 2^+ and 4^+ states in the even-even ^{76}Zn core. An assignment of spin $11/2^-$ to the 1477-keV level is also in agreement with the $E1$ character for the 551-keV transition de-exciting the $9/2^+$ isomeric state at 2029 keV.

The spectroscopic information extracted in the present analysis for the levels observed in ^{77}Ga is summarized in Table IV.

TABLE IV. Excitation energies, transition energies and intensities, and initial and final spins and parities for the transitions observed in ^{77}Ga. The intensities are normalized to the 551-keV transition, set to be 100. The experimental errors on the transition energies are 0.2 keV for the intense γ rays and 0.5 keV for the weak ones ($I_\gamma < 5\%$).

E_{level} (keV)	E_γ (keV)	I_γ (%)	$I_i^\pi \rightarrow I_f^\pi$
189.3	189.3	264(19)	$(5/2^-) \rightarrow (3/2^-)$
473.4	473.4	9(1)	$(5/2^-) \rightarrow (3/2^-)$
626.1	152.7	35(3)	$(7/2^-) \rightarrow (5/2^-)$
	436.8	74(7)	$(7/2^-) \rightarrow (5/2^-)$
	626.1	120(9)	$(7/2^-) \rightarrow (3/2^-)$
1116.0	926.7	188(12)	$(9/2^-) \rightarrow (5/2^-)$
1477.0	361.0	101(11)	$(11/2^-) \rightarrow (9/2^-)$
	850.9	274(21)	$(11/2^-) \rightarrow (7/2^-)$
1969.7	853.7	41(9)	$(11/2^-) \rightarrow (9/2^-)$
2028.7	551.4	100	$(9/2^+) \rightarrow (11/2^-)$
	912.7	34(5)	$(9/2^+) \rightarrow (9/2^-)$
2206.8	1090.8	94(6)	$(13/2^-) \rightarrow (9/2^-)$
2620.8	592.1	11(4)	$(13/2^+) \rightarrow (9/2^+)$
3217.4	1010.6	24(6)	$(17/2^-) \rightarrow (13/2^-)$

V. DISCUSSION

A. Negative-parity states

The systematics of the low-lying $3/2^-$, $1/2^-$, $5/2^-$, and $9/2^+$ states as a function of neutron number can be found in the bottom panel of Fig. 1. The levels included in the systematics are those for which previous transfer reaction studies indicate a dominant single-particle character arising from the $p_{3/2}$, $p_{1/2}$, $f_{5/2}$, and $g_{9/2}$ proton orbitals, respectively. These systematics indicate that in the lighter ^{65,67,69}Ga isotopes, the single-particle $5/2^-$ state is located ~200 keV above the $1/2^-$ level. The sharp rise in excitation energy observed for the $1/2^-$ level in ^{71}Ga appears to be accompanied by only a small decrease in the energy of the $5/2^-$ state. It should be noted, however, that a lower energy $1/2^-$ level remains at 390 keV (see Fig. 4) that is not strongly populated in the transfer reaction studies and must, therefore, arise from collective effects. In addition, low-energy $1/2^-$ levels are also found at 22 and 106 keV in ^{75,77}Ga, respectively. Hence, the possibility of a $1/2^-$ ground state for ^{73}Ga is consistent with the observed structures in ^{75,77}Ga. Stated in another way, it would be quite surprising if there were no $1/2^-$ levels in ^{73}Ga below the level at 1113 keV that is strongly populated in transfer reaction experiments. It is also worth noticing that the proposed drop by 390 keV for the position of this $1/2^-$ level coincides with the splitting of the $\ell = 0$ transfer strength observed for the population of ^{73}Ga levels in the ^{71}Ga(t, p) reaction [17].

Calculations within the framework of the Alaga model [36] involving the coupling of a three-particle valence shell cluster to a quadrupole deformed core provided a relatively simple qualitative understanding of the low-energy levels observed in ^{65,67,69}Ga but could not account for the experimental spectroscopic factors [37]. The particle-plus-vibrational core coupling model was also employed to describe the low-lying levels of ^{65,67,69}Ga [38]. Although the positions of the excited levels were found to be consistent with the predictions of the model, this simple picture was not supported by the experimental $B(E2)$ values, which indicated considerable mixing of the core-coupled states with single-particle levels. Thus, to shed some light on the structure of the low-energy levels in the odd-A Ga nuclei beyond $N = 40$, a measurement of the transition probabilities is highly desirable.

The systematics of the lowest negative-parity states $7/2^-$ and $11/2^-$ and $9/2^-$ and $13/2^-$ as a function of neutron number are given in Figs. 14 and 15, respectively, along with the observed trend for the 2^+ and 4^+ positive-parity yrast levels in the neighboring even-even Zn cores. As seen in Fig. 14, the $7/2^-$ and $11/2^-$ levels closely follow the core energies, supporting their interpretation as states arising from the coupling of the $p_{3/2}$ odd proton with the 2^+ and 4^+ excited levels in the even-even Zn cores.

The $9/2^-$ and $13/2^-$ levels included in the systematics presented in Fig. 15 are suggested to originate from the $\pi f_{5/2} \otimes 2^+$ and $\pi f_{5/2} \otimes 4^+$ configurations, respectively. As seen in the figure, their excitation energies are systematically higher than the 2^+ and 4^+ levels in the neighboring even-even Zn

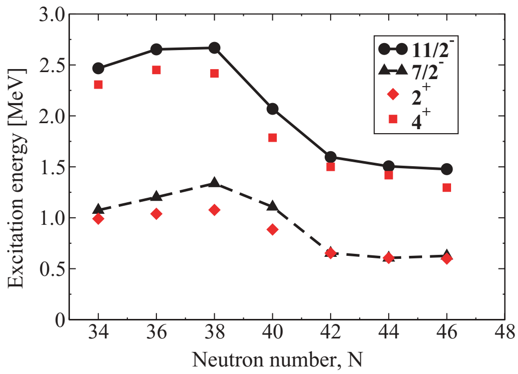

FIG. 14. (Color online) Neutron-number dependence for the $11/2^-$ (full circles) and $7/2^-$ (full triangles) states relative to yrast $3/2^-$ levels identified in the odd-A Ga isotopes. The 2^+ (red diamonds) and 4^+ (red squares) excitation energies in the respective even-even Zn cores are shown for comparison.

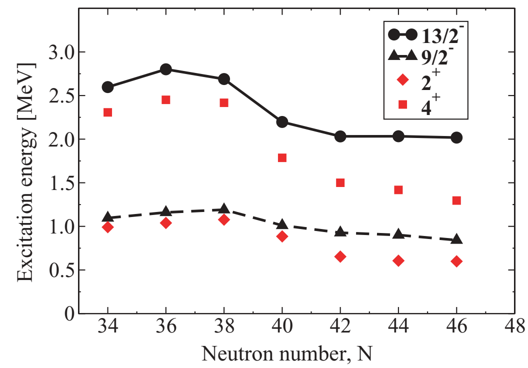

FIG. 15. (Color online) Neutron-number dependence for the $13/2^-$ (full circles) and $9/2^-$ (full triangles) states relative to the yrast $5/2^-$ levels identified in the odd-A Ga isotopes. The 2^+ (red diamonds) and 4^+ (red squares) excitation energies in the respective even-even Zn cores are shown for comparison.

cores and the $7/2^-$ and $11/2^-$ core-coupled states. This can be attributed to the blocking effect of the occupancy of the $\pi f_{5/2}$ single-particle level. When the odd proton occupies the $f_{5/2}$ orbital, it costs more energy to create the 2^+ and 4^+ excited states than when the proton occupies the $\pi p_{3/2}$ orbital. The effect is seen to become more pronounced as N rises beyond 40, where theoretical calculations predict the lowering of the energy of the $f_{5/2}$ proton orbital by the tensor interaction [5].

Shell-model calculations have been recently reported for the neutron-rich Se, As, Ge, and Ga isotopes [39]. In the model a phenomenological pairing plus quadrupole-quadrupole interaction is assumed for all even-even and odd-even nuclei considered in the calculations. The valence space consisted of the four single-particle orbitals $p_{3/2}$, $f_{5/2}$, $p_{1/2}$, and $g_{9/2}$ occupied between the magic numbers $Z, N = 28$–50. Negative-parity excited states up to spin $11/2^-$ were calculated in the odd-A ^{75,77,79}Ga and the results were compared to the existing experimental data. The model reproduced very well the energies of the three low-lying $1/2^-, 3/2^-$, and $5/2^-$ states observed below a 500 keV excitation energy in both ^{75}Ga and ^{77}Ga. The calculations also predict the yrast $7/2^-$ and $11/2^-$ levels should be around 600 keV and 1.5 MeV in ^{75}Ga; these can be associated with the states observed in the present work at 606 and 1506 keV, respectively.

B. Positive-parity states

Figure 1 also indicates that, beyond $N = 38$, the excitation energy of the $9/2^+$ single-particle state decreases and reaches a minimum at $N = 42$ before it starts rising again at $N = 44$. The observed trend is remarkably symmetric around the minimum, which was associated with a maximum in collectivity in the Ga isotopic chain [21].

Indeed, the minimum position of the $9/2^+$ level at $N = 42$ falls at exactly the point where the transfer strength in the (t, p) reaction splits and where the unobserved $1/2^-$ ground-state spin has been proposed. Moreover, for $N = 42$ and $N = 44$, the positions of the proposed $13/2^+$, $17/2^+$, and $21/2^+$ levels are seen to correspond quite closely to the positions of the 2^+, 4^+, and 6^+ states in the even-even Zn core nuclei (see Fig. 16). As can be seen from the figure, the nearly constant excitation energies of the yrast positive-parity states in the Zn isotopic chain beyond $N = 42$ is noteworthy. The measured $B(E2; 2^+ \rightarrow 0^+)$ values in the even-even Zn nuclei with $N = 34$–50 indicate a maximum collectivity for the midshell nucleus, ^{74}Zn. Beyond $N = 44$, the experimental transition probabilities start decreasing as the $N = 50$ shell closure is approached [40].

The $g_{9/2}$ bands observed in the odd-mass Ga isotopes below $N = 40$ were discussed in the framework of various models. A triaxial-rotor approach was used to describe the states of the $g_{9/2}$ band in ^{65}Ga, when first identified in a fusion-evaporation reaction [41]. More recently, calculations performed in the framework of interacting boson-fermion plus broken pair model assigned most of the yrast high-spin levels observed in ^{65,67}Ga to quasiparticle-plus-phonon and three-quasiparticle configurations [18]. The model parameters

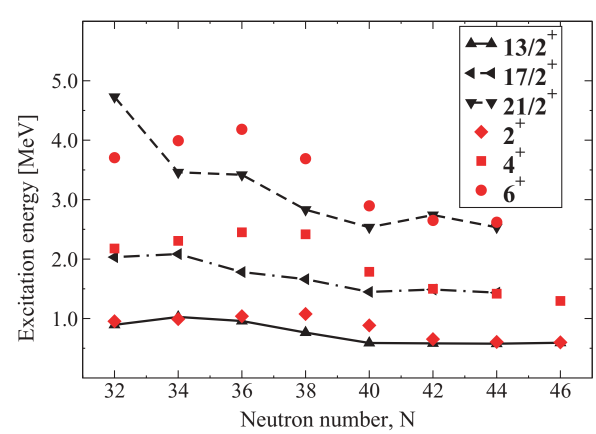

FIG. 16. (Color online) Systematics of positive-parity states $13/2^+$ (black solid line), $17/2^+$ (black dashed-dotted line), and $21/2^+$ (black dashed line) relative to the position of the $9/2^+$ level proposed in the odd-A Ga isotopes. The positive-parity yrast states 2^+ (red diamonds), 4^+ (red squares), and 6^+ (red circles) in the neighboring even-even Zn cores are shown for comparison.

used to fit the observed levels were found to correspond to a transition between the SU(5) (vibrational) to O(6) (γ-soft) dynamical symmetries, being closer to the vibration limit.

VI. CONCLUSIONS

Collective structures built on top of the $9/2^+$, $5/2^-$, and $3/2^-$ levels were identified in the odd-mass ^{71,73,75,77}Ga isotopes, produced in deep-inelastic reactions of a ^{76}Ge beam at 530 MeV with a thick ^{238}U target. The $9/2^+$, $5/2^-$, and $3/2^-$ states were determined in previous transfer reaction to contain significant components from the $g_{9/2}$, $f_{5/2}$, and $p_{3/2}$ proton orbitals, respectively. The observed sequences reflect the change in structure suggested by the results of a previous (t, p) transfer reaction and show approximately constant energy spacing with increasing neutron number. The comparison with the positive-parity excited states in the even-even Zn isotopes indicates that the observed high-spin levels can be regarded as arising from the coupling of the odd proton to the yrast states in the neighboring cores. However, rather complex configurations are expected for the newly identified high-spin levels, owing to mixing with configurations involving broken proton and neutron pairs.

The present data set was also used to clarify the decay paths identified previously for the low-lying states in all four isotopes. Prior to this work, only a few negative-parity levels in ^{73}Ga were reported from transfer reactions, but their γ decay had never been observed. Thus, the high selectivity of the three-fold coincidence data obtained in the present experiment provided detailed spectroscopic information at low and high excitation energies in the odd-A ^{71,73,75,77}Ga isotopes, allowing for new insight into how their structure changes with increasing neutron number.

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[1] I. Stefanescu *et al.*, Phys. Rev. Lett. **100**, 112502 (2008).
[2] S. Franchoo *et al.*, Phys. Rev. Lett. **81**, 3100 (1998).
[3] S. Franchoo *et al.*, Phys. Rev. C **64**, 054308 (2001).
[4] N. A. Smirnova, A. De Maesschalck, A. Van Dyck, and K. Heyde, Phys. Rev. C **69**, 044306 (2004).
[5] T. Otsuka, T. Suzuki, R. Fujimoto, H. Grawe, and Y. Akaishi, Phys. Rev. Lett. **95**, 232502 (2005).
[6] E. Caurier, computer code ANTOINE, IRES, Strasbourg, 1989–2002.
[7] M. Hjorth-Jensen, T. T. S. Kuo, and E. Osnes, Phys. Rep. **261**, 125 (1995).
[8] F. Nowacki, Ph.D. thesis, IReS, Strasbourg, 1996; F. Nowacki (private communication).
[9] B. Zeidman, R. H. Siemssen, G. C. Morrison, and L. L. Lee Jr., Phys. Rev. C **9**, 409 (1974).
[10] G. Rotbard, G. LaRana, M. Vergnes, G. Berrier, J. Kalifa, F. Guilbault, and R. Tamisier, Phys. Rev. C **18**, 86 (1978).
[11] G. Rotbard, M. Vergnes, G. Berrier-Ronsin, and J. Vernotte, Phys. Rev. C **21**, 2293 (1980).
[12] B. P. Kay *et al.*, Phys. Rev. C **79**, 021301(R) (2009), XUNDL, http://www.nndc.bnl.gov.
[13] W. H. Zoller, W. B. Walters, and G. E. Gordon, Nucl. Phys. **A142**, 177 (1970).
[14] E. Runte *et al.*, Nucl. Phys. **A399**, 163 (1983).
[15] B. Ekström, B. Fogelberg, P. Hoff, E. Lund, and A. Sangariyavanish, Phys. Scr. **34**, 614 (1986).
[16] M. Ivaşcu *et al.*, Nucl. Phys. **A225**, 357 (1974).
[17] D. E. Velkley, K. C. Chung, A. Mittler, J. D. Brandenberger, and M. T. McEllistrem, Phys. Rev. **179**, 1090 (1969).
[18] I. Danko *et al.*, Phys. Rev. C **59**, 1956 (1999).
[19] P. Bakoyeorgos, T. Paradellis, and P. A. Assimakopoulos, Phys. Rev. C **25**, 2947 (1982).
[20] M. N. Vergnes *et al.*, Phys. Rev. C **19**, 1276 (1979).
[21] M. Behar, A. Filevich, G. García Bermúdez, and M. A. J. Mariscotti, Phys. Rev. C **17**, 516 (1978).
[22] W. Scholz and F. B. Malik, Phys. Rev. **176**, 1355 (1968).
[23] M. Asai, T. Ishii, A. Makishima, I. Hossain, M. Ogawa, and S. Ichikawa, Phys. Rev. C **62**, 054313 (2000).
[24] T. Ishii *et al.*, Phys. Rev. Lett. **84**, 39 (2000).
[25] A. A. C. Klaasse, Ph.D. thesis, Instituut voor Kernphysisch Onderzoek, Amsterdam, 1978 (unpublished).
[26] A. A. C. Klaasse and V. Paar, Nucl. Phys. **A297**, 45 (1978).
[27] R. Broda *et al.*, in *Fission and Properties of Neutron-Rich Nuclei: Proceedings of the International Conference, Sanibel Island, Florida, 1997*, edited by J. H. Hamilton and A. V. Ramayya (World Scientific, Singapore, 1998), p. 202.
[28] I.-Y. Lee, Nucl. Phys. **A520**, 641 (1990).
[29] M. R. Bhat, Nucl. Data Sheets **68**, 579 (1993).
[30] B. Cheal *et al.* (in preparation).
[31] K. Forssten and M. Brenner, Z. Phys. A **278**, 27 (1976).
[32] A. Hecht *et al.* (submitted to Phys. Rev. C).
[33] B. Singh, Nucl. Data Sheets **101**, 193 (2003).
[34] K. Aleklett, E. Lund, G. Nyman, and G. Rudstam, Nucl. Phys. **A285**, 1 (1977).
[35] A. R. Farhan and B. Singh, Nucl. Data Sheets **86**, 785 (1999).
[36] G. Alaga, in *Lectures in Physics*, edited by M. Jean (Gordon and Breach, New York, 1969), Vol. 3, p. 579.
[37] V. Paar, Nucl. Phys. **A211**, 29 (1973).
[38] L. Harms-Ringdahl, J. Sztarkier, and Z. P. Sawa, Phys. Scr. **9**, 15 (1976).
[39] N. Yoshinaga, K. Higashiyama, and P. H. Regan, Phys. Rev. C **78**, 044320 (2008).
[40] J. Van de Walle *et al.*, Phys. Rev. C **79**, 014309 (2009).
[41] H. Kawakami *et al.*, Phys. Rev. C **21**, 1311 (1980).