

**Ground-state spins and moments of  $^{72,74,76,78}\text{Ga}$  nuclei**

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Laser spectroscopy was performed on the  $^{72,74,76,78}\text{Ga}$  isotopes at On-Line Isotope Mass Separator (ISOLDE) facility, CERN. Ground-state nuclear spins and moments were extracted from the measured hyperfine spectra. The results are compared to shell-model calculations, which provide a detailed probe of the nuclear wave function. The spin is established from the shape of the hyperfine structure and the parity inferred from a comparison of shell-model calculations with the measured nuclear moments. The ground states of  $^{76,78}\text{Ga}$  are both assigned a spin and parity of  $I^\pi = 2^-$ , while  $^{74}\text{Ga}$  is tentatively assigned as  $I^\pi = 3^-$ . For  $^{72}\text{Ga}$ , the results are consistent with the previous  $I = 3$  assignment.

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**I. INTRODUCTION**

Recent optical measurements on gallium [1,2] and copper [3–5] isotopes have investigated the inversion of ground-state (g.s.) spin, suggested to be caused by the monopole component of the tensor interaction [6]. In the case of gallium, a lowering of the  $\pi f_{5/2}$  orbital relative to the  $\pi p_{3/2}$  orbital as the  $\nu g_{9/2}$  orbital is filled was seen to cause a change in g.s. spin between  $^{79}\text{Ga}$  ( $I = 3/2$ ) and  $^{81}\text{Ga}$  ( $I = 5/2$ ) [1]. Additionally, a previously unknown isomeric state was discovered in  $^{80}\text{Ga}$  [2]. These studies have now been extended to investigate the odd-odd gallium isotopes and therefore the role of odd-even effects with neutron number.

Laser spectroscopy provides direct measurements of nuclear g.s. spin, irrespective of the nuclear moments that are subsequently extracted from the hyperfine structure (hfs) [7]. Once the g.s. spin is established, it permits assignments for excited levels. This was particularly pertinent for  $^{73}\text{Ga}$ , where an anomalous g.s. spin of  $I = 1/2$  was established in Refs. [1,8] as well as for  $^{75}\text{Cu}$  having spin  $5/2$  [3,9]. In addition, the nuclear magnetic dipole moment  $\mu$  and spectroscopic electric quadrupole moment  $Q_s$  are extracted from the hfs without model dependence [1]. Similar  $g$  factors ( $g = \mu/I$ ) were observed for the odd- $A$  isotopes  $^{67,69,71}\text{Ga}$  and  $^{75,77}\text{Ga}$ , dominated by  $\pi p_{3/2}$  configurations. However, while  $^{67,69,71}\text{Ga}$  are prolate deformed, the  $^{75,77}\text{Ga}$  are oblate deformed, suggesting a transition from a  $p_{3/2}^3$  hole configuration to  $p_{3/2}^1$  particle structure.

Shell-model calculations were performed using the  $jj44b$  and  $JUN45$  effective interactions, with the  $jj44b$  interaction providing a slightly better match to data overall [1]. A comparison of experimental and theoretical moments for  $^{79}\text{Ga}$  [1] revealed that it was the calculated *first excited*  $I = 3/2$  state ( $\pi f_{5/2}^3$  dominated), which matched its measured g.s. properties. A gradual emptying of the  $\pi p_{3/2}$  level with neutron number is therefore seen for the odd- $A$  Ga isotopes [1]. The present paper reports the hfs measurements of  $^{72,74,76,78}\text{Ga}$ , which were performed during the same experiment as those reported in Refs. [1,2].

**II. EXPERIMENTAL METHOD**

Isotopes of gallium, including  $^{72,74,76,78}\text{Ga}$ , were produced by neutron-induced fission of a thick ( $45\text{ g/cm}^2$ ) uranium carbide target. The neutrons were produced using a  $2\text{-}\mu\text{A}$  average current of  $1.4\text{-GeV}$  protons incident on a tantalum rod, which acted as a proton-neutron converter [10]. Ionization of Ga atoms was selectively enhanced using the Resonance Ionization Laser Ion Source (RILIS) laser ion source [11], while the use of the converter ensured suppression of the neutron-deficient Rb isobars, which are not produced by neutron-induced fission of uranium. A singly charged ion beam was extracted and mass selected before delivery to the ISOLDE cooler and buncher (ISCOOL) [12]. The ions were accumulated and released in bunches of  $2.5\text{ }\mu\text{s}$  full width at half maximum (FWHM) every 50 ms and delivered to the collinear laser spectroscopy (COLLAPS) experimental setup

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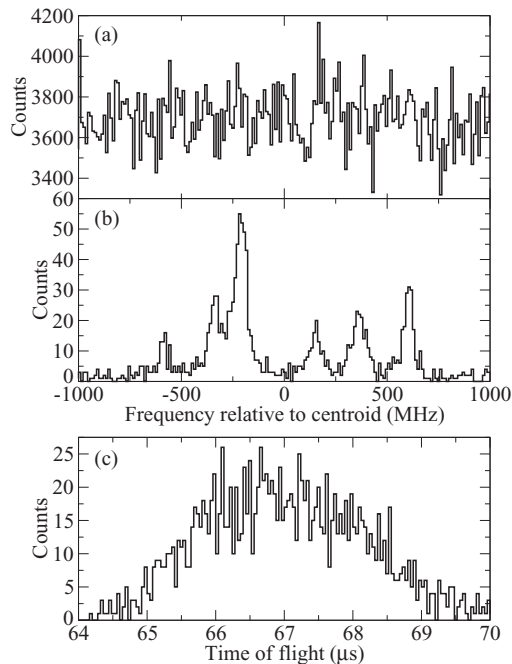


FIG. 1. Optical spectra for  $^{76}\text{Ga}$  (a) without using a gate and (b) with a  $6\text{-}\mu\text{s}$  gate ( $64\text{--}70\ \mu\text{s}$  for  $^{76}\text{Ga}$ ) applied to the photon signal. (c) The arrival of the atom bunch in the interaction region, where the range  $x$  axis corresponds to the gate applied.

[13], where the ion beam was neutralized via passage through a Na vapor cell and overlapped in a collinear geometry with a frequency-doubled narrow-linewidth ( $\sim 1$  MHz) cw laser beam. By applying a Doppler tuning potential to the neutralization cell, a frequency scan was performed. Fluorescence photons were detected perpendicularly to the flight direction using a photomultiplier tube (PMT). To reduce the photon background due to continuous scattering of laser light into the PMT, a  $6\text{-}\mu\text{s}$  gate was applied corresponding to the laser and atom-bunch interaction time. Figure 1 shows the effect of applying the gate to the PMT signal.

### III. DATA ANALYSIS

Full hyperfine structures of the  $^{72,74,76,78}\text{Ga}$  ground states were measured on the  $417.3\text{-nm } 4p^2P_{3/2} \rightarrow 5s^2S_{1/2}$  atomic line. These are shown in Fig. 2 with the  $^{80}\text{Ga}$  ground and isomeric states for completeness [2]. Model structures were fitted to the data using a  $\chi^2$ -minimization technique, yielding the magnetic hfs constants [ $A = \mu B(0)/I J h$ ] of both atomic states and the quadrupole hfs constants ( $B = eQ_s V_{zz}/h$ ) of the  $^2P_{3/2}$  level.

For  $^{74,76,78}\text{Ga}$ , the g.s. nuclear spin values were unconfirmed prior to this work. Due to the selection rules for the atomic transition, a nuclear spin of  $I = 1$  can be immediately ruled out for  $^{76,78}\text{Ga}$  since six (rather than five) hfs peaks are observed in each case. Fitting of the hfs was repeated for the alternative spin assignments  $I = 2, 3, 4$ . The spins and respective  $\chi^2$  values from the fits are compared in Table I. Fitting with nuclear spin values higher than  $I = 3$  produces an increasingly poorer match to the data, and thus the results are not listed in Table I.

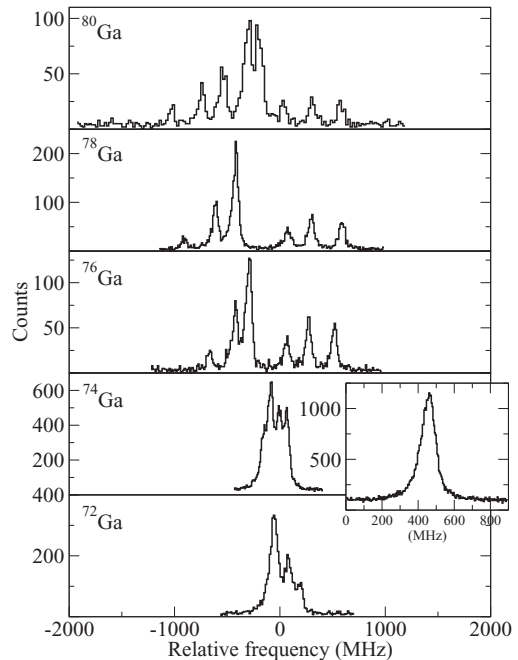


FIG. 2. Hyperfine structures arising from the ground states of  $^{72,74,76,78,80}\text{Ga}$ , measured on the  $417.3\text{-nm } 4p^2P_{3/2} \rightarrow 5s^2S_{1/2}$  line. Additional scans were taken (not shown) to improve statistical confidence.  $^{74}\text{Ga}$  was also measured on the  $403.4\text{-nm } 4p^2P_{1/2} \rightarrow 5s^2S_{1/2}$  line and is shown in the inset.

To improve confidence, the ratio of the hfs  $A$  coefficient was constrained to the value  $A_u/A_l = +5.592$ , established from the odd- $A$  isotopes [1]. For confirmation, this analysis was repeated without such a constraint, but with the hfs relative intensities constrained to values expected from weak-field angular momentum coupling estimates. An assignment of  $I = 2$  can unambiguously be made for the g.s. of both the  $^{76}\text{Ga}$  and  $^{78}\text{Ga}$  isotopes.

Unlike the  $^{76,78}\text{Ga}$  isotopes, the hfs splitting of  $^{72,74}\text{Ga}$  is condensed, and the structure is not fully resolved. For this reason, the hfs fitting was performed constraining both the ratio of the hfs  $A$  parameters and the relative hfs intensities. However, the fitted values for  $^{72}\text{Ga}$  remained unchanged from a fit with free intensities and are consistent with published values [14]. The g.s. spin of  $^{72}\text{Ga}$  has been firmly established as  $I = 3$  [15], whereas the g.s. spin of  $^{74}\text{Ga}$  has only been tentatively assigned as  $I = (3, 4)$  [16]. The  $\chi^2$  analysis shows a preference for  $I = 3$  (Fig. 3), but for completeness the hfs coefficients for both spin assumptions are given in Table II. An  $I = 2$  structure produces a significantly poorer match to the data, with  $\chi^2 = 490.7$  for the data set shown in Fig. 3.

To provide clarity for the  $^{74}\text{Ga}$  structure, the spectrum was also measured on the  $403.4\text{-nm } 4p^2P_{1/2} \rightarrow 5s^2S_{1/2}$  line. This transition is only sensitive to the magnetic moment, and the absence of any hyperfine splitting of the resonant peak (Fig. 2, inset) confirms that the  $A$  coefficient is within the range quoted in Table II. A 9.5-s isomeric state believed to exist in this isotope [17] was not evident in any optical spectrum taken nor in any nuclear decay spectroscopy test performed at the

TABLE I. Comparison of  $\chi^2$  values for hfs fitting with alternative spin assignments  $I = 2$  and  $I = 3$ . The procedure is repeated for the five scans taken for  $^{76}\text{Ga}$  and the two scans of the  $^{78}\text{Ga}$  hfs. In each case, the ratio of the magnetic hyperfine parameter was constrained to the known value  $A_u/A_1 = +5.592$  [1], and separately, the relative hfs intensities were constrained to the model values. Reducing the laser power density to a few tenths of a milliwatt per  $\text{mm}^2$  minimized optical pumping effects. A strong and consistent preference is seen for  $I = 2$  in both isotopes.

A	Data set	$A_u/A_1$ ratio	Relative intensities	$I = 2$		$I = 3$	
				$\chi^2$	$\chi_r^2$	$\chi^2$	$\chi_r^2$
76	1	fixed	free	223	1.18	423	2.24
76	2	fixed	free	174	0.92	298	1.57
76	3	fixed	free	262	1.39	352	1.86
76	4	fixed	free	227	1.20	341	1.80
76	5	fixed	free	158	0.84	234	1.24
76	1	free	fixed	256	1.33	332	1.72
76	2	free	fixed	192	1.00	268	1.39
76	3	free	fixed	290	1.50	315	1.63
76	4	free	fixed	237	1.23	302	1.57
76	5	free	fixed	168	0.87	205	1.06
78	1	fixed	free	278	1.47	475	2.51
78	2	fixed	free	233	1.24	512	2.71
78	1	free	fixed	284	1.47	502	2.60
78	2	free	fixed	247	1.28	430	2.23

On-Line Isotope Mass Separator (ISOLDE) facility [18] nor in ISOLDE Penning trap (ISOLTRAP) mass measurements [19].

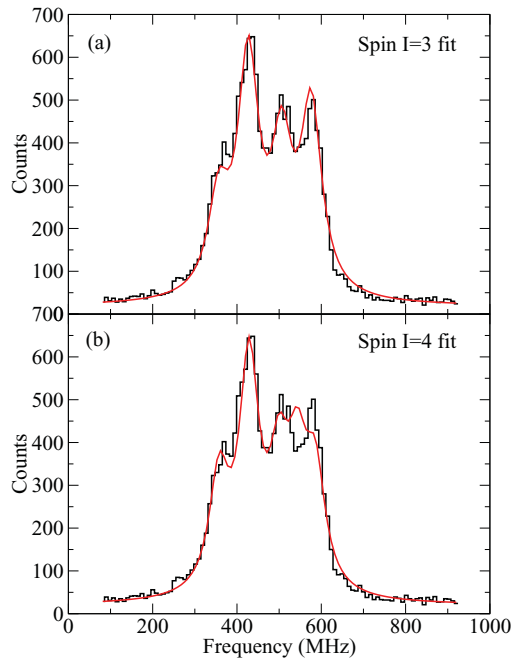


FIG. 3. (Color online) Hyperfine structure of  $^{74}\text{Ga}$  with fits assuming (a)  $I = 3$  ( $\chi^2 = 210.9$ ) and (b)  $I = 4$  ( $\chi^2 = 246.7$ ). For a second data set that was taken,  $\chi^2 = 141.9$  ( $I = 3$ ) and  $\chi^2 = 156.3$  ( $I = 4$ ). The number of data points was 94 in each case.

TABLE II. The hfs coefficients of the  $4s^25s^2S_{1/2}$  and  $4s^24p^2P_{3/2}$  states. For  $^{76,78}\text{Ga}$ , these were determined (after having determined the spin) from a fit without restrictions on peak intensities or  $A_u/A_1$  ratio. For  $^{72,74}\text{Ga}$ , the hfs coefficients were constrained to the known ratio,  $A_u/A_1 = +5.592$ , and the errors account for any discrepancies between fits using constrained or free relative peak intensities.

A	I	$A(^2S_{1/2})$ (MHz)	$A(^2P_{3/2})$ (MHz)	$B(^2P_{3/2})$ (MHz)
72	3	-35.6(10)		+195.3(26)
74	(3)	0(20)		+200(10)
74	(4)	0(15)		+220(10)
76	2	-376.2(16)	-66.8(3)	+120(3)
78	2	-483.0(20)	-85.7(10)	+119.1(15)

#### IV. DISCUSSION

The nuclear moments for the isotopes measured in this work were determined relative to the known moments and hyperfine coefficients for  $^{71}\text{Ga}$  [1,20,21]. Shell-model calculations of the level energies, spins, and moments were performed using the NUSHELLX code [22]. The jj44b effective interaction was used as for the odd-Ga isotopes [1]. This interaction was developed for the  $p_{3/2}f_{5/2}p_{1/2}g_{9/2}$  model space using a fit to around 600 binding and excitation energies (250-keV rms deviation) in the  $Z = 28 - 30$ ,  $N = 48 - 50$  region [1]. A comparison of these results with the experimental values is shown in Table III. Figure 4 shows the level structures calculated for this interaction.

The energy levels calculated with the jj44b interaction for  $^{80}\text{Ga}$  are consistent with the observed optical spectra but with the  $5^-$  state lying below the  $3^-$  state [2]. Two long-lived states have been observed, with spin and parity  $6^-$  (calculated to be the ground state) and a  $3^-$  isomeric state. Their moments are well reproduced by the shell-model calculations, giving support to the calculated wave functions, which are dominated

TABLE III. Experimental magnetic dipole moments  $\mu_{\text{expt}}$  and electric quadrupole moments  $Q_{\text{expt}}$  determined in this work. Also shown are the values of  $\mu_{\text{SM}}$  and  $Q_{\text{SM}}$  from shell-model estimates using the jj44b effective interaction. These moments are calculated for the lowest-energy state corresponding to the nuclear spin indicated. An effective  $g_s^{\text{eff}} = +0.7g_s^{\text{free}}$  is used for the magnetic moments, while the effective charges used are  $e_p^{\text{eff}} = +1.5e$ ,  $e_n^{\text{eff}} = +1.1e$ .

A	I	$\pi_{\text{SM}}$	$\mu_{\text{expt}} (\mu_N)$	$Q_{\text{expt}} (\text{b})$	$\mu_{\text{SM}} (\mu_N)$	$Q_{\text{SM}} (\text{b})$
72 <sup>a</sup>	3		-0.134(4)	+0.536(29)		
72 <sup>b</sup>	3		-0.13224(2)	+0.52(1)		
74	(3 <sub>1</sub> )	-	0.000(75)	+0.549(40)	-1.423	+0.211
74	(3 <sub>2</sub> )	-			-0.324	+0.441
74	(4)	-	0.000(75)	+0.604(42)	-0.301	+0.066
76	2 <sub>1</sub>	-	-0.946(4)	+0.329(19)	-1.370	+0.336
76	2 <sub>2</sub>	+			+0.629	+0.307
78	2 <sub>1</sub>	-	-1.215(5)	+0.327(18)	-1.548	+0.332
78	2 <sub>2</sub>	+			+1.347	+0.292

<sup>a</sup>Shell-model values not calculable due to an issue with the NUSHELLX code (B. A. Brown, private communication).

<sup>b</sup>Values published in Ref. [20].

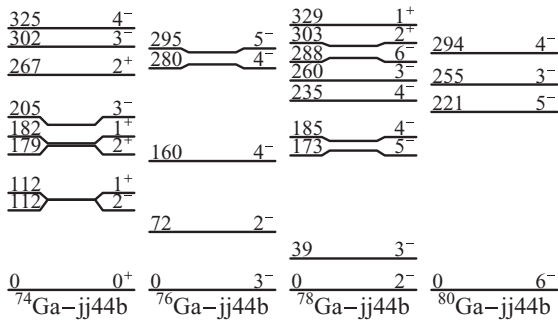


FIG. 4. Level structure in  $^{74,76,78,80}\text{Ga}$  according to shell-model calculations using the *jj44b* effective interaction.

for both states by protons in the  $\pi f_{5/2}$  orbital (see occupation probabilities in Fig. 5 and main configurations in Fig. 6).

For  $^{78}\text{Ga}$ , the shell model correctly predicts a g.s. spin of  $I = 2$ . The parity of the level is negative, based on the good agreement between the calculated magnetic and quadrupole moments for the  $2^-$  g.s. with the observed values. The positive-parity level at 303 keV is excluded as the ground state, based on the disagreement between the calculated  $2^+$  magnetic moment (positive) and the measured negative value (while their quadrupole moments are similar; see Table III).

Similar arguments can be used to establish the parity for  $^{76}\text{Ga}$ . The lowest calculated  $I = 2$  state, with negative parity, lies at 72 keV (Fig. 4), and its calculated moments match the measured g.s. moments, while the calculated magnetic moment of the  $2^+$  state at 359 keV has the wrong sign (Table III).

For  $^{74}\text{Ga}$ , the observed hfs contains many peaks, and therefore its g.s. spin is definitely not  $I = 0$  as predicted. A  $\chi^2$  analysis of the hfs shows a preference for  $I = 3$ , but due to the collapsed structure it may be susceptible to other optical excitation effects, and a spin  $I = 4$  cannot be ruled out (spin 2 can be excluded, however). The lowest calculated  $3^-$  level appears at 205 keV and another one appears at 302 keV, while a  $4^-$  state appears at 325 keV. No positive-parity states

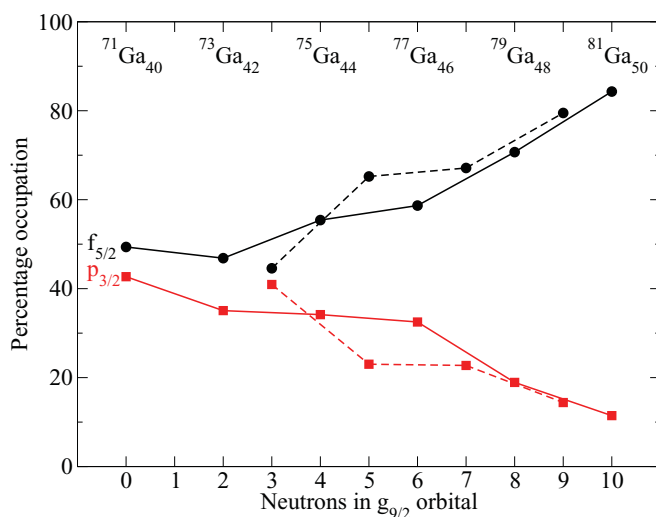


FIG. 5. (Color online) Percentage occupation of the  $\pi p_{3/2}$  and  $\pi f_{5/2}$  levels in the ground states of  $^{71-81}\text{Ga}$ .

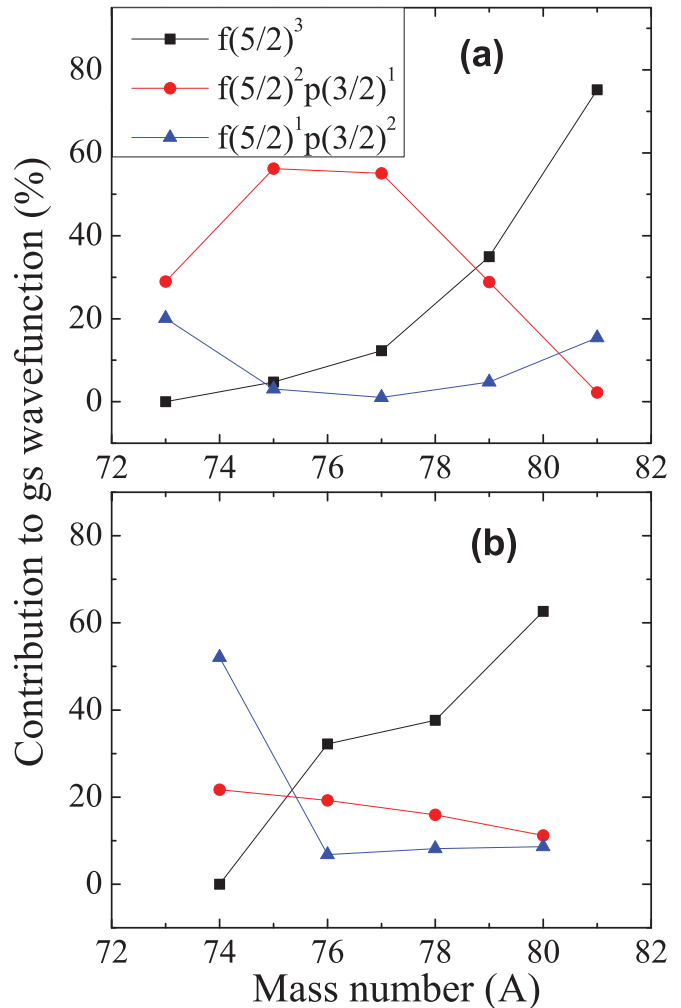


FIG. 6. (Color online) Leading proton configurations (as a percentage contribution to the wave function) for the (a) odd and (b) odd-odd Ga isotopes determined from the shell-model configurations.

with these spins occur below 400 keV. All of these states are candidates for the observed ground state. Only for the second  $3^-$  state the calculated magnetic and quadrupole moment are both in reasonable agreement with the observed values (see Table III), and this therefore provides further confidence in a spin-3 assignment.

The good agreement of the calculated moments with the observed values (from [1] and this work) supports the calculated wave functions (although the state is not always calculated as the ground state). Thus, by observing the orbital occupation numbers for these wave functions, the evolution of the  $\pi p_{3/2}$  and  $\pi f_{5/2}$  orbitals can be studied as a function of the filling of the  $\nu g_{9/2}$  from  $N = 40$  to  $N = 50$ . In Fig. 5 these are given as a percentage of the total occupation for the three protons outside the  $Z = 28$  core.

In the odd-Ga isotopes a gradual increase is observed for the  $f_{5/2}$  occupation, with a sudden change in the slope at  $^{77}\text{Ga}$  (six neutrons in the  $\nu g_{9/2}$  shell). For the odd-odd Ga isotopes, a strong staggering is observed at the  $\nu g_{9/2}$  midshell in  $^{76}\text{Ga}$ . Both effects are correlated with a sudden change

in leading proton configuration, as illustrated in Fig. 6. In Fig. 6, the probability of the three major proton configurations is presented for the ground states of the gallium isotopes. The probability for a  $p_{3/2}^3$  configuration is below 5% in all isotopes and therefore is not shown in Fig. 6. In  $^{73}\text{Ga}$  [Fig. 6(a)], the g.s. has a rather mixed configuration with g.s. spin  $I = 1/2$  [1]. In  $^{75,77}\text{Ga}$  the wave function is dominated by the  $f_{5/2}^2 p_{3/2}$  configuration with an  $I = 3/2$  g.s. spin. This proton particle configuration explains the negative sign for the  $^{75,77}\text{Ga}$  quadrupole moments [1,23,24]. In  $^{79}\text{Ga}$ , which also has a g.s. spin  $3/2$ , this configuration competes with a seniority three ( $f_{5/2}^3$ ) $_{3/2}$  configuration, and therefore the sign of its quadrupole moment is positive. This changes again in  $^{81}\text{Ga}$ , where 90% of the wave function consists of an odd number of protons in the  $f_{5/2}$  orbital coupling to g.s. spin  $I = 5/2$ . The quadrupole moment of this ( $f_{5/2}^3$ ) $_{5/2}$  configuration is zero, and the observed very small negative quadrupole moment is due to the small contribution from the  $f_{5/2} p_{3/2}^2$  proton particle configuration.

In the odd-odd Ga isotopes [Fig. 6(b)] the situation is very different. In  $^{74}\text{Ga}$  the two leading configurations have respectively one and two protons in the  $f_{5/2}$  orbital, while from midshell  $^{76}\text{Ga}$  onward, the  $f_{5/2}^3$  configuration is the leading one. This explains the sudden jump in the  $f_{5/2}$  occupation probability for  $^{76}\text{Ga}$  (Fig. 5) and the prolate deformation in these nuclei. As for  $^{80}\text{Ga}$ , the wave function is dominated by three protons in the  $\pi f_{5/2}$  orbit. The purity of this proton configuration can be attributed to the reduced neutron excitation probability to the  $\nu g_{9/2}$  orbital. Since the  $\nu g_{9/2}$  orbital has only one hole below the  $N = 50$  shell gap, neutron

excitations to this level are hindered, and as a consequence, there are fewer  $p$ - $n$  coupling possibilities available for the protons and thus a reduced number of proton excitations as well.

In conclusion, a firm assignment of  $I^\pi = 2^-$  has been made for the ground states of  $^{76}\text{Ga}$  and  $^{78}\text{Ga}$ . The  $^{74}\text{Ga}$  ground state is tentatively assigned  $3^-$ . This will have consequences for the feeding and spin and parity assignments for excited states studied via decay spectroscopy techniques. Nuclear moments were also measured in this work. Although shell-model calculations reproduce the values well for  $^{76,78}\text{Ga}$ , the agreement is not as good for  $^{74}\text{Ga}$ , especially for its magnetic moment, suggesting a very mixed ground-state configuration.

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