Nuclear Spins and Moments of Ga Isotopes Reveal Sudden Structural Changes between $N = 40$ and $N = 50$

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Collinear laser spectroscopy was performed on Ga ($Z = 31$) isotopes at ISOLDE, CERN. A gas-filled linear Paul trap (ISCOOL) was used to extend measurements towards very neutron-rich isotopes ($N = 36–50$). A ground state (g.s.) spin $I = 1/2$ is measured for $^{73}$Ga, being near degenerate with a $3/2^-$ isomer (75 eV $\leq E_{\text{ex}} \leq$ 1 keV). The $^{79}$Ga g.s., with $I = 3/2$, is dominated by protons in the $\pi f_{5/2}$ orbital and in $^{81}$Ga the $5/2^-$ level becomes the g.s. The data are compared to shell-model calculations in the $f_{5/2}p_{9/2}$ model space, calling for further theoretical developments and new experiments.

Nuclear structure has for some time been described by the single-particle (SP) states of nucleons in the shell model. The evolution and reordering of these levels along isotopic chains is explored at radioactive ion beam facilities to provide information on the nature of the nucleon-nucleon interaction. Key to these studies is the determination of the value of the nuclear spin of each state, which may sometimes be inferred from nuclear decay and $\gamma$-spectroscopy data, laser spectroscopy [1,2] permits a measurement of the nuclear spin, in addition to the state’s magnetic dipole and electric quadrupole moments. The latter two observables are very sensitive to the wave function and thus to the SP shell evolution. The sensitivity of the laser technique has been critically enhanced using bunched beams from a gas-filled linear rf quadrupole known as an ion beam cooler [3]. In this Letter we report the application of ISCOOL [4]—an ion beam cooler recently installed at ISOLDE—for collinear laser spectroscopy on Ga isotopes from stable to the magic $N = 50$ shell gap, located 15 isotopes away from stability. For the first time g.s. spins have been measured, revealing sudden changes not observed in earlier experiments.

The Ga isotopes have three protons outside the $Z = 28$ shell gap. In a normal shell-model ordering, the three protons would occupy the $\pi p_{3/2}$ level, leading to a g.s. spin $I = 3/2$ for all odd-A Ga isotopes. However, in the Cu isotones with two protons fewer, it has been demonstrated that the proton SP ordering changes when neutrons start occupying the $\nu g_{9/2}$ orbital around $N = 40$ [5–15]. An inversion of the $\pi p_{3/2}$ and $\pi f_{5/2}$ SP levels was established recently in $^{75}$Cu at $N = 46$ [11], where the $5/2^-$ g.s. is near degenerate with a $3/2^-$ and $1/2^-$ state [11]. In this Letter we establish the g.s. spins and structure of the odd-A Ga isotopes from $N = 36$ up to the $N = 50$ shell closure, and we investigate the systematics of the $1/2^-$, $3/2^-$ and $5/2^-$ levels.

Fission fragments were produced in a thick UC$_4$ target (45 g/cm$^2$) using 1.4 GeV protons at an average current of $\sim 2 \mu$A. A proton-neutron converter [16] was used to suppress the Rb production. The Ga yield was selectively enhanced by a factor of 100 using the Resonant Ionization Laser-Ion Source [17], extracted and accelerated to 30 keV and mass selected. The ions were cooled and bunched by the newly-installed ISCOOL [4] and delivered to the collinear laser spectroscopy setup [18]. The ion beam was
neutralized by passage through a Na vapor cell and overlapped with a laser beam in order to resonantly excite the Ga atoms. A tuning potential applied prior to neutralization acted to Doppler-shift the laser frequency, allowing a scan over the hfs resonances. The 417.3 nm $4p^2P_{3/2} \rightarrow 5s^2S_{1/2}$ and 403.4 nm $4p^2P_{1/2} \rightarrow 5s^2S_{1/2}$ lines were studied using 0.1–0.4 mW of light from a frequency-doubled titanium-sapphire laser, locked to a stabilized HeNe laser with use of an interferometer. Ions were accumulated in ISCOOL every 50 ms before release. A 6 µs gate, marking the laser-ion bunch interaction time, was applied to the photon signal to reduce the background by a factor of $\sim 10^4$.

Figure 1 shows sample spectra measured on the 417.3 nm line for $^{67,69,71,73,75,77,79,81}$Ga and the 403.4 nm line for $^{73}$Ga. Full hyperfine structures (hfs) were fitted to the data using a $\chi^2$-minimisation technique yielding the magnetic hfs constants ($A = \mu B(0)/I I$) and the quadrupole hfs constants ($B = Q/V_{xc}$) of the upper and lower level and the isotope shift [2]. Fits were made assuming different spins and from the measured hfs shapes and from the $\chi^2$ analysis, spins are determined. Prior to this work a spin $I = 3/2$ had been assigned to all ground states up to $^{79}$Ga, although tentatively in the cases of $^{71}$Ga and $^{79}$Ga.

The $^{67,69,71}$Ga spectra clearly reveal a g.s. spin of $I = 3/2$. As can be seen from Fig. 1, the spectrum of $^{73}$Ga appears markedly different. A nuclear spin of $I = 3/2$ was assigned to the g.s. by Vergnes et al. [19], but the observed hfs is incompatible with such a spin. A second measurement, on the 403.4 nm $^2P_{1/2} \rightarrow ^2S_{1/2}$ line, was therefore performed on $^{71,73,77,79}$Ga for comparison. Only 3 peaks are seen for $^{73}$Ga (Fig. 1 inset) which is only possible if the nuclear spin is $I = 1/2$. If an $I = 3/2$ state would have been present in the beam, a peak should have been observed around 300 MHz, as in $^{71,73}$Ga. Thus the observed $^{73}$Ga hfs must come from its g.s. and a spin $I = 1/2$ can be unambiguously assigned to it. A spin $I = 1/2$ g.s. is compatible with the $^{73}$Ga $\beta$-decay data [20], where a spin of $I = 3/2$ was assigned to the g.s. based on systematics. A recent shell-model calculation in the $\pi
nu f_s(5/2)\nu s(9/2)$ model space reproduced the experimentally observed lowering of the $1/2^-$ level from $^{79}$Ga down to $^{75}$Ga [21]. No calculation was done for $^{73}$Ga, because the model space was too large.

Low-lying $I = 1/2$ states have been observed in $^{67,69,71,75,77}$Ga [22], but not in $^{73}$Ga (Fig. 2(a)). Based on the low energy of the $1/2^-$ level in $^{75}$Ga (at 22 keV), Stefanescu et al. [22] suggest the $1/2^-$ state in $^{73}$Ga might become the g.s. and be quasidegenerate with a $3/2^-$ level at less than 1 keV excitation energy. This $3/2^-$ state was seen previously in a $(t, p)$ reaction study [19], where it was assigned to the g.s.. Because of the slow release of Ga from the ion source [23] and the accumulation time in the cooler, the half-life of this $3/2^-$ state would have to be $>200$ ms to be observed in our study, assuming equal production with the $1/2^-$ state. This upper limit on the isomeric lifetime allows putting a lower limit of 75 eV on the $3/2^-$ isomeric excitation energy, by assuming a similar $B(M1, 3/2^- \rightarrow 1/2^-)$ rate as in $^{71}$Ga [24].

For $^{75,77}$Ga the g.s. spin $I = 3/2$ has been confirmed by our data. A more extensive analysis was required to assign spins for $^{79,81}$Ga. Their hyperfine structures were fitted assuming different spins, constraining the peak intensities to the Racah values and the hfs coefficients to a fixed ratio $A(^2S_{1/2})/A(^2P_{3/2}) = +5.592(9)$, being the weighted mean of the ratios of the other odd-Ga isotopes. The $\chi^2$ values are shown in Table I for spins 3/2 and 5/2 (spin 1/2 is excluded as $>3$ hfs transitions are observed). From a comparison of these numbers it is concluded that a change of the g.s. spin occurs from $^{79}$Ga to $^{81}$Ga, from $I = 3/2$ to $I = 5/2$. The hfs $A$ and $B$ coefficients [2] determined from

**TABLE I.** Values of $\chi^2$ and $\chi^2_f$ (reduced) for each assumed spin, $I$. For the purposes of spin determination, the peak intensities were constrained to the Racah intensities and ratio of the hfs A coefficients was constrained.

<table>
<thead>
<tr>
<th>I</th>
<th>Data Set</th>
<th>$\chi^2$</th>
<th>$\chi^2_f$</th>
<th>$\chi^2$</th>
<th>$\chi^2_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/2</td>
<td>79</td>
<td>299</td>
<td>1.54</td>
<td>563</td>
<td>2.90</td>
</tr>
<tr>
<td>3/2</td>
<td>79</td>
<td>259</td>
<td>1.33</td>
<td>398</td>
<td>2.05</td>
</tr>
<tr>
<td>3/2</td>
<td>81</td>
<td>274</td>
<td>1.40</td>
<td>205</td>
<td>1.05</td>
</tr>
<tr>
<td>3/2</td>
<td>81</td>
<td>369</td>
<td>1.89</td>
<td>234</td>
<td>1.20</td>
</tr>
<tr>
<td>5/2</td>
<td>81</td>
<td>288</td>
<td>1.48</td>
<td>176</td>
<td>0.90</td>
</tr>
<tr>
<td>5/2</td>
<td>81</td>
<td>402</td>
<td>2.06</td>
<td>256</td>
<td>1.31</td>
</tr>
</tbody>
</table>
the data for a given spin without restriction on the peak intensities or hfs ratios are shown in Table II. Those of 67,69,71Ga are consistent with the previous measurements [25–27]. The A-factor ratio for 79Ga (assuming $I = 5/2$) is 5.73(4) (Table II), which deviates more than 3σ from the weighted mean of all isotopes. This is another proof that the g.s. spin of 79Ga is $I = 3/2$. For 81Ga, assuming a g.s. spin of $I = 3/2$, the A-factor ratio is +6.01(4)—a deviation of 10σ.

Shell-model calculations of energy levels and nuclear moments were performed using two effective interactions: JUN45 [15] and jj44b [28]. Both have been developed for the $3p_3/2s_1/2p_1/2g_9/2$ model space with 56Ni as a core. Figure 2 shows a comparison of predicted levels below 1 MeV with experimental levels and spins taken from this work and Refs. [22,29–31].

Let us first consider the evolution of the 1/2− and 5/2− levels between $N = 40$ and $N = 50$. Experimentally, the 1/2− level reaches a minimum energy in 73Ga where it becomes the g.s. Both effective interactions reproduce the lowering of this level towards $N = 42$, 44, but it remains at around 90 keV with the jj44b interaction and at 220 keV with the JUN45 interaction. Considering that the wave function of this 1/2− state is very mixed (illustrating that indeed it is a collective structure) the agreement with theory is remarkably good. The collective nature of the 1/2− states in the 71,73Cu isotopes was observed through their large transition moments to the 3/2− g.s. [10]. It is this collective 1/2− state that becomes the g.s. in 79Ga. The lowering of the 5/2− level from $N = 40$ to $N = 50$ is reproduced by both interactions, but the spin inversion at $N = 50$ is predicted correctly only by the jj44b interaction, which also shows a better overall agreement in the trend. With JUN45 the 5/2− level is systematically at too low energies and the inversion between the 3/2− and 5/2− levels already occurs in 70Ga.

Table III shows the moments extracted from the hfs coefficients using the known magnetic moment [32] and quadrupole moment [33] of 71Ga as a reference. Theoretical moments obtained with both interactions, for the lowest level with the corresponding spin assignment, are also given. An effective $e_p^{eff}$ = 0.7 $g_s^{eff}$ is used for the magnetic moments, while the effective charges are $e_p^{eff}$ = 1.5 $e$, $e_n^{eff}$ = 1.1 $e$ [15] for both JUN45 and jj44b.

Details on the composition of the g.s. wave functions is revealed by the measured nuclear moments. The magnetic moment of 71Ga is closest to the effective SP moment $e_p^{eff} (\pi p_{3/2}) = +2.96 \mu_N$, thus an odd number of protons in the $\pi p_{3/2}$ orbit forms the leading configuration in its wave function. For the 67,69Ga and 73,75,77Ga isotopes, their moments approach the $\pi f_{5/2}$ effective single nucleon value ($= +1.46 \mu_N$), suggesting these isotopes have a more mixed configuration. The opposite sign in their quadrupole moments suggests a significantly different structure, which can be understood as due to the emptying of the $p_{3/2}$ orbital. The normal $\pi (p_{3/2})$ configuration has a positive quadrupole moment but the $\pi (p_{1/2})$ configuration has a negative quadrupole moment. This suggests that in 75,77Ga the g.s. wave function is dominated by the $\pi (p_{3/2})$ odd-particle configuration, having two protons excited into the

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**TABLE II.** The hfs coefficients of the $4s^2 5s^2 S_1/2$ and $4s^2 4p^2 P_3/2$ states determined from a fit without restrictions on peak intensities or hfs ratios. Spins are determined from the least squares analysis (see text). Results for 79Ga, assuming $I = 5/2$, and 81Ga ($I = 3/2$) are given for completeness (see text).

<table>
<thead>
<tr>
<th>A</th>
<th>I</th>
<th>$A(^3S_1/2)$ (MHz)</th>
<th>$A(^3P_1/2)$ (MHz)</th>
<th>$B(^3P_3/2)$ (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>67</td>
<td>3/2</td>
<td>+979.7(2.5)</td>
<td>+175.8(1.0)</td>
<td>+73(4)</td>
</tr>
<tr>
<td>69</td>
<td>3/2</td>
<td>+1069.5(1.5)</td>
<td>+191.5(9)</td>
<td>+63(2)</td>
</tr>
<tr>
<td>71</td>
<td>3/2</td>
<td>+1358.2(1.6)</td>
<td>+242.8(7)</td>
<td>+39(2)</td>
</tr>
<tr>
<td>73</td>
<td>1/2</td>
<td>+332(3)</td>
<td>+60.7(1.3)</td>
<td>0</td>
</tr>
<tr>
<td>75</td>
<td>3/2</td>
<td>+973.1(1.5)</td>
<td>+173.6(9)</td>
<td>-104.9(1.3)</td>
</tr>
<tr>
<td>77</td>
<td>3/2</td>
<td>+1070.6(1.2)</td>
<td>+191.8(5)</td>
<td>-76.7(1.5)</td>
</tr>
<tr>
<td>79</td>
<td>3/2</td>
<td>+555.0(1.4)</td>
<td>+98.3(9)</td>
<td>+58.2(1.5)</td>
</tr>
<tr>
<td>79</td>
<td>5/2</td>
<td>+369.5(0.6)</td>
<td>+64.5(4)</td>
<td>+118.6(2.1)</td>
</tr>
<tr>
<td>81</td>
<td>3/2</td>
<td>+831.2(1.6)</td>
<td>+138.4(8)</td>
<td>-43.4(1.8)</td>
</tr>
<tr>
<td>81</td>
<td>5/2</td>
<td>+556.5(1.3)</td>
<td>+98.9(4)</td>
<td>-17.2(2.7)</td>
</tr>
</tbody>
</table>

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**FIG. 2** (color online). Experimental levels in 71–81Ga compared to calculated levels using jj44b and JUN45 interactions (see text for details). The ground states of 71,73,75,77,79Ga are measured to have spin $I = 3/2$ (black lines), while 73Ga and 81Ga have a ground state spin of $I = 1/2$ (red) and $I = 5/2$ (green), respectively.

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higher proton orbits. This is confirmed by the JUN45 calculations, which reproduce the observed sign inversion in the quadrupole moments and have a dominant $\sigma(p_{3/2}f_{5/2})$ g.s. configuration. The sign inversion occurs around $^{79}$Ga, where the g.s. is a collective $1/2^-$. This is due to the near-degeneracy of the $f_{5/2}$ and $p_{1/2}$ effective SP levels which induces large off-diagonal quadrupole matrix elements and a very mixed wave function [15]. Measuring the $B(E2)$ and $B(M1)$ transition moments from the g.s. to higher levels should provide additional proof for the onset of collectivity in these $N = 42, 44, 46$ Ga isotopes. In the cases of $^{69-71}$Ga, where the jj44b quadrupole moments have the opposite sign to the observed quadrupole moments (Table III), a 20%–30% mixing of the second excited state wave function into the g.s. wave function is sufficient to reproduce their experimental magnetic and quadrupole moments. This illustrates that experimental moments are very sensitive to subtle effects of mixing between low-lying states of similar spin and parity. The energy of a level is less sensitive to the exact composition of the wave function.

For $^{79}$Ga, having also $I = 3/2$, the discrepancy between the experimentally observed moments and the JUN45 and jj44b calculations is substantially higher than for the other isotopes. The experimental magnetic moment is significantly lower and the measured quadrupole moment has the opposite sign to that from both calculations. A much closer agreement with the experimental values is achieved in each case by using the calculated moments of the “second” (or “first excited”) $3/2^-$ state in $^{79}$Ga, appearing, respectively, at 270 keV (jj44b) and 350 keV (JUN45). These values are also shown in Table III. The experimental nuclear $g$ factors ($g = \mu/I$) of $^{79}$Ga and $^{81}$Ga are exactly the same (+0.698 and +0.699, respectively) and close to the effective $\pi f_{5/2}$ SP value (+0.58). This shows that the g.s. wave function of $^{79}$Ga is dominated by an odd number of protons in the $\pi f_{5/2}$ orbital. With both interactions the g.s. and first excited $3/2^-$ level have a mixed wave function with $|1\rangle = \pi(f_{5/2}^3)$ and $|2\rangle = \pi(p_{1/2}f_{5/2}^2)$ as the leading terms. Configuration $|2\rangle$ is dominant in the g.s. wave function in both calculations (50% and 78% for jj44b and JUN45, respectively). This wave function does not reproduce the observed moments. Configuration $|1\rangle$ is dominant in the second $3/2^-$ level (35% and 63%, respectively), and the wave function of this state reproduces well both observed moments, suggesting that the g.s. wave function of $^{79}$Ga has $\pi(f_{5/2}^3)$ as the main component in its wave function.

In summary, the nuclear spins, magnetic dipole, and electric quadrupole moments have been measured for the odd-A Ga isotopes in the range $A = 67–81$. The anomalous g.s. spins of $^{71}$Ga ($I = 1/2$) and $^{81}$Ga ($I = 5/2$), as well as the sign change in the quadrupole moments of $^{75,77,79}$Ga, suggest a changing shell structure from $N = 42$ onwards. Comparing these experimental observables to calculations in the $f_{5/2}p_{9/2}$ model space using two different effective interactions illustrates the strong influence of the $\pi(f_{5/2})$ orbital in the g.s. wave functions from $N = 42$ onwards. This provides further evidence for the suggested lowering of the $f_{5/2}$ level due to the attractive tensor interaction when neutrons occupy the $g_{9/2}$ orbital. The suggested onset of collectivity around neutron midshell calls for measurements of the $B(E2)$ and $B(M1)$ transition moments between $N = 36$ and $N = 50$, as this observable is very sensitive to collectivity in the g.s. wave function. A dedicated measurement will be needed to search for the isomeric decay of the $3/2^-$ state in $^{73}$Ga, with excitation energy between 75 eV and 1 keV. Further theoretical developments, including the $\pi(f_{3/2})$ orbital in the model space, are needed to investigate a possible effect of proton excitations across $Z = 28$.

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[28] B. A. Brown (unpublished). The jj44b Hamiltonian was obtained from a fit to about 600 binding energies and excitation energies with a method similar to that used for the JUN45 Hamiltonian. Most of the energy data for the fit came from nuclei with $Z = 28–30$ and $N = 48–50$. With 30 linear combinations of the good $J-T$ two-body matrix elements varied, the rms deviation between experiment and theory for the energies in the fit was about 250 keV.