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 $\lesssim E_{ex} \lesssim$ 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 $f_{5/2} p g_{9/2}$ 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 provides a means of level identification. Whereas the spin may sometimes be inferred from nuclear decay and γ-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_x target (45 g/cm^2) using 1.4 GeV protons at an average current of ~ 2 μA. 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 over-
lapped 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 χ^2-minimisation technique yielding the
magnetic hfs constants ($A = \mu B(0)/IJ$) and the quadru-
pole hfs constants ($B = Q_s V_{zz}$) of the upper and lower
level and the isotope shift [2]. Fits were made assuming
different spins and from the measured hfs shapes and χ^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 ^{77}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 measure-
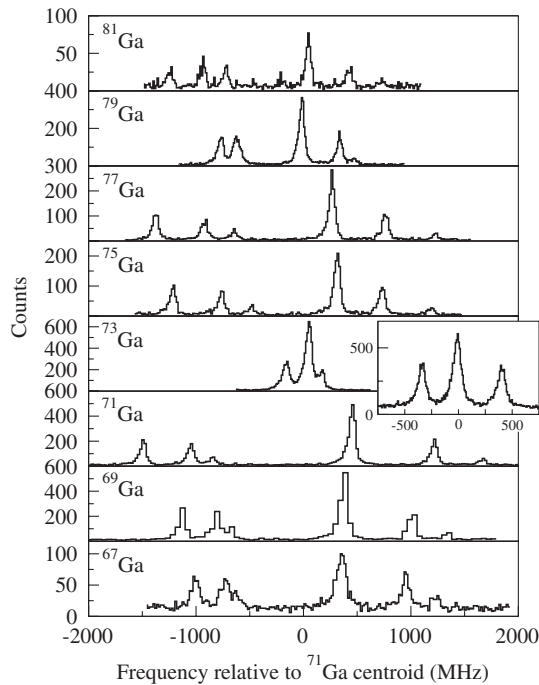ment, on the 403.4 nm $^2P_{1/2} \rightarrow {}^2S_{1/2}$ line, was therefore

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 ob-
served around 300 MHz, as in ^{71,75}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 com-
patible with the ^{73}Ga β-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 $\pi\nu(f_{5/2}pg_{9/2})$ model
space reproduced the experimentally observed lowering of
the $1/2^-$ level from ^{79}Ga down to ^{75}Ga [21]. No calcu-
lation 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 be 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 χ^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

FIG. 1. Optical spectra for ^{67,69,71,73,75,77,79,81}Ga, measured on
the 417.3 nm $4p^2P_{3/2} \rightarrow 5s^2S_{1/2}$ line, and the 403.4 nm
$4p^2P_{1/2} \rightarrow 5s^2S_{1/2}$ spectrum for ^{73}Ga (inset).

TABLE I. Values of χ^2 and χ^2_r (reduced) for each assumed
spin, I. For the purposes of spin determination, the peak inten-
sities were constrained to the Racah intensities and ratio of the
hfs A coefficients was constrained.

A	Data Set	$I = 3/2$		$I = 5/2$	
		χ^2	χ^2_r	χ^2	χ^2_r
79	1	299	1.54	563	2.90
79	2	259	1.33	398	2.05
81	1	274	1.40	205	1.05
81	2	369	1.89	234	1.20
81	3	288	1.48	176	0.90
81	4	402	2.06	256	1.31

TABLE II. The hfs coefficients of the $4s^2 5s\,^2S_{1/2}$ and $4s^2 4p^2\,^2P_{3/2}$ 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 ^{79}Ga, assuming $I = 5/2$, and ^{81}Ga ($I = 3/2$) are given for completeness (see text).

A	I	$A(^2S_{1/2})$ (MHz)	$A(^2P_{3/2})$ (MHz)	$B(^2P_{3/2})$ (MHz)
67	3/2	+979.7(2.5)	+175.8(1.0)	+73(4)
69	3/2	+1069.5(1.5)	+191.5(9)	+63(2)
71	3/2	+1358.2(1.6)	+242.8(7)	+39(2)
73	1/2	+332(3)	+60.7(1.3)	0
75	3/2	+973.1(1.5)	+173.6(9)	−104.9(1.3)
77	3/2	+1070.6(1.2)	+191.8(5)	−76.7(1.5)
79	3/2	+555.0(1.4)	+98.3(9)	+58.2(1.5)
79	5/2	+369.5(0.6)	+64.5(4)	+118.6(2.1)
81	3/2	+831.2(1.6)	+138.4(8)	−43.4(1.8)
81	5/2	+555.6(1.3)	+98.9(4)	−17.7(2.7)

the data for a given spin without restriction on the peak intensities or hfs ratios are shown in Table II. Those of ^{67,69,71}Ga are consistent with the previous measurements [25–27]. The A-factor ratio for ^{79}Ga (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 ^{79}Ga is $I = 3/2$. For ^{81}Ga, 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 $(p_{3/2} f_{5/2} p_{1/2} g_{9/2})$ model space with ^{56}Ni 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 ^{73}Ga 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 ^{71,73}Cu isotones 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 ^{73}Ga. 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 ^{79}Ga.

Table III shows the moments extracted from the hfs coefficients using the known magnetic moment [32] and quadrupole moment [33] of ^{71}Ga as a reference. Theoretical moments obtained with both interactions, for the lowest level with the corresponding spin assignment, are also given. An effective $g_s^{\rm eff} = 0.7 g_s^{\rm free}$ is used for the magnetic moments, while the effective charges are $e_p^{\rm eff} = 1.5e$, $e_n^{\rm eff} = 1.1e$ [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 ^{71}Ga is closest to the effective SP moment $g_{\rm eff}(\pi p_{3/2}) = +2.96\ \mu_N$, thus an odd number of protons in the $\pi p_{3/2}$ orbit forms the leading configuration in its wave function. For the ^{67,69}Ga and ^{75,77}Ga 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 $\pi(p_{3/2}^3)$ configuration has a positive quadrupole moment but the $\pi(p_{3/2}^1)$ configuration has a negative quadrupole moment. This suggests that in ^{75,77}Ga the g.s. wave function is dominated by the $\pi(p_{3/2}^1)$ odd-particle configuration, having two protons excited into the
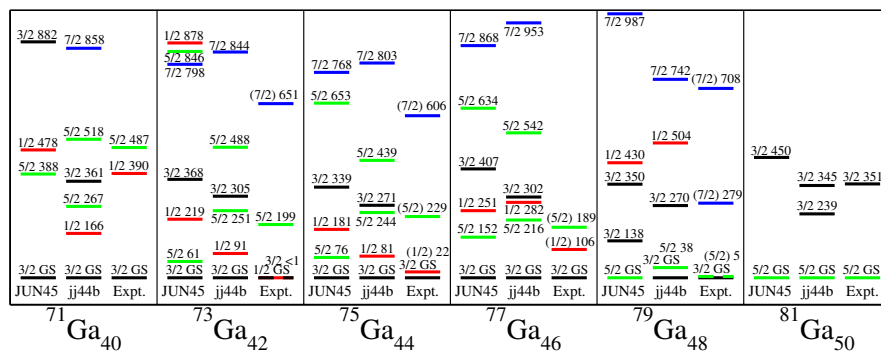

FIG. 2 (color online). Experimental levels in $^{71-81}$Ga compared to calculated levels using jj44b and JUN45 interactions (see text for details). The ground states of ^{71,75,77,79}Ga are measured to have spin $I = 3/2$ (black lines), while ^{73}Ga and ^{81}Ga have a ground state spin of $I = 1/2$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

TABLE III. Magnetic moments, μ, and electric quadrupole moments, Q_s, obtained from the hfs coefficients $A(4s^2 5s^2 S_{1/2})$ and $B(4s^2 4p^2 P_{3/2})$. The moments for ^{71}Ga [32,33] were used as a calibration. Theoretical predictions are included for the moments of the lowest state with the experimental nuclear spin.

A	I	μ_{expt} (μ_N)	μ_{JUN45} (μ_N)	μ_{jj44b} (μ_N)	$Q_{s,\text{expt}}$ $(e\,b)$	$Q_{s,\text{JUN45}}$ $(e\,b)$	$Q_{s,\text{jj44b}}$ $(e\,b)$
67	3/2	+1.848(5)	+1.588	+2.079	+0.198(16)	+0.256	+0.117
69	3/2	+2.018(4)	+1.715	+2.284	+0.171(11)	+0.236	−0.112
71	3/2	+2.56227(2)	+2.188	+2.203	+0.106(3)	+0.192	−0.244
73	1/2	+0.209(2)	−0.130	−0.176	0	0	0
75	3/2	+1.836(4)	+2.441	+2.093	−0.285(17)	−0.149	−0.256
77	3/2	+2.020(3)	+2.463	+2.146	−0.208(13)	−0.203	−0.147
79	3/2	+1.047(3)	+2.543	+2.070	+0.158(10)	−0.207	−0.057
79[a]	3/2	...	+0.832	+1.320	...	+0.161	+0.038
81	5/2	+1.747(5)	+1.461	+1.477	−0.048(8)	+0.044	−0.035

[a]The calculated first excited $3/2^-$ level.

higher proton orbits. This is confirmed by the JUN45 calculations, which reproduce the observed sign inversion in the quadrupole moments and have a dominant $\pi(p_{3/2}f_{5/2}^2)$ g.s. configuration. The sign inversion occurs around ^{73}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 $|2\rangle = \pi(p_{3/2}f_{5/2}^2)$ 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 ^{73}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 $f_{5/2}pg_{9/2}$ 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 $\pi(f_{7/2})$ orbital in the model space, are needed to investigate a possible effect of proton excitations across $Z = 28$.

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