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Laser spectroscopy of gallium isotopes beyond $N = 50$

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Abstract. The installation of an ion-beam cooler-buncher at the ISOLDE, CERN facility has provided increased sensitivity for collinear laser spectroscopy experiments. A migration of single-particle states in gallium and in copper isotopes has been investigated through extensive measurements of ground state and isomeric state hyperfine structures. Lying beyond the $N = 50$ shell closure, ^{82}Ga is the most exotic nucleus in the region to have been studied by optical methods, and is reported here for the first time.

1. Introduction

Recent laser spectroscopic measurements have probed the ground state properties of neutron-rich gallium ($Z = 31$) [1, 2, 3] and copper ($Z = 29$) isotopes [4, 5, 6, 7, 8] and reached the vicinity of ^{78}Ni . Single-particle level migrations were systematically studied through the measurements of ground-state nuclear spins and moments. Shell model calculations predict an inversion of the $\pi p_{3/2}$ and $\pi f_{5/2}$ levels, with the latter replacing the former as the ground state, as the $\nu g_{9/2}$ orbital is filled. This is due to the interaction between the proton and neutron levels caused by the monopole component of the tensor force [9, 10].

2. Experimental techniques

Laser spectroscopy provides model-independent measurements of the nuclear spin, magnetic dipole moment, electric quadrupole moment and mean-square charge radius [11]. Coupled with shell model calculations, the nuclear moments in particular become a sensitive probe of the nuclear wave function. Collinear laser spectroscopy was performed on the COLLAPS [12, 13]

experimental set-up at ISOLDE, CERN. In most experiments, the isotopes were produced from proton bombardment of a thick target and extracted as a ~ 30 keV ion beam, with the flux of the particular element under study selectively enhanced using the Resonant Ionisation Laser Ion Source (RILIS) [14]. Following mass selection, this ion beam was neutralised by passage through an alkali vapour cell before being overlapped with a co-propagating laser beam. A Doppler tuning potential was applied to the vapour cell, and photons detected using a photo-multiplier tube (PMT) as the effective laser frequency was scanned.

The dominant source of photon background arises from the continuous scattering of laser light into the PMT, limiting the sensitivity of the technique. Use of the newly installed ISCOOL [15, 16] cooler–buncher permitted ions to be accumulated and released in cycles of typically 100 ms duration. Each ion bunch emitted has a temporal length of the order of 10 μ s, compressing the resonant photon signal into a time window 10^4 times smaller than the accumulation time. This allows a gate to be applied to the signal which conserves the resonant counts while suppressing the background from laser scatter by four orders of magnitude [17].

Bunch accumulation times can, however, be limited by large isobaric components present in the ion beam. This simultaneously limits the suppression factor by which the laser scatter is reduced, and contributes directly to the photon background within the 10 μ s time window as a result of collisions with residual gas in the laser–ion interaction region. In the case of the neutron–rich gallium isotopes, neutron–deficient rubidium isobars were abundant which saturated the trapping region of ISCOOL. These were produced from spallation and non-resonantly ionised through the process of surface ionisation. By directing the proton beam onto a proton–neutron converter [18], spallation neutrons were used to induce only fission reactions in the uranium carbide target, eliminating the rubidium isobars.

3. Nuclear spins and moments between $N = 40$ and $N = 50$

Laser spectroscopy was performed for the gallium isotopes $^{63,64,66-82}\text{Ga}$, covering the region between $N = 40$ and $N = 50$ where the $\nu g_{9/2}$ shell is filled. Initially, the odd– A isotopes were studied, where the nuclear spins are expected to arise from couplings of the three unpaired protons lying beyond the $Z = 28$ shell gap. The precise pattern of the hyperfine components is dependent on the nuclear spin, permitting a measurement for all odd– A isotopes in the range $^{71-81}\text{Ga}$. In the case of ^{73}Ga , the ground–state spin could be assigned unambiguously as $I = 1/2$ [1]. A $3/2^-$ state had been previously observed in a (t, p) reaction study and assumed to be the ground state [19]. Since the energies of these two states have not been resolved by other techniques [20, 21], they must be nearly degenerate (sub keV).

Analysis of the nuclear moments revealed that the spin $I = 3/2$ ground states of $^{67,69,71}\text{Ga}$ and $^{75,77}\text{Ga}$ had similar magnetic moments, and indicated the role of an unpaired $p_{3/2}$ proton [1]. However, a structural change appears to occur around ^{73}Ga , since $^{67,69,71}\text{Ga}$ are prolate deformed, whereas $^{75,77}\text{Ga}$ are oblate in character. This change is a result of the $\pi p_{3/2}$ orbital emptying with neutron number as the $\pi f_{5/2}$ orbital lowers in relative energy and becomes occupied. Shell model calculations, which reproduce these moments, show that while the leading configuration of the $^{67,69,71}\text{Ga}$ ground states is $\pi p_{3/2}^3$ (a proton hole, and therefore likely to be prolate), the $^{75,77}\text{Ga}$ isotopes have a $\pi p_{3/2} f_{5/2}^2$ leading configuration (so particle–like and therefore oblate deformed).

The nuclear spins of ^{79}Ga and ^{81}Ga were determined to be $I = 3/2$ and $I = 5/2$, respectively, showing that a change in the ground–state spin does indeed occur, between $N = 48$ and $N = 50$ [1]. However, for ^{79}Ga , the experimental moments matched the shell model calculations for the *first excited* $I = 3/2$ state. This state has a $\pi f_{5/2}^3$ leading configuration, as does ^{81}Ga , suggesting that the $\pi f_{5/2}$ orbital has already become dominant in this isotope. In the copper chain, the change in ground–state spin from $I = 3/2$ to $I = 5/2$ was observed to take place

between ^{73}Cu ($N = 44$) and ^{75}Cu ($N = 46$) [4].

For the odd-odd $^{76,78}\text{Ga}$, a definite and model-independent assignment of $I = 2$ was made from the hyperfine structure [3]. A comparison of the experimental moments with shell model calculations for the 2^+ and 2^- states gave a clear indication that the ground states were both negative parity. The occupancy of the $\pi f_{5/2}$ single-particle level was found to be higher in ^{76}Ga than expected from the smooth increase displayed by the odd- A isotopes. This may be related to the prolate (odd- N)/oblate(even- N) staggering observed along $^{74,75,76,77,78}\text{Ga}$. In ^{80}Ga , an isomeric state was discovered [2], which seems to lie too low in energy to be resolved by Penning trap mass measurements [22].

4. Spectroscopy of ^{82}Ga

At $N = 51$, ^{82}Ga significantly lies past the $N = 50$ shell closure. From β -decay feeding, the ground-state spin has been assigned to be in the range of $I = (1, 2, 3)$ [23]. Figure 1 shows three separate measurements of the hyperfine structure of ^{82}Ga , measured on the $417.3\text{ nm } 4p\ ^2P_{3/2} \rightarrow 5s\ ^2S_{1/2}$ atomic line.

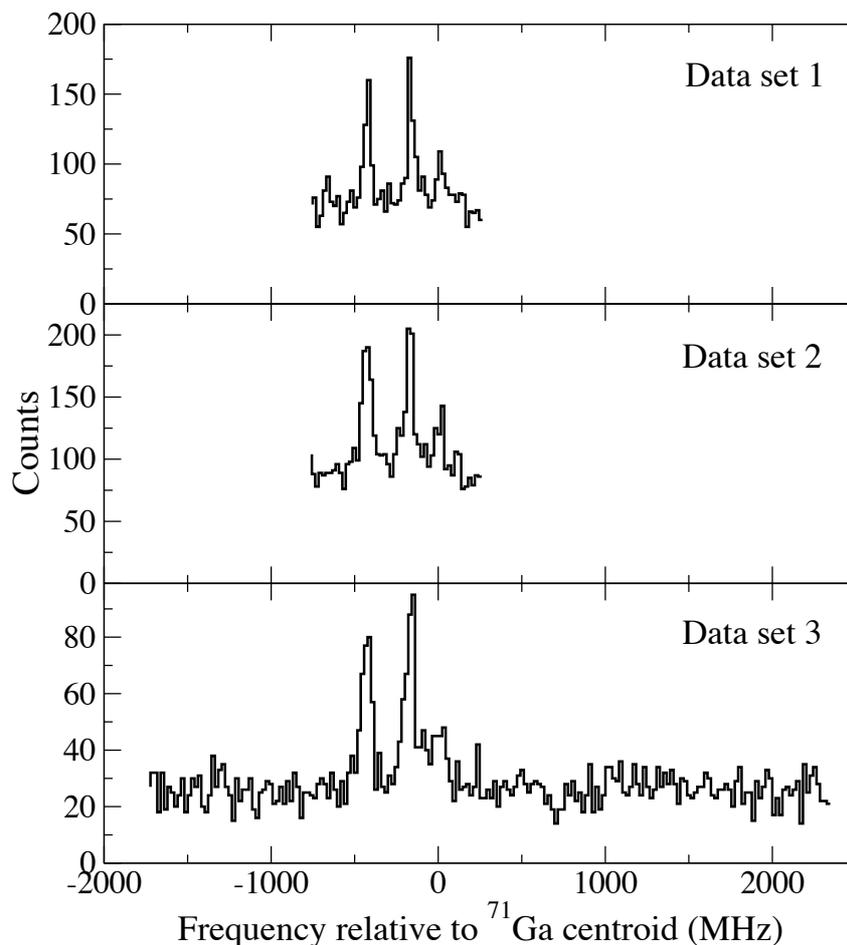


Figure 1. Three separate data sets showing the optical spectrum of the 417.3 nm atomic line in ^{82}Ga .

Compared with the other optical spectra measured on this transition [1, 3], the ^{82}Ga hyperfine structure appears to have a very different shape. From the nuclear and atomic angular

momentum coupling the lower atomic level will split into four states (three in the case of $I = 1$) and the upper atomic level into two states. From the selection rules, these lead to six allowed transitions and therefore six peaks in the hyperfine structure (five in the case of $I = 1$). A spin $I = 0$ ground state would not have any splitting and can be immediately ruled out.

At first, it would appear that the ^{82}Ga spectrum has only three resolved peaks. To test the hypothesis that these three peaks are those corresponding to the transitions to only one of the levels of the upper state, the scan region was widened (see the third data set in Figure 1). From a fitting of the three peaks, the splitting of the upper atomic level, and therefore the full hyperfine structure, is calculable from the known ratio of the hyperfine coefficients [1]. In each case, regardless of the nuclear spin, the additional peaks of the hyperfine structure would have been clearly visible within the extended scan region. It can therefore be concluded that all of the hyperfine structure peaks are contained within the narrower scan regions shown in Figure 1.

Since the hyperfine peaks are not all resolved, the χ^2 values were plotted as a function of the hyperfine A and B coefficients (with the other parameters being minimised for each pair of values). This process was repeated for all three possible values of nuclear spin. Four clear minima can be seen. Table 1 gives the χ^2 values and atomic and nuclear quantities that would result in each case.

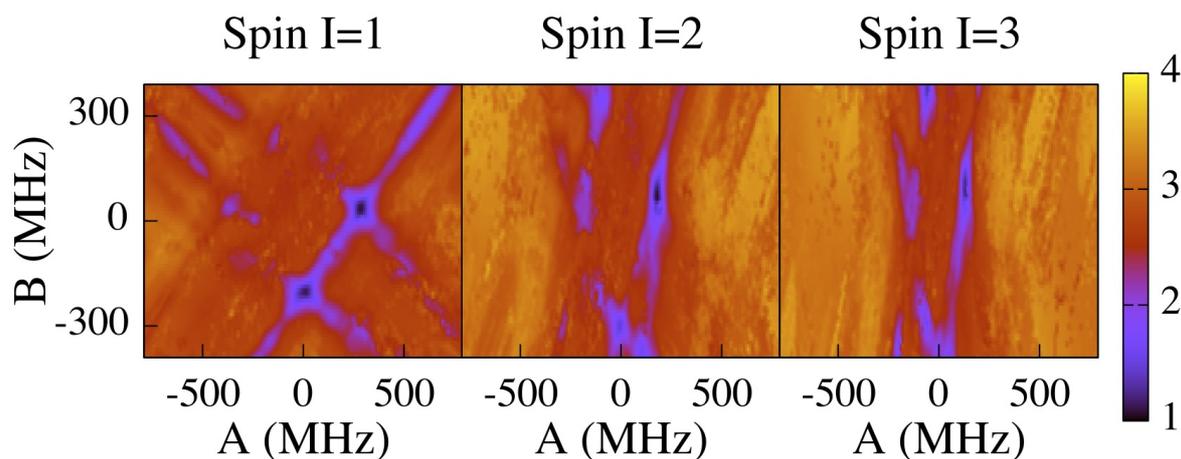


Figure 2. Values of (reduced) χ^2 as a function of fixed $A(S_{1/2})$, $B(P_{3/2})$ and I from fitting the observed hyperfine structure of the ^{82}Ga ground state. Relative peak intensities were constrained to angular momentum coupling estimates, and $A(P_{3/2})$ was constrained to equal $A(S_{1/2})/5.592$ as determined from stable isotope measurements. The nuclear g -factor ($= \mu/I$) and spectroscopic quadrupole moment, Q_s , are proportional to the values deduced for the hyperfine coefficients A and B , respectively. Four χ^2 minima are observed, each being candidates for the ground-state structure of ^{82}Ga .

A comparison of the χ^2 values in Table 1 indicates that the spin of the ^{82}Ga ground state is $I = 2$. Although the difference in the values is rather small, a consistent preference for $I = 2$ is also seen when each data set is fitted separately. The first option for $I = 1$ would correspond to an unreasonably large quadrupole moment. Also shown in the table are the isotope shift values. Irrespective of the correct value of the nuclear spin, the centroid of the fitted ^{82}Ga structure changes little, and the isotope shift can be quoted as $\nu^{82} - \nu^{71} = -222(9)$ MHz. This indicates that an upward kink in the charge radius occurs at $N = 50$ ($\nu^{81} - \nu^{71} = -271.8(1.5)$ MHz). A full analysis of the mean-square charge radii is underway.

Table 1. Hyperfine coefficients $A(S_{1/2})$, $B(P_{3/2})$ and nuclear spins corresponding to the four χ^2 minima shown in Figure 2. Four candidates are shown for the ground-state properties of ^{82}Ga . Also shown are the corresponding magnetic dipole, μ , and electric quadrupole, Q_s , moments determined from the hyperfine coefficients in each case. The χ^2 minimisation was performed fitting structures to three independent data sets simultaneously.

| I | A (MHz) | B (MHz) | $\nu^{82} - \nu^{71}$ (MHz) | μ_{exp} (μ_N) | $Q_{s,\text{exp}}$ (b) | χ^2 | χ_r^2 |
|-----|------------|------------|-----------------------------|--------------------------------|------------------------|----------|------------|
| 1 | +15.5(31) | -200.2(18) | -212.0(20) | +0.019(4) | -0.549(29) | 314 | 1.086 |
| 1 | +289.2(26) | +42.7(23) | -212.9(20) | +0.364(3) | +0.117(9) | 302 | 1.046 |
| 2 | +182.5(14) | +71.7(30) | -224.4(20) | +0.459(4) | +0.197(13) | 292 | 1.011 |
| 3 | +135.2(11) | +98.8(37) | -228.8(20) | +0.510(4) | +0.271(17) | 321 | 1.110 |

5. Outlook

The nuclear spin of the ^{82}Ga ground state has been tentatively assigned as $I = 2$. Although laser spectroscopy often provides a model-independent measurement of the nuclear spin, the difference in the χ^2 values in the case of ^{82}Ga is relatively small. Shell model calculations of the moments for the lowest-lying spin $I = 1, 2$ and 3 levels could be performed to add further confidence in this assignment, if there is a close correspondence with the moments in Table 1 for a specific spin value. At present it has not been possible to perform these calculations due to the $\nu d_{5/2}$ level lying outside of the model spaces previously used. Further theoretical treatment of this area is suggested.

Irrespective of the ^{82}Ga ground-state spin, the isotope shift changes little and a definite kink is seen at $N = 50$. Publications of the mean-square charge radii for gallium [24] and copper [25] isotopes are in progress. This requires extensive multi-configurational Dirac Fock calculations of the two atomic factors needed to extract the mean-square charge radii from the measured isotope shifts. The collaboration also intends to perform laser spectroscopy of the intermediate chain of zinc ($Z = 30$). Several isotopes of zinc are stable, unlike in copper and gallium, permitting radii measurements using non-optical techniques. These will provide a useful and reliable calibration of the atomic factors.

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