Addendum to INTC-P-224 / IS457

Laser spectroscopy of gallium isotopes using the ISCOOL RFQ cooler.

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At the February 2007 meeting of the INTC, the above proposal was submitted to perform laser spectroscopy of both neutron-rich and neutron-deficient isotopes of gallium using the newly installed ISCOOL. The INTC awarded 15 shifts for the study of the neutron-rich isotopes and requested that a status report then be submitted—discussing the measurements, performance of ISCOOL and beam purity—before proceeding to the neutron-deficient cases. The report is given here, with a request for 9 shifts to continue the study to the neutron-deficient isotopes.

1. Radioactive measurements performed in 2008 and 2009

High resolution optical spectroscopy of gallium atoms was performed at ISOLDE using cooled and bunched beams from ISCOOL. A uranium carbide target produced measurable yields of isotopes $^{67-82}$Ga. Beam time was taken in two separate campaigns: in 2008 and in 2009.

The first suffered from reduced efficiency, principally due to a faulty frequency doubling crystal, which was replaced soon after. This resulted in the photon-ion detection under performing by around a factor of 30. Nevertheless, spectra were taken on the 417 nm line, providing nuclear data for $^{67-79}$Ga, and many being additionally measured on an alternative, 403 nm line (from the ground state) for comparison. The experiment was invaluable in benchmarking ISCOOL and the ability to produce bunched beams. A gate was applied to the photon signal to accept only those photons in coincidence with the arrival of an atom bunch in the detection region. This suppresses the background
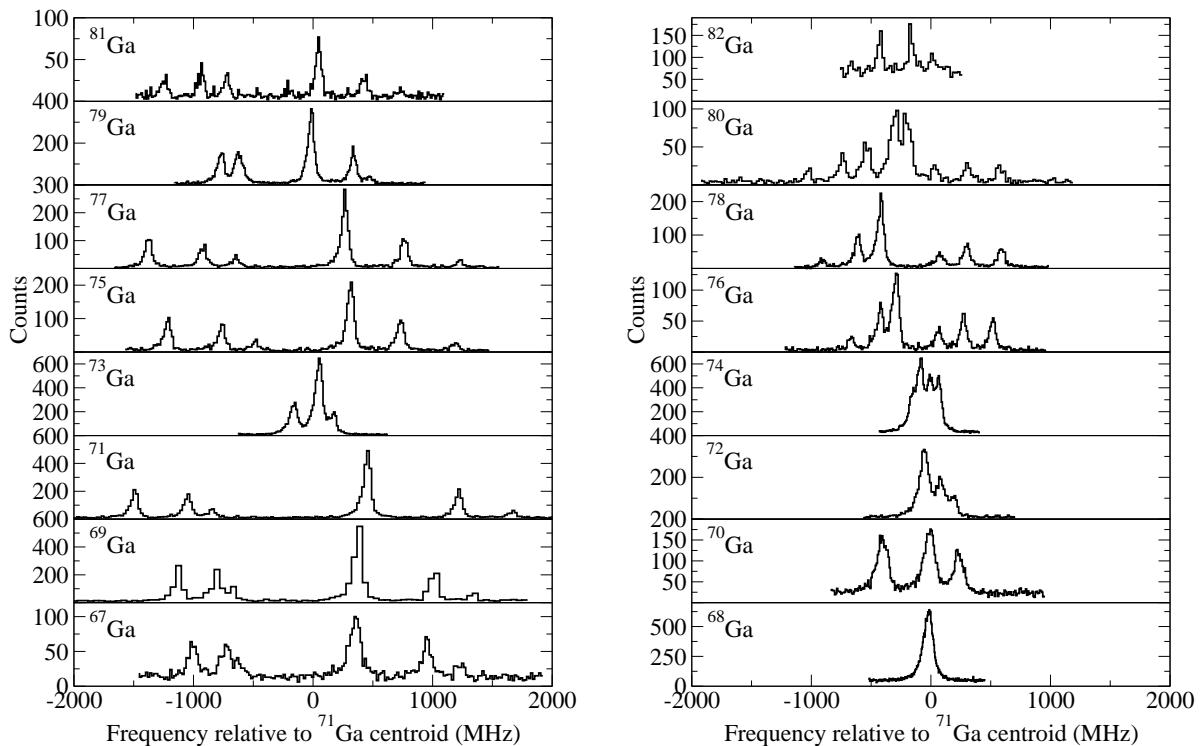
Figure 1: Optical spectra measured on the 417 nm $J = 3/2 \rightarrow J = 1/2$ transition.

(dominated by the continuous scattering of laser light) by around four orders of magnitude [1]. For consistency in resonant peak positions it was found necessary to ensure the ion bunch was kept below $\sim 10^7$ ions—beyond which the trapping region of the cooler (and potentially the optical detection) could become saturated. Higher masses suffered from very large fluxes of neutron-deficient rubidium, which limited bunch accumulation times to below 50 ms, preventing optimal operation of the cooler and highlighted the need to use a proton-neutron converter in the subsequent 2009 experimental run.

In 2009, with a new crystal in place, and the converter in use, the previous measurements from stability to ^{79}Ga were repeated in quick succession. In addition, these were extended to ^{80,81,82}Ga (figure 1). Despite the order of magnitude decrease in yield due to the use of the converter (and PSB problems) all isotopes were remeasured multiple times to ensure reproducibility of all observables.

Figure 2(a) shows the raw photon signal compared in fig 2(b) with a bunched beam where a gate was applied to the photon signal defining the atom-laser interaction time. All spectra (including calibration scans) were taken using a bunched beam, and a 6 μs gate was found to be optimal and applied in all cases. The ion TOF (measured using the resonant photon signal, and shown in figure 2(c)) was monitored to ensure that the gate covered the ion bunch profile, which has a weak mass dependence.

2. Analysis of the neutron-rich gallium isotopes

Nuclear spins, magnetic and quadrupole moments and isotope shift measurements were extracted from these measurements (see table 1) and were largely unknown prior to this work. The primary physics motivation in this region was to investigate the phenomenon of
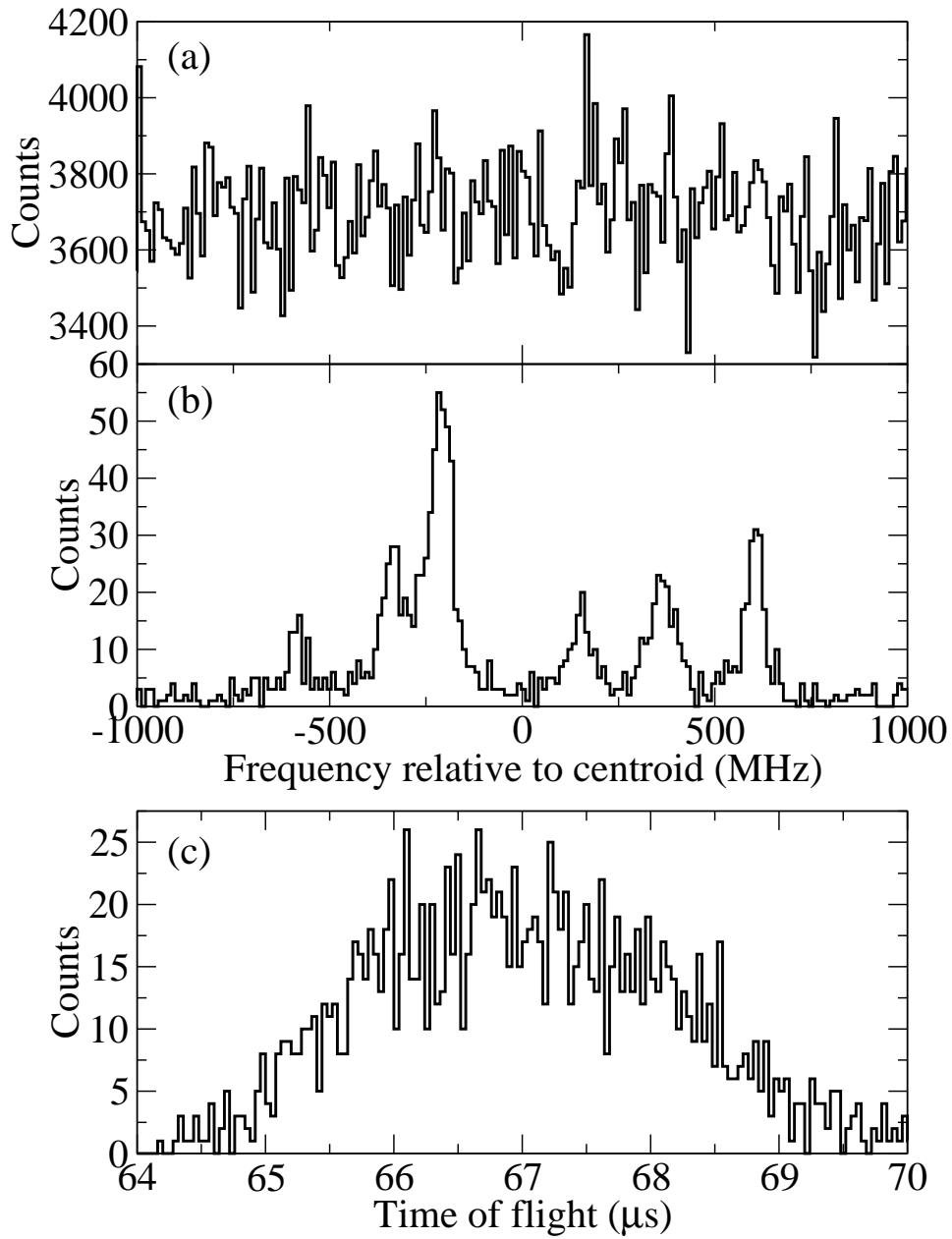
Figure 2: Optical spectra for a continuous beam (a), and with a 6 μs gate applied to the photon signal (b), corresponding to the ion/atom bunch TOF (c).

monopole migration [2]—in this case the reduction of the $f_{5/2}$ proton level as the neutron $g_{9/2}$ level is filled between $N = 40$ (^{71}Ga) and $N = 50$ (^{81}Ga). Shell model calculations of the energy levels, magnetic and quadrupole moments were produced independently using both the JUN45 (M. Honma [3]) and jj44b (B.A. Brown, private communication) interactions. An inversion of the ground state spin was predicted in each case but with disagreement regarding the neutron number. Analysis of the data produced nuclear spin measurements concluding that the inversion takes place between ^{79}Ga ($I = 3/2$, $N = 48$) and ^{81}Ga ($I = 5/2$, $N = 50$). A similar inversion was also observed in the copper isotopes (IS439) between $N = 44$ and $N = 46$ (published recently in PRL [4]).

Table 1: Nuclear spins, magnetic dipole moments, μ, and electric quadrupole moments, Q_{s} determined in this work. Also shown are the isotope shift measurements. Calculation of the atomic field shift and mass shift factors is underway to enable the extraction of the nuclear mean-square charge radius. These are preliminary results, with the full analysis of ^{80,80m,82}Ga in progress. The known moments shown for ^{71}Ga (indicated by an asterisk) were used as a calibration.

A	I	μ (μ_{N})	$Q_{\mathrm{s,expt}}$ (b)	$\nu^A - \nu^{71}$ (MHz)
67	3/2	+1.848(5)	+0.198(16)	...
69	3/2	+2.018(4)	+0.171(11)	+40(4)
71	3/2	+2.56227(2)*	+0.106(3)*	0
72	3	−0.134(4)	+0.53(3)	+23(3)
73	1/2	+0.209(2)	...	+15.5(15)
74	(3)	−0.075(4)	+0.53(3)	−64(2)
75	3/2	+1.836(4)	−0.285(17)	−45.3(16)
76	2	−0.946(4)	+0.326(21)	−86(2)
77	3/2	+2.020(3)	−0.208(13)	−109.4(15)
78	2	−1.215(5)	+0.324(19)	−160(2)
79	3/2	+1.047(3)	+0.158(10)	−186.2(19)
81	5/2	+1.747(5)	−0.048(8)	−271.8(15)

Despite the assignment of $I = 3/2$ to the ground state of ^{79}Ga in this work, the measured g-factor is very similar to the g-factor of ^{81}Ga, and different to the other $I = 3/2$ cases. This suggests a more collective $(5/2^- \otimes 2^+)3/2^-$ configuration dominated by an $f_{5/2}$ proton configuration, thus suggesting that in the gallium chain the transition from a $p_{3/2}$ to an $f_{5/2}$ dominated ground state structure appears between $N = 46$ and $N = 48$. The experimental moments correspond much better to the theoretical predictions for the state with this configuration, but the calculations had placed this state much higher (400 keV) than the $I = 3/2$ level calculated to be the ground state (which provided a poor match to the experimental moments). These are shown in figure 3.

Agreement was reached with all previously published nuclear data where available, with the exception of the ground state spin of ^{73}Ga. This was established unambiguously in this work to be $I = 1/2$, despite a previous "definite" assignment of $I = 3/2$—consistent with the other odd-A isotopes. Neither set of shell model calculations have reproduced this anomaly though both interactions do predict a steep lowering of the $1/2^-$ level in ^{73}Ga.
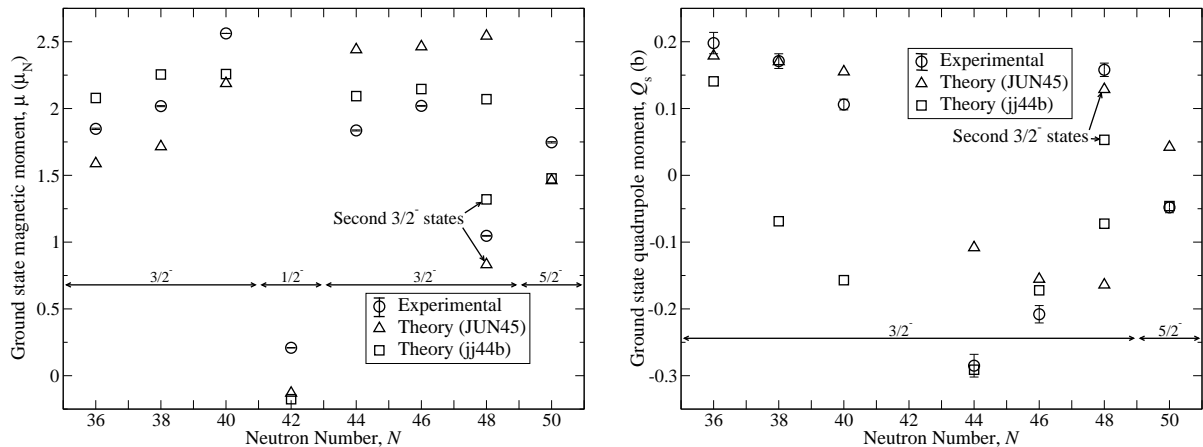
Figure 3: Nuclear moments for the odd-A Ga isotopes with theoretical calculations for the levels corresponding to the measured ground state spin. Nuclear spins and moments were also obtained for the odd-odd cases, which are to be the subject of further theoretical analysis and interpretation.

The publication of the neutron-rich data is now in progress, with continuing support from theoreticians [5]. This includes the discovery of a previously unknown isomeric state found in ^{80}Ga during the second experiment.

3. Physics case for the neutron-deficient isotopes

As stated in the original proposal, the primary motivation for extending the study towards ^{62}Ga follows the anomalous behaviour of the Ga, Ge, As, Se and Br matter radii, measured by Lépine-Szily *et al.* at GANIL [6]. Particularly for the Ga isotopes, a monotonic increase in the rms. matter radius was seen with decreasing neutron number from $N = 36$ down to $N = 32$. They argue that this cannot be associated with any substantial change in deformation and is therefore evidence for the development of a proton skin. Only small deformations were inferred from the first excited state with $J = J_{gs} + 2$, which is above 1 MeV for all even-N Ga isotopes between $N = 34 - 40$. More extensive and reliable data on the 2_1^+ excitation energies are available for the neighbouring Zn and Ge isotopes chains (figure 4). These show a clear effect of the $N = 50$ shell and a smaller effect of the $N = 38$ subshell closure. Below this there is little change in the 2_1^+ energy and no evidence for increasing deformation. Laser spectroscopy of this region will be able to determine the deformation. If a proton skin is formed, the effect on the mean-square charge radius will be dramatic. The transition used in this work is of an $s - p$ character and displays optimum sensitivity to such changes.

Magnetic dipole moments will be extracted for all neutron-deficient isotopes, and the spin value of the ^{63}Ga ground state will be measured. Shell model calculations conducted as part of this work disagree as to whether the $I = 1/2$ level becomes the ground state in this nucleus. Like the neutron-rich cases, these measurements will provide a strong probe for the evolution of the effective single particle energies.
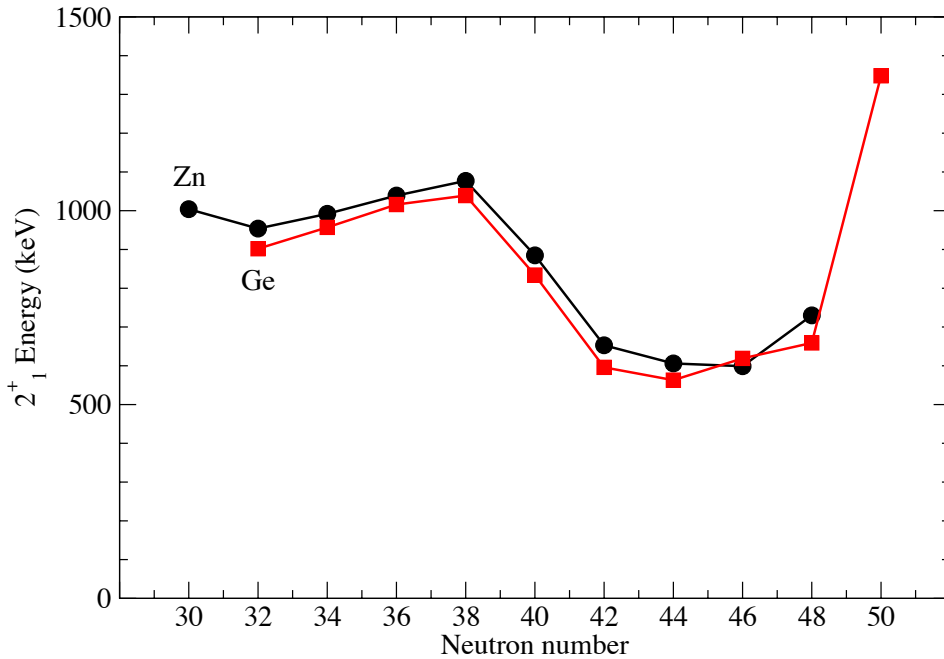
Figure 4: Energy of the 2^+_1 level in Zn and Ge isotopes.

4. Beam time request

We require the use of HRS, RILIS and ISCOOL for 9 shifts to study $^{62-68}$Ga, using a zirconium carbide target to eliminate titanium oxide contamination [7]. A minimum yield of 1000 ions/s (for ^{62}Ga) should ensure measurement within a reasonable time frame. A single shift of access to stable beam will also be required prior to the period of running in order to tune the beam line and optimise the detection. An improved RILIS scheme was developed for the 2009 experiment which excites both the ground state and the thermally populated (50%) 826.240 cm^{-1} metastable level, and then from the 34781.67 cm^{-1} level to ionisation with 532 nm YAG light. An enhancement factor of 100 (lasers on:lasers off) was observed.

References

[1] E. Mané *et al.*, *Eur. Phys. J.* A **42** (2009) 503.
[2] T. Otsuka *et al.*, *Phys. Rev. Lett.* **95** (2005) 232502.
[3] M. Honma *et al.*, *Phys. Rev.* C **80** (2009) 064323.
[4] K.T. Flanagan *et al.*, *Phys. Rev. Lett.* **103** (2009) 142501.
[5] B. Cheal *et al.*, *in preparation*
[6] A. Lépine-Szily *et al.*, *Eur. Phys.* A **25** (2007) 227.
[7] E.J. Prime *et al.*, *Hyperfine Interact.* **171** (2006) 127.