EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Shell structure and level migrations in zinc studied using collinear laser spectroscopy

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Abstract: We propose to perform collinear laser spectroscopy of zinc isotopes to measure the nuclear spin, magnetic dipole moment, electric quadrupole moment and mean–square charge radius. The yield database indicates that measurements of the isotopes $^{60-81}$Zn will be feasible. These measurements will cross the $N = 50$ shell closure and provide nuclear moments in a region where an inversion of ground–state spin has been identified in neighbouring chains.

Requested shifts: 21 shifts (split into 2 runs over 2 years)
1 Physics motivation

Recent laser spectroscopic measurements on copper (IS439) and gallium (IS457) isotopes have been performed to investigate level migrations around the \( Z = 28, N = 40 \) (sub) and \( N = 50 \) shell closures. These results have since been published as two articles in Physical Review Letters [1, 2], three further articles [3, 4, 5] and additional papers are in preparation. Tensor effects are predicted to cause the lowering in energy of the \( \pi f_{5/2} \) \((l - 1/2)\) orbital relative to the \( \pi p_{3/2} \) \((l + 1/2)\) orbital. Laser spectroscopy provides measurements of the ground–state spin. In both cases, an inversion of the proton levels (and change in ground–state spin from \( I = 3/2 \) to \( I = 5/2 \)) was found to occur: between \( ^{75}\text{Cu}_{44} \) and \( ^{75}\text{Cu}_{46} \) in copper (\( Z = 29 \)), but at higher neutron number, between \( ^{79}\text{Ga}_{48} \) and \( ^{81}\text{Ga}_{50} \) in gallium (\( Z = 31 \)). This study of the intermediate chain of zinc (\( Z = 30 \)) will allow the \( Z \)-dependence of the point of inversion to be studied.

Much experimental effort has been devoted to the evolution of shell structure and the disappearance and replacement of magic numbers. The tensor force is predicted to cause a weakening of the \( N = 50 \) and \( Z = 28 \) shell gaps towards \( ^{78}\text{Ni} \) due to the interaction of the \( \pi f_{5/2} \) level with the \( \nu g_{9/2} \) and \( \nu d_{5/2} \) levels [6]. However, Penning trap mass measurements indicated that the size of the gap in \( ^{79}\text{Zn} \) (also the subject of IS491) increases relative to \( ^{81}\text{Ge} \) [7, 8]. Previous experiments at ISOLDE have used Coulomb excitation to study zinc [9, 10]. From the \( B(E2) \) values (figure 1) no breaking of the \( N = 50 \) shell gap is evident, although a large proton effective charge was required to reproduce the values using the shell model, implying some degree of core polarisation.

As pointed out in reference [11] (\( \beta \)-decay studies of \( ^{77}\text{Zn} \) performed at ISOLDE, see also reference [12]) the study of the region around \( ^{78}\text{Ni} \) is of paramount importance to \( r \)-process calculations (see also reference [13]). The authors also invite the investigation of these nuclei using laser spectroscopy. Nuclear spins are only tentatively assigned (or wholly unassigned) for the odd–mass neutron rich isotopes (and isomers) from \( ^{73}\text{Zn} \) onwards (see table 1). Laser spectroscopy will allow unambiguous assignments to be made for the ground and isomeric states which, when combined with the nuclear decay data, will permit definite assignments to be made for excited levels. Recent nuclear decay work at ISOLDE [14] has also indicated the need to identify long–lived isomeric states in \( ^{79}\text{Zn} \) [15]. Laser spectroscopy is placed not only to establish the existence of such states [4] but to measure their spins, moments and radii.

Isotopes of zinc, unlike those of (odd–\( Z \)) copper and gallium, have ground–state spins which are either \( I = 0 \) (even–\( N \)) or arise from the coupling of an odd number of neutrons. However, a sensitive probe of the nuclear wave function is provided by the nuclear moments—also measured using laser spectroscopy. In a comparison between theory and experiment for \( ^{79}\text{Ga} \), the nuclear moments were essential in matching the correct \( I = 3/2 \) state to the measured \( I = 3/2 \) ground state [2]. Although shell model calculations using the jj44b interaction appeared to correctly predict a ground–state spin of \( I = 3/2 \), analysis of the nuclear moments revealed that it was the calculated moments for the first excited \( I = 3/2 \) state which matched those measured for the ground state. This was also true for shell model calculations using the JUN45 [21] interaction. With the exception of \( ^{63,65,67}\text{Zn} \), neither of the nuclear moments have been measured for any of the nuclear
neutron number

B(E2) (e$^2$ fm$^4$)

Figure 1: $B(E2)$ measurements for zinc [10].

ground states (see table 1). These will be measured in this work, along with the nuclear moments for the isomeric states in $^{71,73,75,77}$Zn.

No mean–square charge radii have been published in this region of the nuclear chart (near $^{78}$Ni). Although isotope shift measurements have been made for both copper and gallium, it is essential to calibrate two atomic factors which relate the isotope shift to changes in mean–square charge radius in order to extract the latter. Non–optical mean–square charge radii data can be used where three or more stable isotopes exist to have permitted such measurements. Copper and gallium each have only two stable isotopes, meaning that the evaluation of the factors can only be done using multi–configurational Dirac–Fock (MCDF) calculations alone, with no independent verification. Zinc has four stable isotopes, allowing a more reliable extraction of mean–square charge radii to be made [17]. MCDF calculations performed for the gallium and copper isotope shift measurements predict rather different charge radii behaviour. Moreover, differences in the detailed structure are apparent irrespective of the calibration. The calibration is particularly important in the case of gallium (IS457) where the suggested formation of a proton skin [22] will reveal itself in the extracted charge radii. If present, this may also be observed in the zinc isotopes. Theoretical analysis aimed at understanding mean–square charge radii appear more common for studies of even–Z elements (e.g. the relativistic mean field model [23]) or preceded by such studies (e.g. density functional theory [24]).
Table 1: Nuclear spins and moments presently known for zinc isotopes. Unconfirmed spins are in parentheses. Nuclear moments are taken from reference [16]. Charge radii measurements have only been made for the stable zinc isotopes ($^{64,66,67,68}$Zn) [17].

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$I$</th>
<th>$\mu$ ($\mu_N$)</th>
<th>$Q_{s,\text{expt}}$ (b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>61</td>
<td>3/2</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>63</td>
<td>3/2</td>
<td>$-0.28164(5)$</td>
<td>$+0.29(3)$</td>
</tr>
<tr>
<td>65</td>
<td>5/2</td>
<td>$+0.7690(2)$</td>
<td>$-0.023(2)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$-0.3(2)$</td>
</tr>
<tr>
<td>67</td>
<td>5/2</td>
<td>$+0.875479(9)$</td>
<td>$+0.150(15)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$+0.8752049(11)$</td>
</tr>
<tr>
<td>67m</td>
<td>1/2</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>69</td>
<td>1/2</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>69m</td>
<td>9/2</td>
<td>$1.157(2)$</td>
<td>$-0.51(5)$</td>
</tr>
<tr>
<td>71</td>
<td>1/2</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>71m</td>
<td>9/2</td>
<td>$1.052(6)$</td>
<td>—</td>
</tr>
<tr>
<td>73</td>
<td>(1/2) [18]</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>73m</td>
<td>(5/2) [18]</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>75</td>
<td>(1/2) [14]</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>75m</td>
<td>(7/2) [14]</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>77</td>
<td>(7/2) [11, 12]</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>77m</td>
<td>(1/2) [11, 12]</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>79</td>
<td>(9/2) [19]</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>81</td>
<td>(5/2) [20]</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

2 Spectroscopic method

Hyperfine structure measurements will be made using collinear laser fluorescence spectroscopy [25]. Fast–ion beams such as those at ISOLDE enhance the spectral resolution and a Doppler tuning voltage provides a reliable means of tuning the effective laser frequency. Resonant photons are detected using a photomultiplier tube, while non-resonant photons originating from a continuous scattering of laser light are suppressed by using a bunched release of ions from ISCOOL [1, 2] and applying a gate to the photomultiplier counts. Laser spectroscopy of zinc was included in the list of priority cases in the Letter of Intent for the development of ISCOOL (INTC–I-048).

Optical transitions from the ground state of the zinc ion are of a wavelength too short to be efficiently produced. Therefore, the spectroscopy must be performed on the atomic state, with neutralisation achieved in–flight via passage through alkali vapour. The ground–state transition in neutral Zn (at 307.6 nm to the $^3P_1$ level at 32501 cm$^{-1}$) is far too weak for efficient spectroscopy. However, the charge exchange process from the ionic to atomic state, if using lithium (or sodium) vapour, quasi–resonantly populates the $4s4p ~^3P_J$ triplet of states. For $J = 0$ and $J = 2$, the transition to the ground–state is spin forbidden, and the $J = 1$ state (which decays only via the 307.6 nm transition)
has a 20 $\mu$s lifetime [17]. This triplet will therefore remain well populated and numerous strong transitions to the $4s6s^3S_1$ and $4s4d^3D_J$ levels are available in the range 300 nm to 335 nm (all accessible with a frequency–doubled dye laser). Stable beam tests will quickly establish which of these offer the optimum compromise between spectroscopic efficiency and sensitivity to changes in mean–square charge radii.

3 Isotope production and yields

Isotopes of zinc across the intended range for study are produced from a uranium carbide target. A proton–neutron converter will be used to suppress the contamination from neutron–deficient rubidium isobars. This was used with great success during the laser spectroscopic study of neutron–rich gallium isotopes [2] (and for Coulomb excitation of zinc [9]). A quartz transfer line would further suppress the surface–ionised production of gallium [26], while the zinc will be selectively enhanced using RILIS.

Figure 2 shows the release of zinc and gallium from the target [27]. Zinc isotopes show a fast release, whereas the release of gallium is quasi–continuous. This provides an opportunity to further suppress the photon background, both from the laser scatter and non-resonant production from contaminant elements in the beam. By only counting photons for ion bunches released from the cooler within $\sim 600$ ms after the proton pulse, the (predominantly non-resonant) photon counts for the few seconds duration before the next proton pulse can be vetoed with negligible loss of signal.

![Figure 2: Release curves from the ISOLDE target [27].](image)

Figure 3 shows the yields for zinc [27]. Assuming 1.5 $\mu$A of protons (the minimum
guaranteed for 2011), a yield of 45,000 ions/s is expected for $^{80}$Zn ($N = 50$) and over 1000 ions/s for $^{81}$Zn ($N = 51$). Optical measurements up to and including $^{81}$Zn should therefore be feasible. On the neutron–deficient side, a yield of 50,000 ions/s is expected for $^{61}$Zn$_{31}$ (protons directly on target) and measurements beyond this isotope should therefore be feasible.

![Graph](image)

Figure 3: Production yields for zinc at ISOLDE [27].

**Summary of requested shifts:** 21 shifts are requested for the study of $^{60−81}$Zn which will be split into two runs (of 9 shifts and 12 shifts, respectively). Stable beam time prior to the first run (3 shifts) will allow alternative transitions to be explored for optimum efficiency and sensitivity. All radioactive beam time will use RILIS and a uranium carbide target. The neutron converter will be used for neutron rich isotopes.

**References**


[16] Stone N 2005 *At. Data Nucl. Data Tables* 90 75
[19] Singh B 2002 *Nuclear Data Sheets* 96 1
[23] Lalazissis G A, Raman S and Ring P 1999 *At. Data Nucl. Data Tables* 71 1
Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises:

<table>
<thead>
<tr>
<th>Part of the COLLAPS installation</th>
<th>Availability</th>
<th>Design and manufacturing</th>
</tr>
</thead>
<tbody>
<tr>
<td>☑ Existing</td>
<td>☑ To be used without any modification</td>
<td></td>
</tr>
</tbody>
</table>

All hazards are named in the document relevant for the COLLAPS installation.