

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

High-resolution laser spectroscopy of nickel isotopes

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Abstract: This proposal aims to measure the nuclear ground-state spins, moments and mean-square charge radii of $^{56-71}\text{Ni}$ using collinear laser spectroscopy. This will enable direct measurements of isotopes in the region of shell closure (^{56}Ni), structural change (^{68}Ni) and monopole migration (beyond $N = 40$). Optical spectroscopy serves as a detailed probe not only of the changing single-particle behaviour, but also for the study of collective properties such as size and shape. Measurements of the most neutron-rich isotopes available at ISOLDE will critically test models which seek to extrapolate the data to the doubly magic region of ^{78}Ni .

Requested shifts: 18 shifts (split into two runs)

1 Physics motivation

Current efforts to develop the nuclear shell model centre around the migration of single-particle levels. Furthermore, as the proton number, or as the neutron number is varied, the magic numbers in terms of the other particle number are observed to vary. The $Z = 28$ region is experimentally challenging, but one rich in such structural changes. Recent experimental campaigns (including laser spectroscopy) have been dedicated to studying the effects of the proton-neutron interaction, which lowers the $\pi f_{5/2}$ level as the $\nu g_{9/2}$ level is filled, and causes an inversion of ground state spin in the copper and gallium chains [1, 2]. Meanwhile, shell or sub-shell closure candidates are suspected at $N = 28, 40$ and 50 . The ability of the shell model to predict the evolution of these is of great importance, as is the need to find reliable cores for calculations to be performed for other regions of the nuclear chart.

In the laser spectroscopic measurements of copper and gallium at ISOLDE, an inversion of the ground state spin, from $I = 3/2$ to $I = 5/2$ was seen with increasing neutron number [1, 2]. This is attributed to the monopole component of the tensor interaction [3, 4], and was observed to occur between $^{73}\text{Cu}_{44}$ and $^{75}\text{Cu}_{46}$ at $Z = 29$, and later, between $^{79}\text{Ga}_{48}$ and $^{81}\text{Ga}_{50}$ for $Z = 31$ (although the ordering of the leading configurations changes prior to this [5]). Studies of zinc (IS519) and nickel, will allow the Z -dependence of this transition to be studied. In the latter case, enhanced core polarisation in ^{70}Ni has been attributed to the monopole interaction [6].

High resolution laser spectroscopy is rather unique in being able to *measure* the spin of a nuclear ground state. Not only will this allow unambiguous assignments to be made here beyond $A = 67$ (the current limit of knowledge), but also allow confirmation of previous “firm” assignments, which have sometimes been shown by laser spectroscopy to be false. Most recently at ISOLDE, this has included the ground state spin of ^{73}Ga [2] and new spin assignments were measured for $^{60\text{g,m}}\text{Mn}$ [7], which contradicted earlier values. This often leads not only to a re-evaluation of the level scheme in these isotopes, but also in other nuclides which are connected via β -decay feeding. For example, ascertaining the nuclear spin (and other properties) of ^{71}Ni , will help underpin the assignments to the excited levels which will be investigated at MINIBALL [8].

Nuclear moments are invaluable in assessing the success of shell model calculations which would then be extrapolated to the ^{78}Ni region [9]. Although magnetic moments have been measured for many nickel isotopes ($A \leq 67$) the ground state quadrupole moment is only known for the odd- A stable isotope, ^{61}Ni . In the study of gallium isotopes [2], the quadrupole moments were essential in determining the shell model configurations needed to explain the structural changes along the chain. For example, while $^{67,69,71}\text{Ga}$ and $^{75,77}\text{Ga}$ had identical magnetic moments, it was the change in sign of the quadrupole moment (from prolate to oblate) that revealed the change in configuration from $\pi p_{3/2}^3$ to $\pi p_{3/2} f_{5/2}^2$, brought about by the p-n interaction between the $\nu g_{9/2}$ and $\pi f_{5/2}$ orbitals.

Figure 1 shows the changes in mean-square charge radii arising from the measurements of IS457 [10] (the analysis of those from IS439 is in progress). In the case of gallium, the measurements could be extended as far as ^{82}Ga [11], revealing a prominent ‘kink’, indicative of a shell closure effect at $N = 50$ (directly above ^{78}Ni). The tensor force is predicted to cause a weakening of the $N = 50$ and $Z = 28$ shell gaps towards ^{78}Ni due to

the interaction of the $\pi f_{5/2}$ level with the $\nu g_{9/2}$ and $\nu d_{5/2}$ levels [12]. However, Penning trap mass measurements (including IS491) point to the shell gap *increasing* as the proton number is decreased towards nickel [13, 14]. Of all proposed doubly-magic nuclei, ^{78}Ni is the most exotic (in terms of N/Z) and indeed the nuclide itself is still experimentally inaccessible. Nevertheless, measurements of mean-square charge radii, for isotopes as neutron-rich as possible, will give an indication of the emerging course of the radii, and serve as a test for the latest models (eg. [15]).

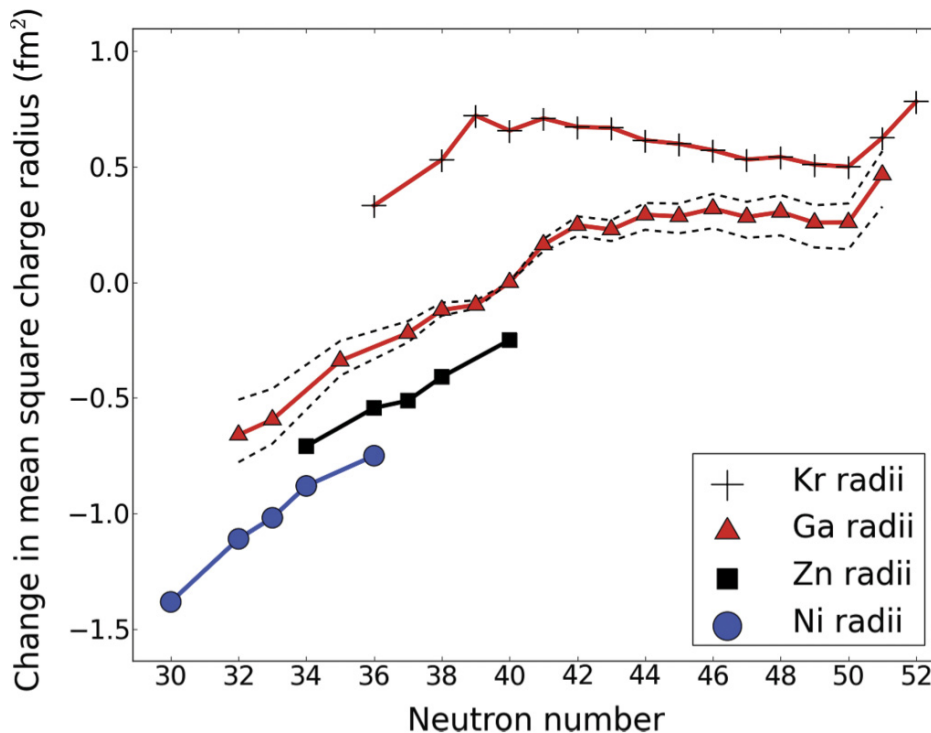


Figure 1: Mean-square charge radii measurements in the $Z = 28$ region [10].

More subtle, is a minimum in the mean-square charge radius for gallium (and copper) at $N = 40$, which is barely perceptible from figure 1. Nevertheless, in both cases, the effect is large enough to invert the normal odd- N /even- N staggering of the radii with neutron number. Moreover, it is in nickel that the appearance of this apparent subshell closure will be most pronounced, as evidenced by the high energy of the first excited 2^+ state in ^{68}Ni . The precise reason for this effect has however been debated [16, 17] with contrary evidence from mass measurements which do not reveal a clear neutron-shell gap [18, 19] and the consequences of the parity change from the pf shell and $g_{9/2}$ orbital being highlighted instead. We propose to now track this behaviour, revealed in the charge radii, along this *isotonic* sequence.

Although isotope shift measurements have been performed in the region for copper and gallium (only), the process of reliably extracting the mean-square charge radii has been complicated by the need to calibrate the atomic factors which relate these two quantities [10, 20]. No mean-square charge radii measurements have been made for any radioactive isotopes of nickel, but the stable isotopes have been comprehensively studied

using non-optical techniques such as muonic atom spectroscopy and electron scattering experiments. This therefore allows, in the case of nickel, the atomic factors to be reliably calibrated for the whole chain. In the copper and gallium chains, only two stable isotopes are present in each case (insufficient for an independent calibration from non-optical data) and MCDF calculations need to be relied upon. Mean-square charge radii values will therefore be extracted for radioactive nickel isotopes with systematic uncertainties very much reduced.

Measurements up to ^{71}Ni will reveal the trend of the changing nuclear structure as the $\nu g_{9/2}$ orbital is filled and ^{78}Ni is approached. The $1/2^-$ isomer in ^{69}Ni , and proposed ($1/2^-$) isomer ^{71}Ni [9, 21] which will also contain valuable nuclear structural information, will also be studied.

2 Experimental method

Nuclear moments (μ, Q_s), spins and $\delta\langle r^2 \rangle$ are all obtainable from high-resolution optical spectra [22]. These will be measured using collinear laser fluorescence spectroscopy. Optimal beams of nickel are produced from a uranium carbide target, fitted with a graphite lining and a neutron converter. Further selective enhancement of nickel is then provided by RILIS, before mass selection using the HRS and delivery via ISCOOL to the COL-LAPS beam line [23]. Here, the ion beam and laser beam are overlapped on the same axis and the velocity spread in the forward direction is reduced. Since no suitable transitions exist in the nickel ion, charge exchange to the neutral atomic state is achieved via passage through an alkali vapour cell. The remaining atomic beam is then excited by the narrow line width continuous wave laser, exciting the atomic transition. Fluorescence photons are detected using four photomultiplier tubes (PMTs), each with a large solid angle acceptance, and the count rate recorded versus the (Doppler tuned) frequency of the laser light. Using ISCOOL in a bunched mode preserves the resonant signal while suppressing by four orders-of-magnitude the dominant source of the photon background which is the continuous scattering of laser light into the PMTs [2].

3 Spectroscopy scheme

Efficient spectroscopy requires the probing transition to be excited from a well populated atomic state. In the charge exchange process to an atom with high level density, such a concentration can be achieved through choice of the alkali vapour. Neutralisation of nickel (IP: 61619 cm^{-1}) using potassium (IP: 35010 cm^{-1}), leaves an energy excess of 26609 cm^{-1} which is well matched to quasi-resonantly excite the 5D_3 atomic level at 26665.9 cm^{-1} . Despite being (the first multiplet) of opposite parity to the ground state, the transitions which link the 5D levels to the ground state and multitude of intermediate states are all very weak. Consequently, the 5D_3 level has a long lifetime of $13\ \mu\text{s}$. This is more than sufficient for the population to survive during transport to the laser-atom interaction region ($\sim 1\ \mu\text{s}$) and for the spectroscopy to be performed from this state. The $323.4069\text{ nm } 3d^8 4s 4p\ ^5D_3 \rightarrow ^5P_2$ (57586.7 cm^{-1}) transition is particularly strong, with an Einstein coefficient of $A = 1.7 \times 10^8/\text{s}$. Following excitation of this transition,

85% of decays are via the same path back to the 5D_3 atomic level at 26665.9 cm^{-1} . The advantages of this would be two-fold. Firstly, it allows a short-pass filter to be placed in front of the PMT (or lens assembly) [24]. Despite having a long lifetime, non-resonant photons will be emitted from the (very slow) decay of the 5D multiplet. A filter will allow the resonant photons emitted via the principal decay branch ($\lambda = 323\text{ nm}$) to be detected, while the “background photons” of longer wavelength ($\lambda \sim 370\text{ nm}$) are excluded. Secondly, a quasi-two level system will enable multiple interactions and therefore several resonant counts per atom may be possible, maximising the spectroscopic efficiency.

We request two shifts of stable beam time prior to the radioactive beam time. This will allow us to investigate the scheme above in addition to a variety of other options. In particular, there are several strong transitions which are accessible within a laser wavelength range of $295\text{nm}–313\text{nm}$. These transitions come from low-lying metastable states, including the lowest-lying and naturally populated 204 cm^{-1} atomic level (which is used for the first step of the RILIS scheme). The relatively short tuning range of the wavelengths will allow several candidates to be tested in a short time frame, and the optimum chosen for this study.

4 Production and yields

Yields are quoted in the online database for isotopes from ${}^{56}\text{Ni}$ ($2000/\mu\text{C}$) to ${}^{70}\text{Ni}$ ($10^4/\mu\text{C}$), produced from a uranium carbide target and using RILIS. These yields would already be sufficient to perform spectroscopy in this mass range. However, more recent yields for ${}^{70}\text{Ni}$ have been as high as $2 \times 10^5/\mu\text{C}$ [8]. An additional factor of two is expected from improvements to the RILIS scheme [25].

As expected, isobars of gallium form the dominant contaminant in beams of neutron-rich nickel [16]. Despite typical values lying in the range of $3 \times 10^6/\mu\text{C}$ for ${}^{70}\text{Ga}$, versus $1 \times 10^5/\mu\text{C}$ for ${}^{70}\text{Ni}$ (using a neutron converter and the previous RILIS scheme) laser spectroscopy would still be routine for ${}^{70}\text{Ni}$. However, improvements to the neutron converter geometry have since enabled the ${}^{70}\text{Ga}$ contaminant to be reduced to $\sim 1000/\mu\text{C}$ (and a factor of 3 – 5 reduction in zinc also) [26]. Without significant contamination (which contributes to the photon background and limits the ISCOOL accumulation time) the maximum sensitivity of the technique is realised.

Collinear laser spectroscopy is routinely performed on ion rates of ~ 1000 atoms/s and under. Yields of ${}^{70}\text{Ni}$ and ${}^{71}\text{Ni}$ are expected to be 4×10^5 ions/ μC and 2×10^4 ions/ μC , respectively [26]. A measurement of ${}^{72}\text{Ni}$ may therefore also be feasible.

5 Shift request

Two shifts of stable beam prior to the on-line time will enable the experimental apparatus to be set up and confirmation of the spectroscopy scheme to be used. During this time, measurements of the stable ${}^{58,60,61,62,64}\text{Ni}$ isotopes will be performed to provide high resolution measurements and to serve as a calibration.

From a comparison with the Mn experiment in November 2012 for IS508, the similarity of the spectroscopy scheme and neutron-rich yield distribution, we estimate a total of 18 shifts will be required. This takes account of the time required to perform two or three independent scans for each of the $^{56,57,59,63,65,66,67,68,69,70,71}\text{Ni}$ isotopes, with an HRS mass change to a stable isotope between each for calibration purposes and to reduce systematic errors.

Summary of requested shifts: 18 shifts of radioactive beam time using a UC_x target with a graphite lining and neutron converter.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: COLLAPS

Part of the	Availability	Design and manufacturing
COLLAPS	<input checked="" type="checkbox"/> Existing	<input checked="" type="checkbox"/> To be used without any modification

HAZARDS GENERATED BY THE EXPERIMENT

Hazards named in the document relevant for the fixed COLLAPS installation.

Additional hazards: None