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Proposal to the ISOLDE and N-ToF Experiments Committee

Laser spectroscopy of gallium isotopes using the ISCOOL RFQ cooler.

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Abstract

We propose to study the radioisotopes of gallium (Z=31) by collinear laser spectroscopy using the ISCOOL RFQ ion cooler. The proposed measurements on $^{62-83}$Ga will span both neutron-deficient and neutron-rich isotopes. Of key interest is the suggested development of a proton-skin in the neutron-deficient isotopes. The isotope shifts measured by laser spectroscopy will be uniquely sensitive to this feature. The measurements will also provide a wealth of new information on the gallium nuclear spins, static moments and nuclear charge radii.

1. Introduction

The analysis of optical hyperfine structures and isotope shifts of radioactive atoms, which can be measured with high precision and sensitivity with laser techniques, provides a detailed picture of the nuclear ground state. It can uniquely provide a measure of the changes in radial charge distribution between isotopes as well as basic nuclear structure information on the nuclear spins and static magnetic dipole and electric quadrupole moments [1]. The imminent installation of the ISCOOL ion cooler-buncher [2] in the ISOLDE hall will allow substantial improvements to be made in the sensitivity of the collinear-beams method of laser fluorescence spectroscopy. Releasing the ions in bunches allows suppression of the photon background by only counting photons as the ions traverse the detection region. A background suppression ratio of 10^4 permits spectroscopic measurements with a beam flux of only 10^3 ions per second. This proposal is a request for on-line time to (i) benchmark this technique with ISCOOL/COLLAPS against the IGISOL/laser facility at Jyväskylä by using yttrium beams, and (ii) use the technique for the first characterization by laser spectroscopy of the gallium chain of isotopes.

2. Physical motivation

The ground states of only three of the 23 known radioisotopes of gallium (Z=31) have had their ground state static moments measured. These radioisotopes lie in the region between the N=28 shell and extend just beyond the N=50 shell. Figure 1 (taken from ref. [3]) shows that, with the exception of the recent measurements of Cu isotopes at ISOLDE [4], there has been no high-resolution laser spectroscopic measurement of radioisotopes in the vicinity of the Z=28 shell.

The primary interest in the gallium isotopes arises from the work of Lépine-Szily and co-workers [5] on the anomalous behaviour of the matter radii of neutron-deficient isotopes of Ga, Ge, As, Se and Br nuclei. Particularly for the Ga isotopes, a monotonic *increase* in the r.m.s. matter radius was seen with *decreasing* neutron number from N=36 down to N=32. They argue that this can not be associated with any substantial change in deformation and is therefore evidence for the development of a proton skin. They inferred only small gallium deformations from the energy of the first excited state with $J = J_{\rm gs} + 2$, which is above 1 MeV for all odd-even isotopes between N=34–40. More extensive and reliable data on the 2_1^+ excitation energies are available for the neighbouring Zn and Ge isotope chains (figure 2). 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. This experimental observation is contrary to the β_2 predictions of Möller *et al* [6] which show a quite complex behaviour but β_2 values are above +0.2 between N=30–34 with prolate/oblate shape changes up to N=40. The actual deformations will be directly measured in this proposal via the quadrupole moments of the even-N isotopes which are all believed to have a spin of $3/2^-$ ($\pi p_{3/2}$) except for the neutron-rich ^{81,83}Ga isotopes. These measurements will also be able to confirm the tentative spin assignments for ^{63}Ga and all isotopes above A=74.

Evidence for a proton skin in the light argon isotopes has been discussed by Ozawa *et al.* [7]. In this case both the r.m.s. matter radius and charge radius decrease with decreasing mass down to A=33, but the matter radii reduce at a faster rate, indicating a proton-rich nuclear surface. In the case of gallium, if the increasing matter radius is due to a proton-rich surface then the effect on the charge radii will be dramatic.

The key feature of interest on the neutron-rich side of stability is the possible inversion of ground state spin due to the monopole migration of the $\pi f_{5/2}$ level. Without definite spin

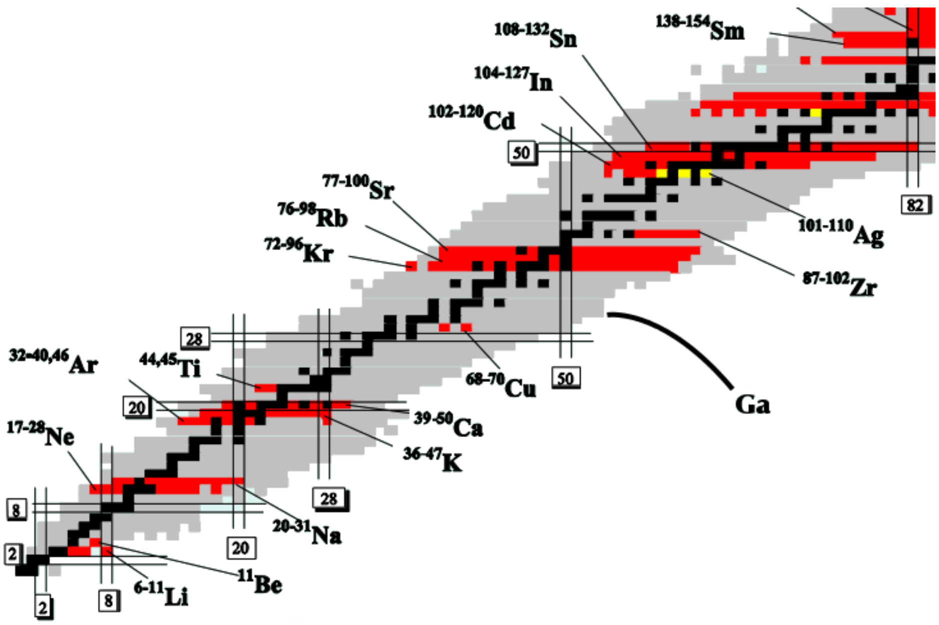

Figure 1: Present status of optical measurements (black – stable; red – measured)

assignments for the ground states (let alone the identification of the $\pi f_{5/2}$ state amongst the low-lying excited states) it is difficult to say much about the current structure, but a β-decay of ^{81}Ga to the ^{81}Ge ($9/2^+$) state with a log ft value of 5.2 appears to rule out the $3/2^-$ assignment. This nuclide is at the N=50 neutron shell closure. Based on the ISOLDE yields, it should be possible to make laser measurements out to N=52 (^{83}Ga) and hence characterize the r.m.s. charge radii trends across the major shell as well as investigate the behaviour around the N=38 subshell closure whose effect is apparent in the 2_1^+ excitation energies shown in figure 2.

The laser measurements will simultaneously provide the basic nuclear data of magnetic moments, spins and quadrupole shapes that are so valuable in guiding the development of shell model interactions in this region. Quite apart from the prediction of the ground state spin, the shell model calculations of the $\pi p_{3/2}$ magnetic moments depend sensitively on the interactions and effective g-factors used.

3. The proposed experiment

Critical to the success of collinear laser fluorescence spectroscopy is the reduction of photon background which is dominated by the continuous scatter of laser light. Releasing the ions in bunches allows suppression of this contribution by the ratio of the ion accumulation time to the temporal length of the ion bunch. The bunch width of ISCOOL is expected to be an order of magnitude shorter than for the Jyväskylä cooler (20–30 μs) and a larger suppression ratio is possible (unless the accumulation time is chosen to be shorter to reduce possible space charge problems).

ISCOOL will also provide a reduced emittance and energy spread of the ion beam. Typical values for the longitudinal energy spread and transverse emittance of ISOLDE beams have been given as 5 eV [8] and 25 π mm.mrad [9], respectively, at 60 kV. Cooling of the ions reduces the longitudinal energy spread to about 1 eV and therefore reduces the residual Doppler broadening of the spectral peaks. The measured ISCOOL transverse emittance is 2–4 π mm.mrad at 30 kV [10]. This will allow better focusing of the ion beam to a narrower waist at the region of

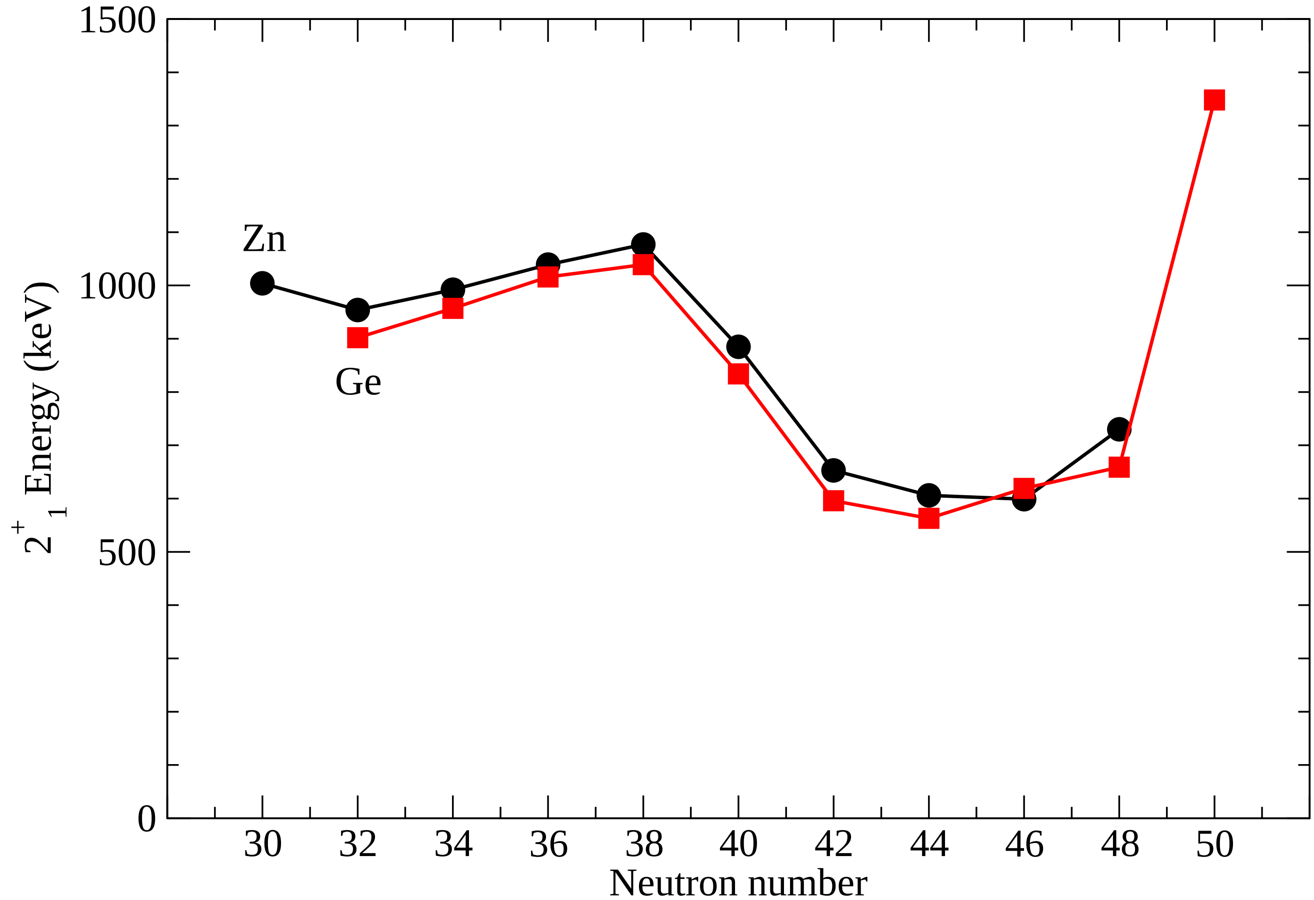

Figure 2: Energy of 2_1^+ level in Zn and Ge isotopes

overlap with the collinear laser beam. The spectroscopy with a narrower laser beam will require less laser power, reducing the amount of scattered laser light still further. In comparison, tests have shown beams delivered by the Jyväskylä cooler to have an energy spread of less than 0.6 eV and an emittance of 3 π mm.mrad at 40 keV [11].

We propose to repeat measurements on some of the yttrium isotopes [12] taken using the cooler-buncher at JYFL, Jyväskylä. This will allow a direct comparison of the devices to be made and optimisation of ISCOOL. Spectroscopy of gallium isotopes will then follow.

3.1 Benchmarking with yttrium isotope beams

The system of yttrium has been previously, but not exhaustively, studied [12] at the JYFL IGISOL facility and the proposed experiment will provide both a vital benchmark for ISCOOL and afford new nuclear structural results. During the study of yttrium it will be possible to determine the efficiency of the ISCOOL facility, the atomic states populated by the laser ionization source, the survival of these states in the ISCOOL device and provide vital nuclear structural information that could not be obtained in the earlier study [12].

In isotope chains around yttrium (Z=39) the existence of a nuclear shape change at $N \approx 60$ is well established. The nature of this shape transition remains however disputed. A variety of nuclear observables in nuclei neighbouring yttrium, such as 2^+ state lifetimes and the observation of 0^+ first excited levels, suggest a sudden transition from spherical to rigidly deformed nuclear shapes. Other measurements and studies [13, 14] have however questioned the existence of strongly deformed excited states and appear to suggest that the onset of deformation is far more gradual and involves a softer transition from vibrational to rotational systems. The latter scenario may also be supported by optical measurements [11, 15, 16] in the region which do not otherwise reflect an abrupt transition from a simple spherical shape.

Information on a vital nuclear ground state parameter, the spectroscopic quadrupole moment, which should otherwise resolve the conflict described above, is unfortunately almost entirely lost as the $N = 60$ shape change is approached (all key isotopes, including the odd-Z and odd-odd systems, have ground state spins which are less than 1). A study on low-lying *isomeric* systems [12] was previously undertaken in order to access systems with $I \geq 1$ (and thus nuclear states with measurable spectroscopic quadrupole moments). Although full hyperfine structures were observed in that experiment, which will provide an excellent benchmark for ISCOOL, no nuclear spins could be independently determined and a range of isotopes and isomers were not, or could not, be measured.

We propose a direct comparison of the two facilities and optimisation of ISCOOL by repeating the previous spectroscopy for some isotopes in the neutron-rich region $^{98-102}$Y where isobaric contamination is expected to be low. Our projected efficiencies and the ISOLDE yields will enable us to greatly extend the previous work (and in particular, to locate 3 missing isomers). In addition, we can explore the populations of, and transitions from, metastable ionic states and further study the survival of these populations in the ISCOOL device. Upon location of a suitable optical transition, other than that previously studied, it will be possible to uniquely determine unknown nuclear spins in the yttrium chain and extract nuclear moment and charge radii data.

3.2 Spectroscopy of gallium isotopes

Neutron-deficient gallium yields with a ZrO_2 target will be sufficient for measurements down to ^{62}Ga (4×10^3 ions per μC). Neutron-rich yields at ^{83}Ga are similar with a UC_x target. The shortest lifetime (^{62}Ga) is 116 ms and comfortably within the range needed for the bunched-beam method. Gallium has a slow release time from the ion source [17] and will be effectively a continuous beam as far as loading the ion cooler-buncher is concerned.

Ion bunch accumulation times as short as 10-20 ms can be anticipated if space charge effects due to isobaric contamination are a problem. This is expected to become significant for A> 80 where rubidium beams become substantial. We are also aware of the problem of TiO contamination for the masses A=62–66. Some beam development may be necessary to reduce the isobaric contamination to a level where trap bunching can still be employed. There are several approaches which might control the contamination. Using the RILIS facility, with gallium production efficiencies of 21%, in combination with low work function surfaces being developed at ISOLDE is one possible approach to reduce the contamination. A suppression of the rubidium yield by more than two orders of magnitude has also been accomplished with the use of a "proton-neutron-converter" [18].

Even with the bunched-beam method it is important to minimize the photon background of scattered laser light. A new light collection region will be tested for neutral-atom spectroscopy which will image light from 230mm of the laser-atom overlap onto a UV fibre-optic bundle and deliver it to a single 50mm diameter photomultiplier tube. The chosen transition in the gallium atom from the 4p $^2P_{3/2}$ metastable state to the 5s $^2S_{1/2}$ upper state (417 nm) will show optimum sensitivity to the charge radius and provide a measurement of the quadrupole moments. The laser light will be generated using 834 nm light from a titanium-sapphire laser, doubled using the Wavetrain delta cavity using existing optics and crystals. The upper state decays with the emission of 417nm light back to the metastable state and 403nm light to the ground state. Further suppression of background laser light (417 nm) may be achieved with a 403 nm interference filter placed between the fibre-optic bundle and the photomultiplier tube.

4. Beam time request

The time required to optimise the cooler and the effect ISCOOL will have on the speed of data taking are hard to predict. The recent experience with laser spectroscopy of copper [4] suggests near-stability isotopes may need as little as half a shift for the measurement. The lower-flux beams will need up to two shifts per isotope. We thus request the radioactive beam time outlined below:-

Isotopes	Target	Requiring	Number of Shifts
Y	UC_x	ISCOOL, RILIS	6
$^{62-68}Ga$	ZrO_2	ISCOOL, RILIS	9
$^{72-83}Ga$	UC_x	ISCOOL, RILIS	15

A shift with access to stable beams will also be required prior to each period of running with radioactive beam in order to tune the beam line and detection equipment.

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