EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Study of the stability of the gallium isotopes beyond the $N = 50$ neutron shell closure.

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Abstract: We propose to study the stability of the nuclear structure beyond $N = 50$ and $Z = 28$ with beams of neutron-rich gallium isotopes at the CRIS experiment at ISOLDE. The study of their hyperfine structure and isotope shift will provide spins, magnetic dipole moments, electric quadrupole moments and changes in the mean-square charge radii. The β decay of ^{80}Ga will be unambiguously measured using the technique of Laser Assisted Nuclear Decay Spectroscopy (LANDS). The half-lives of the very neutron-rich isotopes with $N > 54$ will be measured for their impact on the astrophysical r-process.

Requested shifts: 33 shifts in 2 runs

1 Introduction

We propose to measure the hyperfine structure, isotope shift and nuclear half-life of the neutron-rich gallium ($Z = 31$) isotopes and isomers around and beyond $N = 50$ using collinear resonance ionisation spectroscopy with the CRIS setup at ISOLDE. These data shall be used to study the stability of the $Z = 28$ and $N = 50$ shell closures in very neutron-rich nuclei. The measurements shall in turn contribute to test the robustness of state-of-the-art density functional theoretical calculations, in part for interest in r-process nucleosynthesis mechanism.

1.1 Nuclear structure at and beyond $Z = 28$ and $N = 50$

The $Z = 28$ and $N = 50$ magic numbers are the first to arise in the neutron-rich region of the nuclear chart from the spin-orbit contribution to the nuclear potential. As such, they have attracted a lot of attention both experimentally and theoretically [1]. This contribution is known to be overcome by n-p interaction an particle pair scattering in the most neutron-rich nuclei, and the persistence of magicity at ^{78}Ni is one of the key questions of modern nuclear structure. Taking the shell model to the extreme, single particles or holes around magic shells should solely describe the properties of the nuclear ground state. Deviations from this picture are often interpreted as a sign of weakening of the magic core. Single-particle and single-hole structures are thus essential in the study of magic numbers as they provide a very strong test of the purity of the magic systems.

^{80}Ga

In this respect, attention has focused on the one-neutron-hole isotones of $N = 49$. They have proven to be useful probes of the persistence (or lack) of magicity at $N = 50$. In the shell model description, they are best described with a hole in the $g_{9/2}$ orbital. On the neutron-rich side of the nuclear chart, all isotopes have long-lived low-lying isomers down to ^{81}Ge. In the even-Z nuclei, they arise from the proximity of the different pf orbitals between $Z = 28$ and $Z = 40$ and the monopole shift induced by their interaction with the neutron hole in the $g_{9/2}$ orbital.

A similar competition between normal and intruder configurations is seen at $Z = 28$. The copper isotopes ($Z = 29$) have been shown to have a $5/2^-$ ground-state spin. This configuration arises from an intruder $f_{5/2}$ proton orbital, and highlights the weakening of the shell closure at $Z = 28$ [2, 3]. The same effect is seen at $N = 50$ in the gallium isotopic chain [4].

The isotope ^{80}Ga, with 3 protons outside the $Z = 28$ core occupying shells in the pf orbitals, is the first $N = 49$ isotone in which no isomerism was found. The coupling of the valence particles and hole results in states ranging from $I = 3^-$ to 7^-. Early decay studies concluded that the ground state spin is in the range 3 to 5 and that isomerism is not present [5]. Mass measurement at the JYFLTRAP Penning trap setup did also not observe any isomer in ^{80}Ga [6]. Recent collinear laser spectroscopy study of the gallium isotopes with the COLLAPS setup at ISOLDE revealed the presence of two long-lived states with spins 3^- and 6^- respectively, as seen in Fig. 1 [7]. Although this discovery

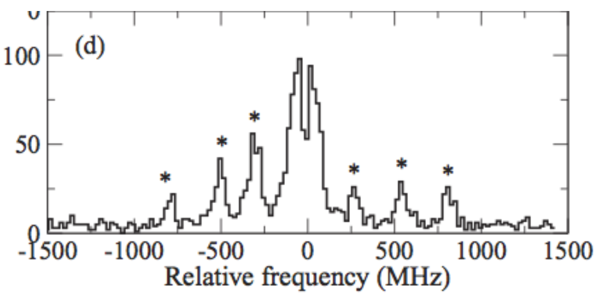

Figure 1: Fluorescence spectrum of ^{80}Ga at COLLAPS using the 417 nm transition. The outer peaks make up the hyperfine structure of the 3^- state while the central double peak is the collapsed hyperfine structure of the 6^- state. [7]

agrees with the systematic of the $N = 49$ isotones, it challenges the interpretation of previous measurements. Moreover, this isomerism can only be reproduced with shell model calculations by considering the polarisation of the ^{56}Ni core, which is a sign of weakening of the $Z = 28$ shell gap.
In the light of that discovery, original data from the PARRNe separator at the ALTO facility have been analysed to account for those two states [8]. Although no clear separation between the two decay patterns could be achieved, half-lives ranging between 1.3(2)s and 1.9(1)s have been identified and have been attributed to the β decay of the 3^- and 6^- states, respectively. Meanwhile, new data have been collected at ISOLDE on the decay of ^{80}Zn to ^{80}Ga, from which the low-lying energy levels in ^{80}Ga could be determined, including the excitation energy of the isomer [9]. In spite of those recent developments, only studies of purified isomeric beams will allow the decay properties of the ground state and isomer in ^{80}Ga to be fully determined.

Beyond $N = 50$

Beyond $N = 50$, the $d_{5/2}$ and $g_{7/2}$ orbitals are filled. Their polarising effect on the nuclear core can be seen in the changes in the nuclear configuration of the ground state and its departure from an extreme shell-model $\pi p_{3/2}$ description, as seen in the copper chain between $N = 40$ and $N = 50$ [2, 3] and in the gallium chain at $N = 50$ [4]. A rapid onset of deformation is also expected from β-decay studies [10]. However, no atomic spectroscopy has been performed in this region [11] and spins are generally inferred from decay considerations and systematics. We therefore propose to study the hyperfine structure of the gallium isotopes up to $N = 54$ (data are currently limited to $N = 51$ [12]), to determine spins, magnetic dipole moments, electric quadrupole moments and extend changes in the mean-square charge radii beyond $N = 50$ [13]. Long-lived isomers that are extracted from the ion source can also be identified with laser spectroscopy [7].

1.2 Nucleosynthesis along the r-process path

Understanding the origin of the heaviest elements in the solar system remains an open question for modern science. One of the scenarios involves very neutron-rich nuclei, most

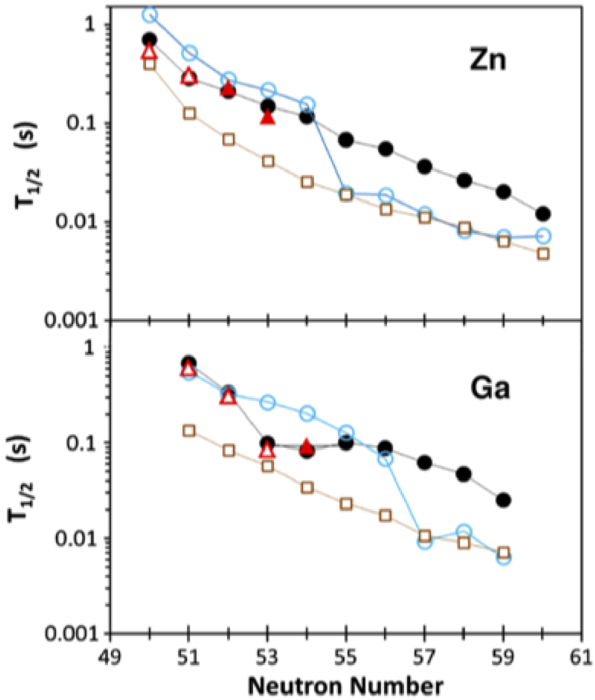

Figure 2: Evolution of the half-life in Zn and Ga beyond $N = 50$. The red triangles are experimental half-lives. The open symbols are previous calculations while the filled symbols are the revised calculations predicting the stabilisation of the gallium half-lives. For more information, please refer to Ref. [14]

of which are currently unavailable at radioactive ion beam facilities, which successively undergo rapid neutron capture and β decay in explosive stellar events. This r-process is determined by the balance between those two processes, and the final element abundances are therefore determined by the neutron separation energy and by the β-decay half-life.
In a recent β-decay study at HRIBF ORNL, the half-life of $^{85}_{54}$Ga has been measured and its value was inconsistent with respect to the trend set by the heavier isotopes, as well as predicted by different nuclear models [14]. New calculations were made to reproduce this effect and predict a stabilisation of the gallium isotope half-life up to $N = 56$, beyond which the downward trend in half-life resumes, as shown in Fig. 2. Their work suggested a 200% impact on abundances of some elements. A direct measurement of the half-life of ^{86,87}Ga is therefore crucial to confirm those calculations.
By combining high selectivity with a dedicated decay spectroscopy station, CRIS offers a unique opportunity to measure the half-life of these isotopes in ultra pure conditions. We thus propose to complement the hyperfine structure measurements by half-life measurements with the decay spectroscopy station.

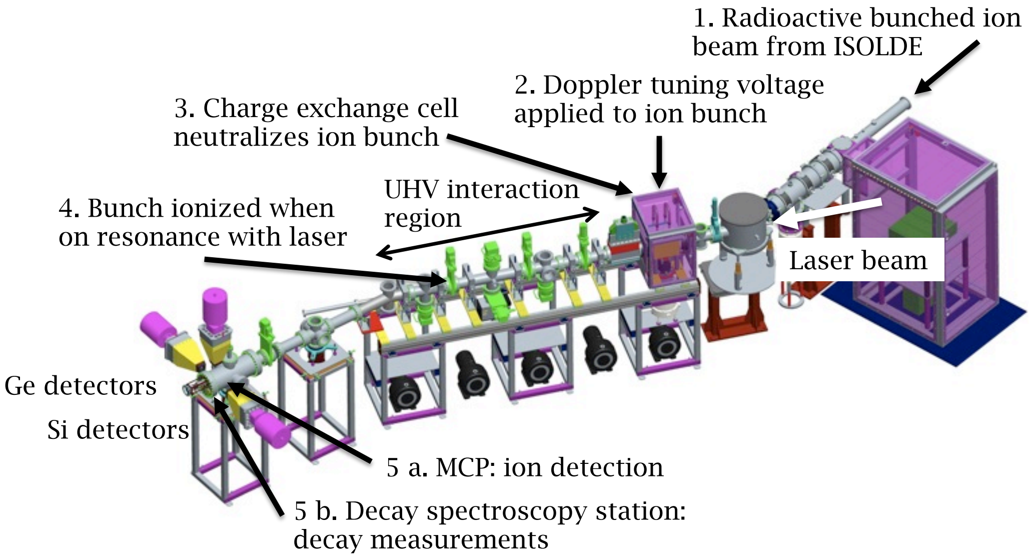

Figure 3: Layout of the CRIS setup

2 Experimental approach

We propose to measure the hyperfine structure spectra, isotope shift and half-lives of neutron-rich gallium isotopes by means of in-flight resonance ionisation laser spectroscopy with the CRIS setup at ISOLDE.

2.1 The CRIS experiment

Mass-separated bunched beams from the HRS are delivered to the CRIS experiment at 40 keV. The ion beam is neutralised through an alkali vapour charge-exchange cell while non-neutralised ions are deflected away. The atom bunch is then overlapped with synchronised, bunched laser beams to resonantly excite an electron beyond the ionisation threshold. The re-ionised bunch is then deflected away to be detected by a multi-channel plate detector (MCP) [15].
The CRIS technique has currently achieved an efficiency of 1% with radioactive beams of francium down to 100 ions/s, with a suppression of isobaric contaminants of the order of at least $1 : 10^5$. Sensitivity to weaker beams down to below 1 ion/s is possible.
The resolution of previous measurements has been limited by the resolution of the laser system (1.2 GHz). This is not the limit of the technique, as demonstrated previously at COLLAPS where the technique was performed with resolution down to 50 MHz [16]. A new laser system has since been acquired by the collaboration, and will provide the required resolution for this proposal.
Beyond the MCP detection, CRIS is equipped with a Decay Spectroscopy Station (DSS), which consists of a 20 ug/cm2 carbon foil implantation site surrounded by two silicon detectors (68% coverage) [17]. Using the high purification power of the CRIS technique, Laser Assisted Nuclear Decay Spectroscopy (LANDS) can be performed [18]. The DSS

Table 1: Estimated yields of neutron-rich gallium isotopes with a UC_x target, neutron converter and RILIS in the 2009 configuration. Note that the efficiency of the RILIS scheme benefits from the RILIS upgrade but that the new neutron-converter geometry should provide up to $\times 10$ improvement. The half-lives for ^{86,87}Ga are estimated [14].

Isotope	$T_{1/2}$ [s]	Yields [/μC]
^{80}Ga	1.7	5.2×10^5
^{81}Ga	1.22	3.2×10^5
^{82}Ga	0.6	5.0×10^4
^{83}Ga	0.31	7.5×10^3
^{84}Ga	0.085	1.3×10^2
^{85}Ga	0.093	2.0×10^1
^{86}Ga	~ 0.1	2.5×10^0
^{87}Ga	~ 0.06	

is currently being modified to allow up to 3 germanium detectors to be placed in close proximity to the implantation site, with aluminium walls to minimise absorption of the low-energy γ rays by the vacuum chamber. Access to the ISOLDE Digital Acquisition System is requested in 2014.

2.2 Beam production and delivery

The radioactive gallium ion beams are produced with a standard ISOLDE UC_x target. The gallium isotopes are ionised on the hot surface with a factor of 100 enhancement provided by the Resonant Ionisation Laser Ion Source (RILIS). Neutron-rich gallium isotopes suffer from isobaric surface-ionised beams of strontium and rubidium which can be suppressed by using neutron-induced fission upon impinging the PS-Booster proton beam on a neutron converter.

Experiments have been performed at the COLLAPS setup up to $N = 51$ in 2009 with a beam intensity of 5×10^4 for ^{82}Ga (UC_x and neutron converter) [4, 7, 15]. The published yields have been rescaled to this value and are shown in Table 1. Note that in 2009, the RILIS lasers were upgraded to increase the ionisation efficiency [19]. The geometry of the neutron converter is also currently under investigation in order to improve its performance by a factor of 10. As such, yields of > 1 ion/s are expected up to $N = 55$ (^{86}Ga) and possibly $N = 56$ in the near future.

The beam has to be produced at the HRS target station in order to use bunched beams from ISCOOL [20] to match the duty cycle of the CRIS technique (30 to 200 Hz).

Beam contamination up to $1 : 10^6$ can be handled at CRIS. The limits will then be reached when ISCOOL saturates.

2.3 Beam time estimate

The CRIS experiment requires 3 online shifts (protons to ISOLDE) for setting up and optimising conditions with respect to on-line isobars. As a collinear laser spectroscopy

experiment, it requires a frequent reference measurement. A stable gallium mass marker is requested. The time necessary for cycling the HRS magnets and study the reference isotope is included in the further estimates.
2 shifts are requested to study the hyperfine structure of each isotope with $N = 82, 83, 84$ in the first run. 3 shifts are requested for the isotopes with $N = 85, 86, 87$, to account for the reduced beam intensity in a second run. A total of **15** shifts are requested for laser spectroscopy.
5 shifts are requested for the decay spectroscopy study of ^{80}Ga, including setting up, identifying the different components (hyperfine structure scan) and measuring the decay patterns. Considering 1% efficiency for the CRIS apparatus, a beam rate of 5000 implanted ions/s is expected at the DSS.
1 shift is requested for identifying the studied isotopes and measuring their half-life at the DSS, for a total of **6** shifts.
The ISOLDE DigiDAQ is requested to operate the DSS (up to 4 channels for Si detectors and up to 3 channels for Ge detectors).

	Run 1		Run 2
	^{80}Ga	$^{82-84}$Ga	$^{85-87}$Ga
Setup	3 shifts		3 shifts
Laser spectroscopy	1 shift	6 shifts	9 shifts
LANDS	4 shifts	3 shifts	3 shifts
TOTAL	18 shifts		15 shifts

Summary of requested shifts: 33 shifts of radioactive beam time are requested, separated in two runs of respectively 18 and 15 shifts.

References

[1] O. Sorlin and M.-G. Porquet. Nuclear magic numbers: new features far from stability. *Progress in Particle and Nuclear Physics*, 61:602–673, 2008.

[2] K. T. Flanagan, P. Vingerhoets, M. Avgoulea, J. Billowes, M. L. Bissell, K. Blaum, B. Cheal, M. De Rydt, V. N. Fedosseev, D. H. Forest, Ch. Geppert, U. Köster, M. Kowalska, J. Krämer, K. L. Kratz, A. Krieger, E. Mané, B. A. Marsh, T. Materna, L. Mathieu, P. L. Molkanov, R. Neugart, G. Neyens, W. Nörtershäuser, M. D. Seliverstov, S. Serot, M. Schug, J. R. Sjoedin, A. M. Stone, N. J. Stone, H. H. Stroke, G. Tungate, D. T. Yordanov, and Yu. M. Volkov. Nuclear spins and magnetic moments of ^{71,73,75}Cu: inversion of $\pi 2p_{3/2}$ and $\pi 1f_{5/2}$ levels in 75Cu. *Physical Review Letters*, 103:142501, 2009.

[3] U. Köster, N. J. Stone, K. T. Flanagan, J. Rikovska Stone, V. N. Fedosseev, K. L. Kratz, B. A. Marsh, T. Materna, L. Mathieu, P. L. Molkanov, M. D. Seliverstov, O. Serot, A. M. Sjödin, and Yu. M.. Volkov. In-source laser spectroscopy of ^{75,77,78}Cu: direct evidence for a change in the quasiparticle energy sequence in ^{75,77}Cu and an absence of longer-lived isomers in ^{78}Cu. *Physical Review C*, 84:034320, 2011.

[4] B. Cheal, E. Mané, J. Billowes, M. L. Bissel, K. Blaum, B. A. Brown, F. C. Charlwood, K. T. Flanagan, D. H. Forest, Ch. Geppert, M. Honma, A. Jokinen, M. Kowalska, A. Krieger, J. Krämer, I. D. Moore, R. Neugart, G. Neyens, W. Nörterhäuser, M. Schug, H. H. Stroke, P. Vingerhoets, D. T. Yordanov, and M. Žaková. Nuclear spins and moments of Ga isotopes reveal sudden structural changes between $N = 40$ and $N = 50$. *Physical Review Letters*, 104:252502, 2010.

[5] P. Hoff and B. Fogelberg. Properties of strongly neutron-rich isotopes of germanium and arsenic. *Nuclear Physics A*, 368:210–236, 1981.

[6] J. Hakala, S. Rahaman, V.-V. Elomaa, T. Eronen, U. Hager, A. Jokinen, A. Kankainen, I. D. Moore, H. Pentilä, S. Rinta-Antila, J. Rissanen, A. Saastamoinen, T. Sonoda, Ch. Weber, and J. Äystö. Evolution of the $N = 50$ shell gap energy towards ^{78}Ni. *Physical Review Letters*, 101:052502, 2008.

[7] B. Cheal, J. Billowes, M. L. Bissel, K. Blaum, F. C. Charlwood, K. T. Flanagan, D. H. Forest, S. Fritzsche, Ch. Geppert, A. Jokinen, M. Kowalska, A. Krieger, J. Krämer, E. Mané, I. D. Moore, R. Neugart, G. Neyens, W. Nörterhäuser, M. M. Rajabali, M. Schug, H. H. Stroke, P. Vingerhoets, D. T. Yordanov, and M. Žaková. Discovery of a long-lived low-lying isomeric state in ^{80}Ga. *Physical Review C*, 82:051302(R), 2010.

[8] D. Verney, B. Tastet, K. Kolos, F. Le Blanc, F. Ibrahim, M. Cheikh Mhamed, E. Cottereau, P. V. Cuong, F. Didierjean, G. Duchêne, S. Essabaa, M. Ferraton, S. Franchoo, L. H. Khiem, C. Lau, Le Du J.-F., I. Matea, B. Mouginot, M. Niikura, B. Roussière, I. Stefan, D. Testov, and J.-C. Thomas. Structure of ^{80}Ge revealed by the β decay of isomeric states in ^{80}Ga: triaxiality in the vicinity of ^{78}Ni. *Physical Review C*, 87:054307, 2013.

[9] L. M. Fraile. Private communication.

[10] M. Lebois, D. Verney, D. Ibrahim, S. Essabaa, F. Azaiez, M. Cheikh Mhamed, E. Cottereau, P. V. Chuong, M. Ferraton, K. T. Flanagan, S. Franchoo, D. Guillemaud-Mueller, F. Hammache, C. Lau, F. Le Blanc, J.-F. Le Du, J. Libert, B. Mouginot, C. Petrache, B. Roussière, L. Sagui, N. de Séréville, I. Stefan, and B. Tastet. Experimental study of ^{84}Ga β decay: evidence for a rapid onset of collectivity in the vicinity of ^{78}Ni. *Physical Review C*, 80:044308, 2009.

[11] K. Blaum, J. Dilling, and W. Nörterhäuser. Precision atomic physics techniques for nuclear physics with radioactive beams. *Physica Scripta*, T152:014017, 2013.

[12] B. Cheal, J. Billowes, M. L. Bissel, K. Blaum, F. C. Charlwood, K. T. Flanagan, D. H. Forest, Ch. Geppert, M. Kowalska, K. Kreim, A. Krieger, J. Krämer, K. M. Lynch, E. Mané, I. D. Moore, R. Neugart, G. Neyens, W. Nörterhäuser, J. Papuga, T. J. Procter, M. M. Rajabali, H. H. Stroke, P. Vingerhoets, D. T. Yordanov, and M. Žaková. Laser spectroscopy of gallium isotopes beyond $N = 50$. *Journal of Physics: Conference Series*, 381:012071, 2012.

[13] T. J. Procter, J. Billowes, M. L. Bissel, K. Blaum, F. C. Charlwood, B. Cheal, K. T. Flanagan, D. H. Forest, S. Fritzsche, Ch. Geppert, H. Heylen, M. Kowalska, K. Kreim, A. Krieger, J. Krämer, K. M. Lynch, E. Mané, I. D. Moore, R. Neugart, G. Neyens, W. Nörterhäuser, J. Papuga, M. M. Rajabali, H. H. Stroke, P. Vingerhoets, D. T. Yordanov, and M. Žaková. Nuclear mean-square charge radii of $^{63,64,66,68-82}$Ga: no anomalous behaviour at $N = 32$. *Physical Review C*, 86:034329, 2012.

[14] M. Madurga, R. Surman, I. N. Borzov, R. Grzywacz, K. P. Rykaczewski, C. J. Gross, D. Miller, D. W. Stracener, J. C. Batchelder, N. T. Brewer, L. Cartegni, J. H. Hamilton, J. K. Hwang, S. H. Liu, S. V. Ilyushkin, C. Jost, M. Karny, A. Korgul, W. Królas, A. Kuźniak, C. Mazzochi, A. J. Mendez II, K. Miernik, S. W. Padgett, S. V. Paulauskas, A. V. Ramayya, J. A. Winger, M. Wolińska-Cichocka, and E. F. Zganjar. New half-lives of r-process Zn and Ga isotopes measured with electromagnetic separation. *Physical Review Letters*, 109:112501, 2012.

[15] T. J. Procter, H. Aghaei-Khozani, J. Billowes, M. L. Bissell, F. Le Blanc, B. Cheal, T. E. Cocolios, K. T. Flanagan, H. Hori, T. Kobayashi, D. Lunney, K. M. Lynch, B. A. Marsh, G. Neyens, J. Papuga, M. M. Rajabali, S. Rothe, G. Simpson, A. J. Smith, H. H. Stroke, W. Vanderheijden, and K. Wendt. Development of the CRIS (Collinear Resonant Ionisation Spectroscopy) beam line. *Journal of Physics: Conference Series*, 381:012070, 2012.

[16] Ch. Schulz, E. Arnold, W. Borchers, W. Neu, R. Neugart, M. Neuroth, E. W. Otten, M. Scherf, K. Wendt, P. Lievens, Yu. A. Kudryavtsev, V. S. Letokhov, V. I. Mishin, and V. V. Petrunin. Resonance ionization spectroscopy on a fast atomic ytterbium beam. *Journal of Physics B*, 24:4831–4844, 1991.

[17] M. M. Rajabali, K. M. Lynch, T. E. Cocolios, J. Billowes, M. L. Bissell, S. De Schepper, K. Dewolf, K. T. Flanagan, F. Le Blanc, B. A. Marsh, P. J. R. Mason, I. Matea, G. Neyens, J. Papuga, T. J. Procter, S. Rothe, G. Simpson, A. J. Smith, H. H. Stroke, D. Verney, P. M. Walker, K. Wendt, and R. T. Wood. A dedicated decay-spectroscopy station for the collinear resonance ionization experiment at ISOLDE. *Nuclear Instruments and Methods in Nuclear Physics A*, 707:35–39, 2013.

[18] K. M. Lynch, M. M. Rajabali, H. Aghaei-Khozani, J. Billowes, M. L. Bissell, F. Le Blanc, B. Cheal, T. E. Cocolios, S. De Schepper, K. Dewolf, K. T. Flanagan, H. Hori, T. Kobayashi, B. A. Marsh, G. Neyens, J. Papuga, T. J. Procter, S. Rothe, G. Simpson, A. J. Smith, H. H. Stroke, and K. Wendt. Laser assisted decay spectroscopy at the CRIS beam line at ISOLDE. *Journal of Physics: Conference Series*, 381:012128, 2012.

[19] B. A. Marsh, L.-E. Berg, D. V. Fedorov, V. N. Fedosseev, O. J. Launila, M. Lindroos, R. Losito, F. K. Österdahl, T. Pauchard, I. T. Pohjalainen, U. Sassenberg, M. D. Seliverstov, A. M. Sjödin, and G. Transtromer. The ISOLDE RILIS pump laser upgrade and the LARIS laboratory. *Hyperfine Interactions*, 196:129–141, 2010.

[20] E. Mané, J. Billowes, K. Blaum, P. Campbell, B. Cheal, P. Delahaye, K. T. Flanagan, D. H. Forest, H. Franberg, C. Geppert, T. Giles, A. Jokinen, M. Kowalska, R. Neugart, G. Neyens, W. Nörtershäuser, I. Podadera, G. Tungate, P. Vingerhoets, and D. T. Yordanov. An ion cooler-buncher for high-sensitivity collinear laser spectroscopy at ISOLDE. *European Physics Journal A*, 42:503, 2009.