Development of the CRIS (Collinear Resonant Ionisation Spectroscopy) beam line.

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Abstract. The CRIS (Collinear Resonant Ionisation Spectroscopy) beam line is a new experimental set up at the ISOLDE facility at CERN. CRIS is being constructed for high-resolution laser spectroscopy measurements on radioactive isotopes. These measurements can be used to extract nuclear properties of isotopes far from stability. The CRIS beam line has been under construction since 2009 and testing of its constituent parts have been performed using stable and radioactive ion beams, in preparation for its first on-line run. This paper will present the current status of the CRIS experiment and highlight results from the recent tests.

1. Introduction

Laser spectroscopy of radioactive atoms is an experimental technique that provides model independent measurements of nuclear isotopes. Many optical measurements have been obtained for hundreds of isotopes from the different mass regions of the nuclear chart. Recent highlights in the field have been the measurements made on the halo nuclei ^{6,8}He [1, 2], ^{8,9,11}Li [3, 4] and ^{7,9,10,11}Be [5], the island of inversion ^{31,33}Mg [6, 7, 8, 9] and ^{31}Na [10], the N = 28 shell closure [11, 12, 13, 14, 15], the monopole migration of the $\pi f_{5/2}$ orbital in neutron rich Cu [16, 17, 18, 19] and Ga [20, 21, 22], the rapid onset of deformation in the N = 60 region [23, 24] and shape coexistence in the Pb, Po region [25, 26]. Developments such as laser ion sources [27, 28], target improvements [29] and work at the IGISOL facilty [30] have allowed for a continuous evolution of the field and have significantly improved isotope production over the last few decades. As well as the advances in production yields, techniques have also been developed

to improve the efficiency of experiments. The major limiting factors in current techniques are detection efficiency, resolution and isobaric contamination of the beam. The new CRIS (Collinear Resonant Ionization Spectroscopy) beam line combines the advantages of collinear laser spectroscopy with resonant ion detection (RIS) to increase sensitivity while maintaining a high resolution. The beam line was proposed in 2008 and the building phase was carried out through 2009 - 2010. 2011 has been a major testing period for the experiment and has been used to prepare the equipment for on-line experiments. This paper will present the current status of the CRIS experiment and highlight the contributing factors that distinguish it from prior experiments. The results from recent off-line tests will also be discussed.

2. Techniques of Laser Spectroscopy

From studying the hyperfine structure (hfs) of an isotope, a number of nuclear properties can be measured using laser spectroscopy. This hfs in the optical transitions is observed as small splittings in energy of the upper and lower electron J states due to the interaction coupling between the nucleus and the electrons' electromagnetic field. The energy splitting between levels can be precisely measured and used to extract μ, Q_s and I. By measuring the shift in frequency between isotopes it is possible to extract $\delta\langle r^2\rangle^{AA'}$ [31].

The majority of recent laser spectroscopy measurements of radioactive nuclei have used either collinear or in-source laser spectroscopy. The underlying advantage of the collinear technique is the high resolution, which results from the acceleration of ions through 30-40 kV. The reduction in the Doppler width of atomic lines is dependent on the electrostatic acceleration (U) used and the energy spread (δE) of the ions, shown by equation 1.

$$\delta\nu = \nu_0 \frac{\delta E}{\sqrt{2eUmc^2}},\tag{1}$$

where $\delta\nu$ is the Doppler width and ν_0 is the transition frequency. For example, a acceleration voltage of 30 kV reduces the Doppler width by $\sim 10^3$. The production of a fast beam from the ion source is supplemented by a fast extraction process. The ions are accelerated as soon as they are ionized and quickly delivered to experiments allowing short lived nuclei ($\tau_{1/2} \approx 1$ ms) to be investigated. The limitations with the collinear technique are the detection efficiency and background suppression. With the development of ion cooler and bunchers at beam facilities [32], the background scattered light can be decreased, dramatically extending the lifetime range of fluorescence measurements. However this method does not change the detection efficiency of photon detection.

The RIS technique uses multiple pulsed lasers to resonantly exicite and ionize atoms. The ion detection efficiency is extremely high due to the quantum efficiency (almost 100%) and solid angle of the modern ion detectors and electron multipliers. In the case of in-source laser spectroscopy the resolution is limited by the Doppler broadening (~ 4 GHz for neutron-rich Cu[19]) due to the high temperature of the ionizer cavity. RIS has been performed on a wide range of cases and is often used as a method of producing high purity isotope beams, for instance RILIS at ISOLDE [27], LISOL at Leuven [33] and IGISOL at Jyväskylä [34].

3. CRIS

The new CRIS beam line is an experiment which will combine the advantages of the collinear and RIS methods [35]. This technique was first proposed in 1982 by Kudryavtsev and Letokhov [36] and was initially tested off-line. The first on-line run was performed at ISOLDE and used a continuous ion beam. An overall detection efficiency of $1 : 10^5$ was achieved, limited by the duty

cycle loss of the pulsed lasers [37]. The CRIS experiment at ISOLDE will aim to demonstrate the CRIS method as a valid technique of performing experiments on radioisotopes far from stability. A schematic of the CRIS beam line is shown in figure 1. For optimal operation, the CRIS
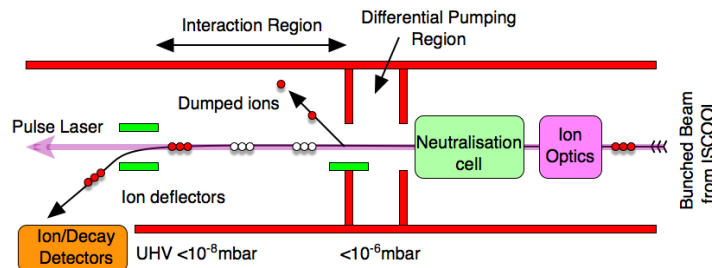

Figure 1. Schematic layout of the CRIS beam line, showing a collinear overlap between pulsed lasers and bunched ions.

experiment employs the ISOLDE ion beam cooler and buncher, ISCOOL [38] . A continuous ion beam and duty cycle of pulsed lasers incurs a loss in efficiency of a factor of 10^4. By using bunched beams, this factor is recovered by 100%. The ion bunch is neutralized in a charge exchange cell (CEC) and then enters the interaction region. The dimensions of the interaction region are such that they allow an entire ion bunch to fit within it and be completely overlapped with the laser pulses before entering the detection region. The detection region is kept at ultra high vacuum (UHV) in order to minimise and potentially remove non-resonant ionization with particles in the vacuum. The atoms are then resonantly ionized by the lasers and then deflected into the ion detection region. A technical drawing of CRIS is shown in figure 2.
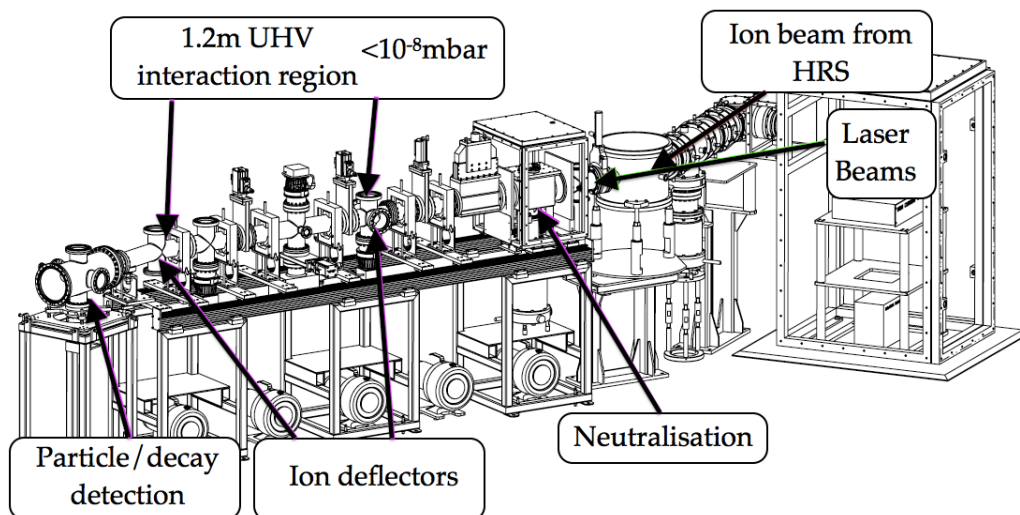

Figure 2. Technical drawing of the CRIS beam line, highlighting the parts of interest.

4. Current Status of CRIS

4.1. Charge Exchange Cell (CEC).
CRIS utilizes a CEC to neutralize ions within the beam line. The CEC maintains a relatively high vapour pressure of an alkali metal for efficient charge exchange with an ion beam. A

schematic of the CEC is shown in figure 3. The alkali metal is placed within the chamber, which is pumped to high vacuum. The cell is heated to around 150°C, which produces a vapour of the alkali. The ends are cooled by a Julabo hot oil circulator, causing the vapour to circulate back towards the centre of the cell. This circulation creates a dense alkali vapour without contaminating the beam line. When placed in the beam line, the CEC can be pumped down to $6x10^{-7}$ mbar and when under heating for experimental use it operates around 10^{-6} mbar. In recent tests the efficiency of the CEC was demonstrated to be 70% for a 30 keV beam of ^{85}Rb. A scanning voltage Doppler tunes the beam across the resonances of the hyperfine spectrum.
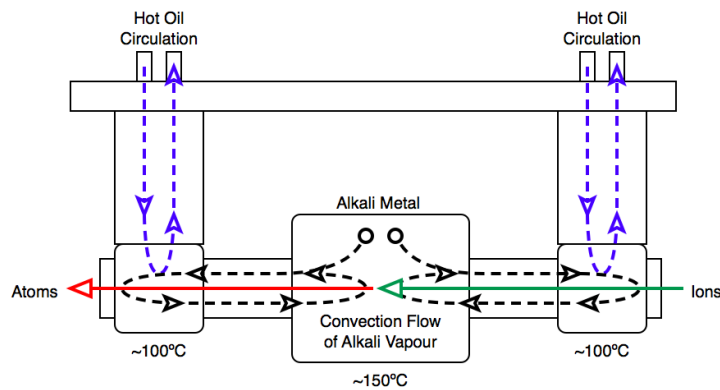

Figure 3. Schematic diagram of the charge exchange cell.

4.2. UHV and Differential Pumping.

The CRIS beam line can achieve pressures of $< 10^{-5}$ mbar in the region connected to ISOLDE, $< 10^{-5}$ mbar in the CEC region, $< 10^{-8}$ mbar in the interaction region and $< 10^{-7}$ mbar in the detection region. Differential pumping apertures are placed before and after the interaction region to allow the region to reach UHV. The differential pumping apertures are 10 mm in diameter with a length of 20 mm. These dimensions allow a pressure differential of around $2x10^{3}$ between the CEC and interaction region.

4.3. Micro Channel Plate (MCP) Ion Detection and Data Acquisition (DAQ).

After the interaction region the resonantly produced ions are detected using a Hamamatsu MCP. The ion bunch is focused onto an off axis copper dynode, held at negative voltage, to produce secondary electrons which are detected by the MCP. Tests show that an increase in dynode voltage results in an increase of detected electrons up to -700 V where detection saturates. The MCP signal is then counted using a LeCroy digital oscilloscope, which can resolve single ions. A Quantum Composers pulse generator is used to generate the master trigger for the experiment, controlling the pulsed lasers, gating detection time and releasing ions from ISCOOL. A plot of the ion bunch time of flight (ToF) tests for ^{86}Rb is presented in figure 4. A ToF of 81.5 μs from ISCOOL to the MCP detector was measured with a FWHM of 1 μs. This measurement of the FHWM equates to a bunch length of ≈ 0.25 m, well within the length of the interaction region.

4.4. Offline Ion Source.

An off-line ion source is situated at the beginning of CRIS to provide stable ions, figure 5. The ion source allows for a continuous beam of elements with an ionization potential below a 6 eV work function limit to be delivered to the experimental set up. A heating current is applied
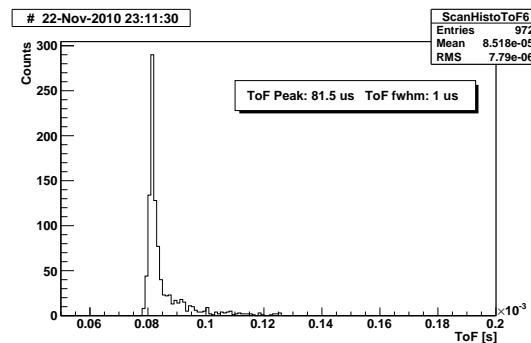
Figure 4. Ion detection after release from the ISCOOL cooler and buncher [39].
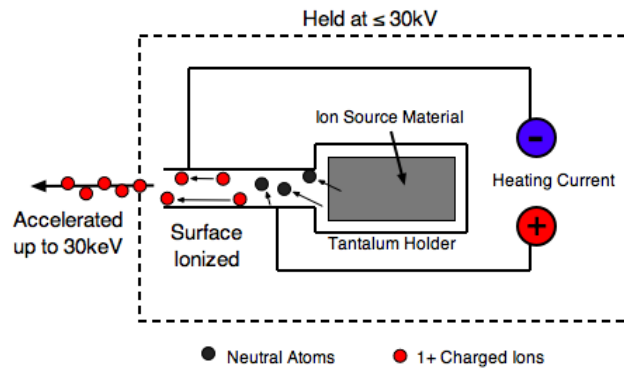
Figure 5. Diagram of the off-line ion source.

to the ion source, by a Delta Elektronika power supply. The atoms are surface ionised on the extraction pipe and then accelerated by the potential of the ion source. Electrostatic steering optics are used along with an einzel lens, figure 6 (a), to steer and focus the beam. The ion source and einzel lens were tested together using a wire scanner and Faraday cup to view the profile of the produced beam. The profile of a 2 keV Cs beam, with a beam diameter ≈ 2 mm, is shown in figure 6 (b).
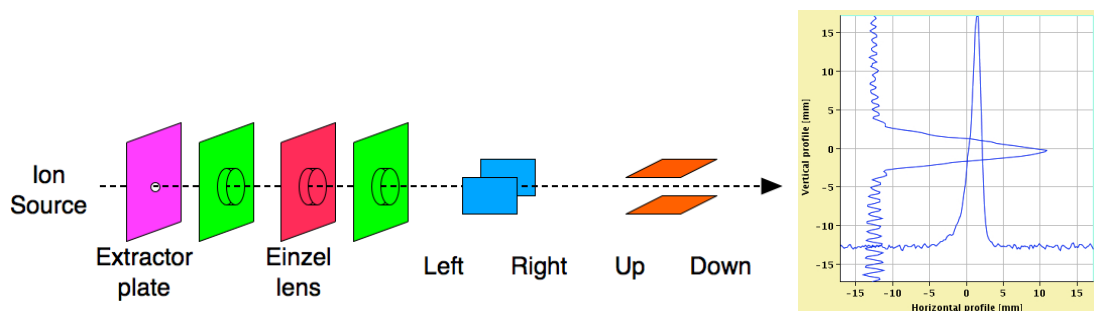
Figure 6. (Left to right) (a) Diagram of the einzel lens. (b) Profile of the Cs beam produced from the CRIS off-line ion source.

4.5. Decay Spectroscopy Station (DSS).
At the end of the beam line the CRIS DSS has been installed. This setup utilizes the high degree of selectivity provided by CRIS to perform decay measurements on rare isotopes. The DSS will allow complementary information on the nuclear level structure of daughter nuclei to be obtained when combined with collinear resonant ionization spectroscopy [40].

5. Summary
The CRIS beam line has been fully commissioned and is approaching its first on-line experimental run on neutron deficient francium. The successful implementation of the off-line ion source has allowed for continuous development of the beam line and testing of the main components. The neutralization cell has been demonstrated to efficiently neutralize accelerated ion bunches while the ion detection has been set up to optimize its efficiency during operation.

References
[1] Mueller P *et al.* 2007 *Phys. Rev. Lett.* **99**(25) 252501
[2] Wang L B *et al.* 2004 *Phys. Rev. Lett.* **93**(14) 142501
[3] Ewald G *et al.* 2005 *Phys. Rev. Lett.* **94**(3) 039901
[4] Puchalski M *et al.* 2006 *Phys. Rev. Lett.* **97**(13) 133001
[5] Nörtershäuser W *et al.* 2009 *Phys. Rev. Lett.* **102**(6) 062503
[6] Kowalska M *et al.* 2008 *Phys. Rev. C* **77**(3) 034307
[7] Neyens G *et al.* 2005 *Phys. Rev. Lett.* **94**(2) 022501
[8] Yordanov D T *et al.* 2007 *Phys. Rev. Lett.* **99**(21) 212501
[9] Kramer J *et al.* 2009/08/03 *Phys. Lett. B* **678** 465 – 9
[10] Huber G *et al.* 1978 *Phys. Rev. C* **18**(5) 2342–2354
[11] Cocolios T E *et al.* 2009 *Phys. Rev. Lett.* **103**(10) 102501
[12] Cocolios T E *et al.* 2010 *Phys. Rev. C* **81**(1) 014314
[13] Vingerhoets P *et al.* 2011 *Phys. Lett. B* **703** 34 – 39
[14] Stone N J *et al.* 2008 *Phys. Rev. C* **77**(6) 067302
[15] Charlwood F C *et al.* 2010 *Phys. Lett. B* **690** 346
[16] Flanagan K T *et al.* 2009 *Phys. Rev. Lett.* **103**(14) 142501
[17] Flanagan K T *et al.* 2010 *Phys. Rev. C* **82**(4) 041302
[18] Vingerhoets P *et al.* 2010 *Phys. Rev. C* **82**(6) 064311
[19] Köster U *et al.* 2011 *Phys. Rev. C* **84**(3) 034320
[20] Cheal B *et al.* 2010 *Phys. Rev. Lett.* **104**(25) 252502
[21] Mané E *et al.* 2011 *Phys. Rev. C* **84**(2) 024303
[22] Cheal B *et al.* 2010 *Phys. Rev. C* **82**(5) 051302
[23] Charlwood F *et al.* 2009 *Phys. Lett. B* **674** 23 – 27
[24] Cheal B *et al.* 2009 *Phys. Rev. Lett.* **102** 222501
[25] De Witte H *et al.* 2007 *Phys. Rev. Lett.* **98**(11) 112502
[26] Cocolios T E *et al.* 2011 *Phys. Rev. Lett.* **106**(5) 052503
[27] Fedosseev V *et al.* 2008 *Nucl. Instrum. Methods* **266** 4378 – 4382
[28] Marsh B *et al.* 2010 *Hyperfine Interactions* **196**(1) 129–141
[29] Kugler E 2000 *Hyperfine Interactions* **129**(1) 23–42
[30] Karvonen P *et al.* 2008 *Nucl. Instrum. Methods Phys. Res. Sect. B* **266** 4454
[31] Cheal B and Flanagan K T 2010 *J. Phys. G* **37**
[32] Campbell P *et al.* 2002 *Euro. Phys. J. A* **15**(1) 45–48
[33] Kudryavtsev Y *et al.* 2003 *Nucl. Instrum. Methods B* **204** 336 – 342
[34] Moore I D *et al.* 2006 *AIP Conference Proceedings* **831** 511–513
[35] Billowes J 2001 *Nucl. Phys. A* **682** 206
[36] Kudryavtsev Y A and Letokhov V S 1982 *Appl. Phys. B* **29**(3)
[37] Schulz C H *et al.* 1991 *J. Phys. B* **24** 4831–44
[38] Mané E *et al.* 2009 *Eur. Phys. J. A* **42** 503
[39] Lynch K M 2010 *Private communication*
[40] Lynch K M 2011 *Rutherford IOP Proceedings*