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High-resolution laser spectroscopy with the Collinear Resonance Ionisation Spectroscopy (CRIS) experiment at CERN-ISOLDE

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ABSTRACT

The Collinear Resonance Ionisation Spectroscopy (CRIS) experiment at CERN has achieved high-resolution resonance ionisation laser spectroscopy with a full width at half maximum linewidth of 20(1) MHz for ^{219,221}Fr, and has measured isotopes as short lived as 5 ms with ^{214}Fr. This development allows for greater precision in the study of hyperfine structures and isotope shifts, as well as a higher selectivity of single-isotope, even single-isomer, beams. These achievements are linked with the development of a new laser laboratory and new data-acquisition systems.

1. Introduction

The Collinear Resonance Ionisation Spectroscopy (CRIS) experiment at CERN-ISOLDE is a laser spectroscopy experiment combining the high-resolution of the accelerated-beam collinear geometry with the high detection efficiency of the resonance ionisation process [1].

In its first application in 1991 [2], the CRIS technique used pulsed laser beams to obtain high power densities, but suffered from the duty cycle losses associated with a poor temporal overlap between the continuous ion beam and the pulsed laser light. This limitation was recently addressed with the development of bunched-beam laser spectroscopy [3–5] and allowed the first study of the francium isotopes at the CRIS experiment [6–8]. The resolution of the spectra in this 2012 campaign was limited by the laser system, which had a full width at half maximum (FWHM) of 1.5 GHz [1,9].

The 2014 campaign has benefited from a high-resolution continuous wave (cw) laser system and a higher repetition rate in the final, ionisation-step, pulsed laser. These two developments have enabled high-resolution laser spectroscopy at CRIS, as well as the study of very short-lived isotopes. A new laser laboratory and new data-acquisition systems are currently being implemented to fully exploit the capabilities of the CRIS experiment.

2. The CRIS experimental setup

2.1. The CRIS beam line

The CRIS beam line (see Fig. 1) receives radioactive ion beams from the CERN-ISOLDE facility [10] at 30–60 keV via the high-resolution separator and linear Paul trap cooler and buncher ISCOOL [11], delivering a pulsed ion beam with 1–6 μs bunch width, and up to 200 Hz repetition rate.

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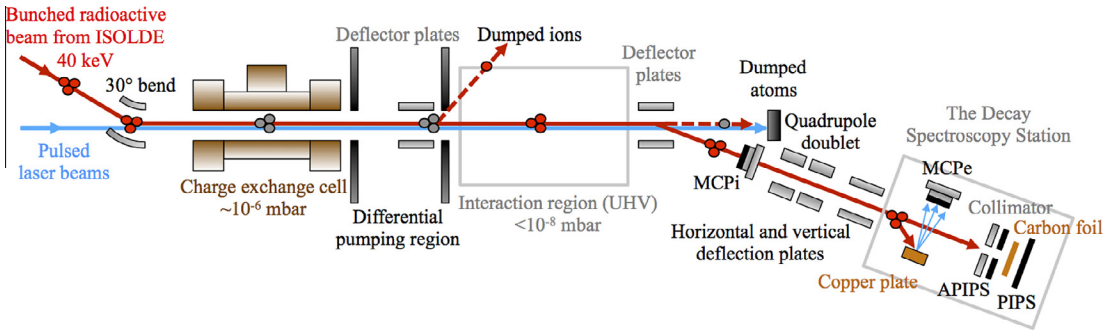

Fig. 1. Schematic layout of the CRIS beam line from the ion beam injection (left) to the detection setups (right), as updated from Ref. [7]. The ion MCP (MCPi) can be removed from the beam path to bring the ions to the DSS. An electric potential can then be applied to the horizontal deflection plates to switch between the copper plate dynode for the electron MCP (MCPe) or the carbon foil, surrounded by two passivated implanted planar silicon (PIPS) detectors, one of which is annular (APIPS).

The ion bunch is neutralised through a charge exchange cell filled with potassium vapour, operated in order to reach 50% neutralisation efficiency with francium beams. The non-neutralised fraction is deflected while the atom bunch is allowed to drift to the interaction region where it is overlapped collinearly with the laser beams. Good vacuum conditions (nominally 5×10^{-9} mbar) in the interaction region are necessary to minimize collisional re-ionisation with rest-gas molecules, which is the main source of background. A series of differential pumping apertures are used between the charge exchange cell and the interaction region, in order to maintain a pressure below 10^{-8} mbar in the interaction region. The re-ionised bunch is then deflected towards the CRIS detection setup.

2.2. The CRIS detection setup

The CRIS detection setup is made of three elements. A multi-channel plate (MCP) detector can be used to directly count impinging ions (MCPi – currently under commissioning). A second MCP detector can be used to measure secondary electrons emitted from a copper plate on which the ion bunch impacts (MCPe). Finally, a decay spectroscopy station (DSS) can be used to study the radioactive decay of the isotope of interest [12].

The MCPe detection system has been used in the study of the hyperfine structure of the francium isotopes. A small bias voltage (< 1 kV) is applied between the copper plate and the front of the MCP to guide the secondary electrons towards the detector. This configuration also ensures that the MCP does not suffer from any implantation damage and that it does not get contaminated by the radioactive ions.

The DSS consists of a rotating wheel housing eight thin carbon foils (20 μg/cm^2 on average) [13] to collect and study the radioactive samples, a copper plate for stable beam tuning, and two 50 Bq ^{241}Am α sources to test and optimise the detectors and acquisition system parameters. The beam-axis position is surrounded by two passivated implanted planar silicon (PIPS) detectors, one of which has a 4 mm hole to let the ion beam through (annular PIPS, APIPS), with a total solid angle of 65% of 4π. An off-axis position is also equipped with two silicon detectors, with 80% solid angle coverage.

2.3. The CRIS laser laboratory

The newly constructed CRIS laser laboratory (see Fig. 2) houses a Matisse DS cw dye laser, pumped by a 10 W Millenia prime Nd:YAG laser. The light from this laser can be frequency-doubled with an external Sirah Wavetrain 2 doubling cavity. The frequency of the cw light can be monitored using a confocal etalon and an iodine

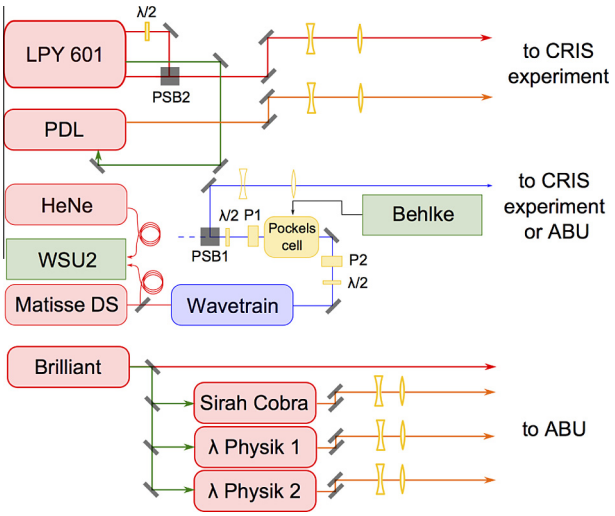

Fig. 2. Schematic layout of the CRIS laser laboratory for high-resolution laser spectroscopy. The cw laser light is chopped by a Pockels cell biased with a high-voltage switch and a polarization-dependent beam splitter to provide high-resolution light synchronised with the 200 Hz Nd:YAG laser and the ion beam delivery. A Brilliant pump laser can be used to pump three PDL lasers that can be used for tests in the ABU.

absorption cell, and is continually measured using a Highfinesse WSU2 wavemeter. The polarization of the light is manipulated via a Pockels cell controled by a fast Behlke high-voltage switch, and then passed through a polarization-dependent beam splitter to chop the cw beam into light pulses down to 50 ns width. The laser laboratory also contains a 10 Hz Quantel Brilliant Nd:YAG laser. The light from this laser can be doubled, tripled or quadrupled. The doubled light can be used to pump a Sirah Cobra pulsed dye laser or two Lambda Physik pulsed dye lasers (under commissioning). Light from these lasers can be sent into an atomic beam unit (ABU) used for ionisation scheme development. This atomic beam unit consists of an effusive atom source and allows for resonance ionisation tests in a perpendicular geometry. The cw laser light can also be sent to the ISOLDE hall, where it can be coupled into the CRIS experiment. The laser table in the ISOLDE hall also features a Litron LPY-601 dual pulsed Nd:YAG laser, providing 1064 nm and 532 nm at either 100 Hz or 200 Hz. This laser light can be used for the ionisation step as well as to pump a pulsed dye laser.

For the most recent francium campaign, a Matisse TS (on loan from the COLLAPS collaboration during the construction of the new laser laboratory) was frequency doubled and chopped using

the Pockels cell. The Litron LPY-601 delivered 1064 nm for the ionisation step.

2.4. The CRIS data acquisition systems

The CRIS experiment has two data acquisition systems: one for the control and monitoring of the laser systems and counting of MCP events, and one for the DSS.

The first system, called CRISTAL (CRIS laser Tuning, Acquisition and Logging) aggregates data from and sends instructions to several computers via TCP/IP. In this way, data from two wavemeters (a WSU2 and a WSU6) and two National Instruments USB-6211 cards (monitoring e.g. photodiodes and counting MCP events) can be combined into a final dataset, which can be visualised during the acquisition. CRISTAL simultaneously updates a LabVIEW Shared Variable which is used by the Matisse Commander software to scan the laser frequency. The CRISTAL software can also update LabVIEW Shared Variables to control and monitor the RILIS narrowband Ti:Sa pulsed laser system [14]. In addition, the software keeps an automatic logbook, which is supplemented by the users to provide an accurate description of the progress of the experiment. All the source code for CRISTAL is open source and written in Python [15].

The second system is an 8-channel digital CAEN V1724 acquisition module equipped with on-board digital pulse processing algorithms developed in partnership with the Daresbury Laboratory. The data acquisition software is based on MIDAS (Multi Instance Data Acquisition System) [16] and records the data event by event, from which correlations in time or between detectors can be reconstructed offline.

3. Recent achievements of the CRIS experiment

In 2014, an experimental campaign on the francium isotopes was performed using the ionisation scheme shown in Fig. 3. Key achievements of this campaign include high-resolution laser spectroscopy of ^{206}Fr and ^{219}Fr [17] and laser spectroscopy of the shortest-lived isotope studied online by laser spectroscopy, ^{214}Fr ($T_{1/2} = 5.0(2)$ ms [18]).

3.1. High-resolution laser spectroscopy of ^{219}Fr

Using the cw chopped laser light a resolution of 20(1) MHz FWHM has been reached in the study of the hyperfine structure of the francium isotopes [17]. A comparison between the pulsed-laser-based data [1,6–8] and the high-resolution data is shown in Fig. 4. This high resolution allows extraction of quadrupole moments and spins from the hyperfine structure, and provides for a greater selectivity in the production of pure ground-state or isomeric beams. Details of the impact of the laser power and synchronisation on the linewidth of the resonance are discussed in Ref. [17].

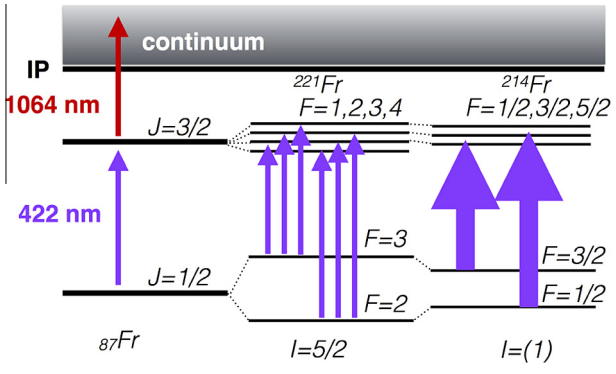

Fig. 3. Resonance ionisation scheme for francium. A resonant step at 422 nm is followed by a non-resonant step at 1064 nm through the ionisation potential (IP) into the ionisation continuum. The hyperfine structure for ^{221}Fr and ^{214}Fr are shown (not to scale). The arrows represent the observed peaks in the spectrum: 6 separated peaks in the high-resolution study of ^{221}Fr; 2 peaks, corresponding to unresolved multiplets, for the low-resolution study of ^{214}Fr.

3.2. Laser spectroscopy of short-lived isotopes: ^{214}Fr

The new Litron LPY-601 laser system has increased the CRIS duty cycle from 30 Hz in 2012 to 200 Hz in the 2014 campaign. This corresponds to a cooling and bunching period of 5 ms, from which decay losses from short-lived isotopes can be minimised. Using the RILIS laser in the low-resolution CRIS mode, the hyperfine structure of the ground state of ^{214}Fr ($T_{1/2} = 5.0(2)$ ms [18]) was successfully scanned (see Fig 5) and was identified at the DSS. This represents the laser spectroscopy study of the shortest-lived isotope produced online at a radioactive ion beam facility.

4. Conclusions

Through continuous developments of the CRIS experiment, high-efficiency, high-resolution laser spectroscopy has been achieved on the francium isotopes. The use of a Pockels cell with a cw laser has allowed the high-resolution study of ^{219}Fr to extract quadrupole moments, and the high-repetition rate of the new final-step laser, the study of the short-lived ^{214}Fr isotope ($T_{1/2} = 5.0(2)$ ms). New data acquisition systems have also allowed the integration of all the features of the CRIS beam line into complete data streams for laser spectroscopy and decay spectroscopy. These developments will enable the study of new cases in the upcoming campaigns, such as the neutron-rich $_{29}$Cu and $_{31}$Ga isotopes in the vicinity of the $N = 50$ shell closure.

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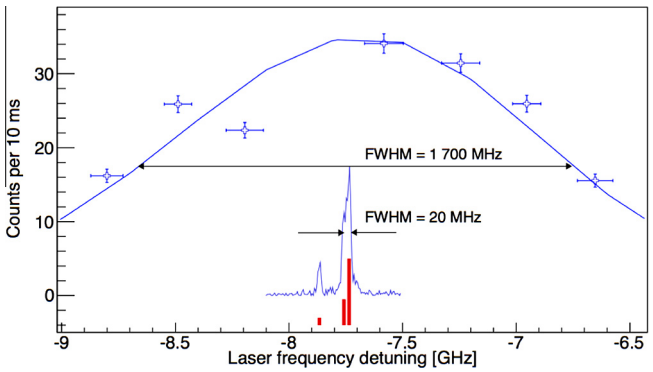

Fig. 4. Part of the hyperfine structure of ^{221}Fr starting from the $F = 3$ hyperfine level from the 2014 campaign using the low-resolution (RILIS laser, FWHM 1.7 GHz) and high-resolution (chopped cw, FWHM 20 MHz) modes. The red bars show the hyperfine components and their theoretical relative intensities.

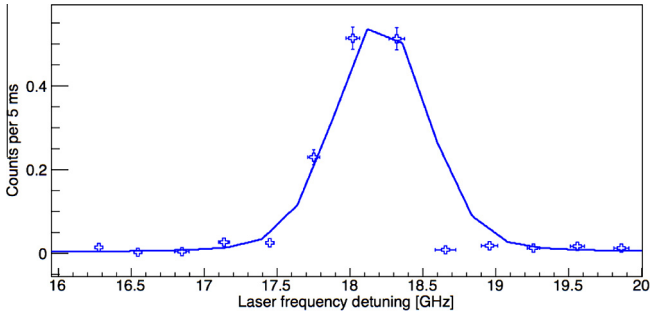

Fig. 5. Part of the hyperfine structure of ^{214}Fr starting from the $F = 1/2$ hyperfine level from the 2014 campaign using the low-resolution (RILIS laser, FWHM 1.7 GHz).

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