EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Status Report to the ISOLDE and Neutron Time-of-Flight Committee

Status report for the CRIS collaboration

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Abstract: This status report presents a summary of the achievements and activity undertaken by the CRIS collaboration during the Run 2 period at CERN. There are outstanding shifts for the I171 letter of intent. This report will present an update on the physics motivation and current relevance as well as technical feasibility of the project with respect to advances made during Run 2.

Requested shifts: 7 shifts of radioactive beam and 6 shifts of stable beam.

1 Summary of activity during Run 2

During the Run 2 period at CERN (2014-2018) the CRIS experiment completed 8 experiments. A summary of the measurements and publications associated with each closed experiment is presented in Table 1. All experiments with remaining shifts will be closed. New proposals for experiments during Run 3 will be prepared and submitted to the next INTC meeting. We will also close the letter of intent I145: Preparation for the study of the transitional nucleus 191Po with high-resolution spectroscopy at CRIS. The experiments listed in Table 1 have contributed to the thesis work of 7 PhD students and 4 masters students, who have now successfully completed their studies. The CRIS collaboration currently has 5 PhD students and 1 masters student analysing data collected in 2018 and working on new technical developments.

Table 1: Summary of activity for experiments completed during Run 2.

Experiment Number	Isotopes	Papers Published or Submitted	PhD Students	References
IS471	$^{202-207,211,214,218-221,229,231}$Fr	7	5	[1, 2, 3, 4, 5, 6, 7]
IS531	$^{64,66,68-78}$Cu	2	1	[8, 9]
IS571	$^{65,67,75,79-82}$Ga	1	1	[10]
IS594	$^{222-233}$Ra	1	1	[11]
IS613	$^{104-111,113}$Sn		1	
IS620	$^{38-47,50-52}$K	1	1	[12]
IS639	$^{101-131}$In	2	3	[13, 14]
IS657	$^{223-226,228}$RaF	1	2	[15]

1.1 Technical Developments

The range of experiments undertaken during the last 5 years have required investment that addressed various technical challenges. These developments have been published in 13 technical papers and proceedings [16, 17, 18, 19, 20, 21, 22, 13, 23, 24, 25, 26, 27]. The construction of building 508 was completed in 2015 providing a new laser laboratory and control room. This laboratory was commissioned in 2015 and new laser systems were installed in the first half of that year. The new building and laser laboratory have made a significant difference in the long term stability and operation performance of the high resolution laser systems. During the Run 2 period the CRIS experiment has acheived several milestones. This included the introduction of high resolution methods such as optical chopping [4, 17, 25] and the installation of an injection seeded TiSa [8, 25]. This has ultimately allowed the CRIS experiment to reach a precision of less than 1 MHz for isotope shift measurements, which has enabled the charge radii of the potassium isotopes to be extended to $N = 32$ [12]. In the period of 2015-2019 the CRIS collaboration has steadily developed and expanded the suite of lasers used for the experiments. The CRIS experiment now has 19 lasers including broadband pulsed dye Ti:Sa lasers as well as new CW

lasers, injection seeded, 10 kHz DPPS pump laser and laser stabilization systems, providing a spectral range from 210-900 nm. This has enabled multistep RIS schemes to be utilized.
The CRIS beam line has been further modified during Run 2 to maximize its capability and capacity. A significant source of background in the CRIS experiment is associated with collisional background which demands the lowest possible pressure to be reached [23]. This has motivated significant investment in the vacuum system to allow the interaction region to reach 10^{-10} mbar. This included the development of a UHV compatible charge exchange cell, additional differential pumping and a new NEG pumping system. During 2019 a new field ionization unit was tested to further reduce the background associated with collisional and photoionization. The field ionization unit reduces the length of the interaction region from 1.2 m to less than 1 cm, which reduces the collisional ionization rate proportionately. We have replaced MCPs with MagneToF detectors that provide a significantly larger dynamic range and higher damage threshold. These detectors can also be used as a Faraday cup when operated at a low gain, which has further improved the beam transport efficiency and beam diagnostic capability of the experiment. We have further modified the decay spectroscopy station [28] by introducing a beta-decay detection counting, which was critical to measure ^{52}K with laser spectroscopy.

1.2 Scientific Highlights

The technical developments highlighted in the previous section have enabled key cases to be measured. The ground state spins and magnetic moments of the K-isotopes have been measured up to $N = 33$, crossing for the first time the proposed new $N = 32$ magic number (paper is in preparation). We have extended the studies on the $Z = 29$ Cu isotopes up to $N = 49$ (^{78}Cu). The spins and moments of ^{76,77,78}Cu reproduced well with LSSM calculations, establish clearly the doubly magic nature of ^{78}Ni [8]. The radii have been compared to different *ab-initio* nuclear theories, that describe binding energies and radii in a quantitative way with nucleon-nucleon interactions derived from from chiral EFT, and fitted to observables of isotopes of up to A=4 only. These theories succeed for the first time to reproduce and understand the small odd-even staggering from a microscopy point of view [9]. Laser spectroscopy on isotopes just a few nucleons away from the exotic self-conjugate and proposed doubly-magic ^{100}Sn, have been performed for the first time. Tin and indium isotopes have been studied in two atomic transitions. One transition is mostly sensitive to the nuclear magnetic moment, while the other one is more sensitive to their quadrupole moment. The charge radii of isotopes and isomers have been measured across the indium isotope chain from $N = 51$ to $N = 82$. The extraction of the moments and charge radii from the laser spectroscopy of indium has been achieved through collaboration with an atomic theorist [13, 14]. The theoretical interpretation of the measured moments and charge radii for both tin and indium will build on the success of the copper work and are currently ongoing. In collaboration with theorists from quantum chemistry and with support from different groups at ISOLDE, the CRIS collaboration measured the low-lying structure of several radium fluo-ride (RaF) molecules [15]. To our knowledge, this is the first ever laser spectroscopy measurement of a short-lived radioactive molecule. These achievements constitute a major step towards the use of radioactive molecule for nuclear structure, electroweak physics, and the study of fundamental symmetries.

1.3 Outlook

The CRIS collaboration will prepare new proposals for experiments in Run 3. With the improved sensitivity of the experiment we aim to extend measurements in the calcium, nickel and tin regions of the nuclear chart. We have now demonstrated the ability to perform high resolution spectroscopy on radioactive molecules at ISOLDE, opening a variety of new physics cases that will be considered during Run 3.

2 Status report for I171

This letter of intent, I171 [29], was submitted in a joint effort with the COLLAPS collaboration. The physics motivation for studying the exotic fluorine isotopes with laser spectroscopy outlined in the LoI remains compelling and relevant for the study of many-body quantum physics. Recent developments in quantum Monte Carlo methods have allowed extension of N-body calculations to nuclei in the vicinity of oxygen isotopes [30], further highlighting the interest in this region of the nuclear chart. Quantum Monte Carlo calculations of the ground-state electromagnetic properties of fluorine isotopes are underway [31].
The fluorine isotope chain with a single valence proton beyond the $Z = 8$ shell closure represents a critical testing point for a variety of nuclear theoretical approaches. This letter of intent aims to establish the optimum laser spectroscopy technique to measure the change in mean-square-charge radii, electromagnetic moments and spins of the fluorine isotope chain. In particular, the isotopes ^{17,23,25}F which are described as having one proton outside a double magic core are particularly suitable to *ab initio* calculations using different many-body methods. Recent developments in computational statistics analyses (subspace-projected coupled-cluster method) in ^{16}O have illustrated the particular sensitivity of nuclear charge radii to constrain the low energy constants of inter-nucleon interactions derived from chiral EFT [32]. Nuclear charge radii measurements across the fluorine isotope chain will provide important and complementary guidance in these studies.
The experimental questions presented in the original LoI [29] must still be addressed before a full experimental proposal can be submitted. The production yield of fluorine isotopes other than ^{17}F remains to be measured with the PSB. In addition to the yield the composition of the beam from the ion source and isobaric contamination must be measured. Both positive and negative ions should be considered. This requires on-line beam time. The efficiency of producing a bunched beam of fluorine with ISCOOL must also be tested. The performance of ISCOOL will be effected by chemistry associated with fluorine and the isobaric contamination levels.
In order to assess the most sensitive transition for both charge radii studies and moment measurements it is critically important that a variety of transitions are measured in ^{17,18,19}F at this stage. As fluorine has only one stable isotope, the sensitivity of a transition for measuring changes in nuclear charge radii requires at least two additional isotopes. The three work plans (outlined in [29]) will be followed to chose the most suitable laser spectroscopy technique and transitions for studying fluorine.
Summary of requested shifts: 7 shifts of radioactive beams and 6 shifts of stable beams were required.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: (*name the fixed-ISOLDE installations, as well as flexible elements of the experiment*)

Part of the	Availability	Design and manufacturing
CRIS	☒ Existing	☒ To be used without any modification
[Part 1 of experiment/ equipment]	☐ Existing	☐ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
[Part 2 of experiment/ equipment]	☐ Existing	☐ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
[insert lines if needed]		

HAZARDS GENERATED BY THE EXPERIMENT (if using fixed installation:) Hazards named in the document relevant for the fixed CRIS installation.

Additional hazards:

Hazards	[Part 1 of experiment/ equipment]	[Part 2 of experiment/ equipment]	[Part 3 of experiment/ equipment]
Thermodynamic and fluidic			
Pressure	[pressure][Bar], [volume][l]		
Vacuum			
Temperature	[temperature] [K]		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid	[fluid], [pressure][Bar], [volume][l]		
Electrical and electromagnetic			
Electricity	[voltage] [V], [current][A]		
Static electricity			
Magnetic field	[magnetic field] [T]		
Batteries	☐		
Capacitors	☐		

Ionizing radiation			
Target material [material]			
Beam particle type (e, p, ions, etc)			
Beam intensity			
Beam energy			
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☐		
• Open source	☐		
• Sealed source	☐ [ISO standard]		
• Isotope			
• Activity			
Use of activated material:			
• Description	☐		
• Dose rate on contact and in 10 cm distance	[dose][mSV]		
• Isotope			
• Activity			
Non-ionizing radiation			
Laser			
UV light			
Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300 MHz)			
Chemical			
Toxic	[chemical agent], [quantity]		
Harmful	[chem. agent], [quant.]		
CMR (carcinogens, mutagens and substances toxic to reproduction)	[chem. agent], [quant.]		
Corrosive	[chem. agent], [quant.]		
Irritant	[chem. agent], [quant.]		
Flammable	[chem. agent], [quant.]		
Oxidizing	[chem. agent], [quant.]		
Explosiveness	[chem. agent], [quant.]		
Asphyxiant	[chem. agent], [quant.]		
Dangerous for the environment	[chem. agent], [quant.]		
Mechanical			

Physical impact or mechanical energy (moving parts)	[location]		
Mechanical properties (Sharp, rough, slippery)	[location]		
Vibration	[location]		
Vehicles and Means of Transport	[location]		
Noise			
Frequency	[frequency],[Hz]		
Intensity			
Physical			
Confined spaces	[location]		
High workplaces	[location]		
Access to high workplaces	[location]		
Obstructions in passageways	[location]		
Manual handling	[location]		
Poor ergonomics	[location]		

Hazard identification:

Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): [make a rough estimate of the total power consumption of the additional equipment used in the experiment]