EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee

Towards laser spectroscopy of exotic fluorine isotopes

June 1, 2016

R.F. Garcia Ruiz[1], C.L. Binnersley[1], J. Billowes[1], M.L. Bissell[1], K. Blaum[2], T.E. Cocolios[3], T. Day Goodacre[1], R.P. de Groote[3], G.J. Farooq-Smith[3], K.T. Flanagan[1], S. Franchoo[4], W. Geithner[5], W. Gins[3], H. Heylen[3], A. Koszorús[3], M. Kowalska[6], J. Krämer[7], K.M. Lynch[8], S. Malbrunot-Ettenauer[8], B.A. Marsh[9], G. Neyens[3], R. Neugart[2,10], W. Nörtershäuser[7], S. Rothe[1], R. Sánchez[5], H.H. Stroke[11], A.R. Vernon[1], K.D.A. Wendt[12], S.G. Wilkins[1], Z. Xu[3], X.F. Yang[3], D.T. Yordanov[4]

[1]*School of Physics and Astronomy, The University of Manchester, Manchester, M13 9PL, UK*
[2]*Max-Planck-Institut für Kernphysik, D-69117 Heidelberg, Germany*
[3]*KU Leuven, Instituut voor Kern- en Stralingsfysica, B-3001 Leuven, Belgium*
[4]*Institut de Physique Nucleaire Orsay, IN2P3/CNRS, 91405 Orsay Cedex, France*
[5]*GSI Helmholtzzentrum für Schwerionenforschung GmbH, D-64291 Darmstadt, Germany*
[6]*Experimental Physics Department, CERN, CH-1211 Geneva 23, Switzerland*
[7]*Technische Universität Darmstadt, 64289 Darmstadt, Germany*
[8]*Physics Department, CERN, CH-1211 Geneva 23, Switzerland*
[9]*Engineering Department, CERN, CH-1211 Geneva 23, Switzerland*
[10]*Institut für Kernchemie, Universität Mainz, D-55128 Mainz, Germany*
[11]*Department of Physics, New York University, New York, New York 10003, USA*
[12]*Institut für Physik, Johannes Gutenberg-Universität, D-55128 Mainz, Germany*

Spokesperson:[Ronald F. Garcia Ruiz] [ronald.fernando.garcia.ruiz@cern.ch]
Contact persons:[Ronald F. Garcia Ruiz] [ronald.fernando.garcia.ruiz@cern.ch]
[Xiaofei Yang][xiaofei.yang@cern.ch]
[Kara M. Lynch] [kara.marie.lynch@cern.ch]

CERN-INTC-2016-037 / INTC-I-171
01/06/2016

Abstract: We propose to study the ground-state properties of fluorine isotopes through collinear laser spectroscopy. Electromagnetic properties of nuclei in the vicinity of oxygen isotopes are important to understand the emergence of shell structures, the role of many-body currents and the inclusion of the continuum effects in the nuclear many-body problem. With the aim of identifying the most suitable way to study these isotopes, the current letter of intent aims to answer technical questions regarding the production of exotic fluorine isotopes, their availability as positive (or negative) ions and the efficiency of bunching such highly reactive elements.

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

1 Motivation

Light nuclear systems are of great relevance for the study of many-body quantum physics. The emergence of shell-structures, the clustering of nucleons, and the formation of nuclear halos are just a few stunning examples that illustrate the richness and uniqueness of the nuclear few-body problem [1]. The long-standing challenge for nuclear theory has been to find a unified and consistent description for such variety of physical phenomena. On the grounds of the development of high precision inter-nucleon potentials [2, 3], the advances of many-body methods [4, 5, 6] and high computing power [7], nuclear ground-state properties of light nuclei can now be described with a high degree of accuracy. *Ab initio* methods have allowed quasi-exact calculations of properties of nuclei in the neighborhood of carbon and oxygen isotopes to be performed [8, 9, 10, 11]. Unfortunately, such nuclei which are now accessible by a diverse range of many-body methods, are particularly challenging for laser spectroscopy. Two technical barriers hinder the extension of laser spectroscopy studies on these nuclei: **i. Atomic or ionic transitions from the ground state lie mainly in the extreme ultra-violet (EUV) region that is not accessible by conventional lasers**, and **ii) they exists mainly as molecular compounds** (e.g. F_2, AlF, O_2, N_2, CO, CO_2).

The main focus of this letter is to develop a strategy to perform laser spectroscopy studies on radioactive fluorine isotopes, giving access to unknown nuclear ground-state spins and electromagnetic properties.
With $Z = 9$ protons, the fluorine isotopic chain allows for the exploration of unique features of the nuclear few-body problem. Within the shell model picture, **the ^{17}F, ^{23}F and ^{25}F isotopes can be used to investigate the behavior of a single proton around three "doubly-magic" cores**: ^{16}O($N = 8$), ^{22}O($N = 14$), ^{24}O($N = 16$). Furthermore, **the self-conjugate nucleus ^{18}F($Z = N = 9$), and the isotopes ^{24}F and ^{26}F can be used as sensitive probes to the proton-neutron interactions** [12, 13, 14], having a single proton in the $d_{5/2}$ orbit, and a single neutron in the $d_{5/2}$, $s_{1/2}$ and $d_{3/2}$ orbits, respectively.

The binding energy and low-lying excited states of light nuclei have been well reproduced by *ab-initio* and conventional configuration interaction (CI) methods [15]. Three-body forces have been proven to play a crucial role in the description of neutron-rich oxygen [16] and fluorine isotopes [12, 15, 17]. These were shown to be an essential ingredient to explain the so-called "oxygen anomaly" [16], which locates the oxygen neutron drip line around ^{24}O [18], while adding a single proton extends the neutron drip line of fluorine isotopes up to ^{31}F [19]. **Work is in progress to include the contribution of many-body currents [5, 20] and continuum effects on the nuclear Hamiltonian [21, 22], which are expected to be important to describe properties of weakly bound systems such as fluorine exotic isotopes [12, 17]**.
Many-body currents (e.g. two-body meson exchange currents, MEC) arise naturally from chiral effective field theory, and are essential to provide a consistent description of the nuclear dynamics and to understand the microscopic origin of the effective operators commonly used in nuclear physics (e.g. effective charges, effective g-factors) [20, 5, 23]. Quantum Monte Carlo calculations demonstrated that two-body MEC contributions produce large corrections to the ground-state electromagnetic properties of light nuclei (i.e. magnetic moment, quadrupole moment and charge radii) [5, 20]. Recently, such studies have been extended to heavier systems, where it has been shown that contributions from two-body currents are necessary to explain the relatively large half-life of ^{14}C as well as the quenching of the Gamow-Teller transition in

Table 1: Literature values for the ground-state properties of fluorine isotopes [30].

Nuclei	$T_{1/2}$	I^π	Yield (ions/μC)	μ[nm]	Q[b]	$< r^2 >^{1/2}$[fm]
^{17}F	64 s	$5/2^+$	1.1 x $10^{5\star}$	+4.7213(3)	0.076(4)	
^{18}F	110 m	1^+	1.8 x 10^{7*}			
^{19}F	stable	1/2		+2.628868(8)		2.855(15)
^{20}F	11 s	2^+	9.7 x 10^{6*}	+2.09335(9)	0.056(4)	
^{21}F	4 s	$5/2^+$	9.4 x 10^{5*}	3.9194(12)	0.11(2)	
^{22}F	4 s	(4^+)	3.1 x 10^{4*}	(+)2.6944(4)	0.003(2)	
^{23}F	2 s	$5/2^+$	1.6 x 10^{3*}			
^{24}F	400 ms	$(1,2,3,4)^+$				
^{25}F	80 ms	$5/2^+$				
^{26}F	9.7 ms	(1^+)				

* Yields available for PSB. * Yields available for SC

^{22,24}O [23]. Moreover, consistent currents and inter-nucleon interactions were used to provide predictions for the ground-state spins of neutron-rich fluorine isotopes [23].

The known ground-state properties of fluorine isotopes are shown in Table 1. The magnetic moments and quadrupole moments of several isotopes have been measured by using the β-NMR technique. The relatively long half-life of the self-conjugate nucleus ^{18}F makes it inaccessible to β-NMR, and ground-state electromagnetic properties and spins are unknown beyond ^{22}F.
The charge radius is known only for the stable ^{19}F. The experimental knowledge for the evolution of nuclear sizes in the region of oxygen isotopes is a rather unexplored area. However, significant progress on the theory side has been made during the last few years on this matter [17]. **The description of charge radii has been a particular challenge for nuclear theory [17, 24], providing an important test for the development of inter-nucleon interactions and** *ab initio* **calculations [17, 25, 26]**. Of notable interest would be the measurement of the size of the charge distribution for the **proton halo nucleus ^{17}F**. This nucleus has been subject of numerous studies (see for example [27]), as there is evidence for the existence of a proton halo in an excited state[1] [28], and in addition this nucleus is of relevance for astrophysics studies [29].

2 Experimental details

The ground-state properties will be obtained from measurements of the hyperfine structure (hfs) and isotope shifts on the F I atomic system by using collinear laser spectroscopy. Three main questions need to be answered to choose the best strategy for the study of F isotopes.

1. What is the production yield of neutron-rich F^+ isotopes?
   → Only the yield of ^{17}F is known at the PSB, see Table 1.

2. Can bunches of F^+ ions be produced efficiently?
   → High bunching efficiency of F^+ is a necessary condition to efficiently perform standard collinear laser spectroscopy for both resonance ionization and optical detection.

[1]The short-lived excited state (∼286 ps) can not be accessed by laser spectroscopy.

3. Are yields considerably higher for F^- ions?
   → As fluorine is found preferably as a negative ion, a considerable increase of the yields could be observed [31]. It would also be important to measure the bunching efficiency for negative ions.

These measurements will clarify the feasibility of the proposed studies and will define the main route to study the exotic fluorine isotopes. **As one of the main physics motivations is the determination of the charge radii, it is important to estimate the electronic field and mass isotope shift factors. Therefore, we ask for 7 shifts to measure the hyperfine structure and isotope shifts of ^{17,18,19}F by using different atomic transitions and by employing complementary techniques.** Below we give a short description of the methodology planned to explore these questions.

Bunched collinear laser spectroscopy from F^+ ions. (Working plan I)

The HRS separator will be used in combination with the cooler-buncher ISCOOL. As fluorine is a highly reactive element, it is important to quantify the bunching efficiency for these ions.
Bunches of singly-ionized F^+ (F II) can be redirected into the COLLAPS or CRIS beam line to perform laser spectroscopy experiments. As the transitions from the ground state of the ion and atomic states lie in the EUV range (< 90 nm), it can not be accessed with conventional lasers. However, it has been shown that a meta-stable state of the atomic state (F I) can be populated by passing the F II beam through a Na vapor cell [32].
The low-lying atomic energy levels of F I are shown in Figure 1. With a lifetime of 7.3(5)μs [33] the meta-stable state 3s $^4P_{5/2}$ at 102405.7 cm$^-$1 provides access to several resonant transitions. Previously, laser spectroscopy studies were performed for the stable ^{19}F by using the 686 nm and 677 nm lines [32]. Such an experiment can be performed at the COLLAPS beam line by using fluorescence detection.
Several ionization paths are also accessible from the mestastable state, as shown in Figure 1. Therefore, collinear resonance ionization is a possible route to explore the neutron-rich fluorine isotopes. At CRIS, the atoms overlap with a laser beam in a collinear geometry along a UHV interaction region (1.2 m) to step-wise excite and ionize the atomic state F I into a F II state. The resonantly-ionized ions are then separated from the non-interacting atoms via electrostatic deflector plates, and finally detected by an MCP particle detector.

Collinear laser spectroscopy on continuous F^+ ion beams (Working plan II)

If considerable ion-beam losses are observed in the cooler-buncher, it would be necessary to use a continuous ion beam. The large background associated with continuous beams does not allow optical detection techniques to be used, and the duty-cycle losses due to the use of pulsed laser will prevent the use of collinear resonance ionization. However, state-selective collisional ionization of fast atomic beams [34, 35, 36] would be a highly sensitive technique applicable to fluorine isotopes. A sketch of the experimental technique is shown in Figure 2. For a beam of F^+ passing through a Na vapor cell at 40 keV, it has been shown that about 25% of the incoming beam can be neutralized following the reaction channel [32]

$$F^+ + Na \rightarrow F^*(3s\ ^4P_{5/2}) + Na^+. \quad (1)$$

The meta-stable state 3s $^4P_{5/2}$ can be resonantly depopulated, e.g, via the 677.4 nm line (3s $^4P_{5/2} \rightarrow$ 3p $^4D^0_{5/2}$), which decays mainly to the ground states $^2P^0_J$ following the decay

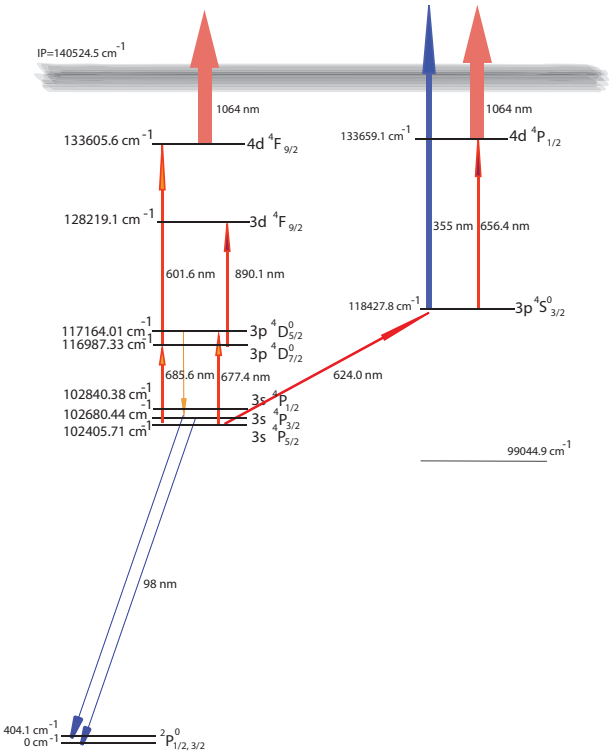

Figure 1: Energy-level diagram for F I.

path $3p\ ^4D^0_{5/2} \rightarrow 3s\ ^4P_{3/2} \rightarrow\ ^2P^0_J$ (Figure 1). The atoms that are resonantly excited by the laser light will be transferred to the ground-state and then directed into the re-ionization cell (Figure 2). The large energy difference between the meta-stable states and the ground states gives a large difference in the re-ionization cross section. If the laser is not in resonance with the atomic beam, the atom remains in the meta-stable state and can be easily re-ionized. Therefore, the resonant laser-ion interaction is translated into a resonant (reduction) on the ion (atom) counting. A re-ionization atom efficiency of about 45% has been reported for fluorine atoms in a hellium cell at 40 keV [32].

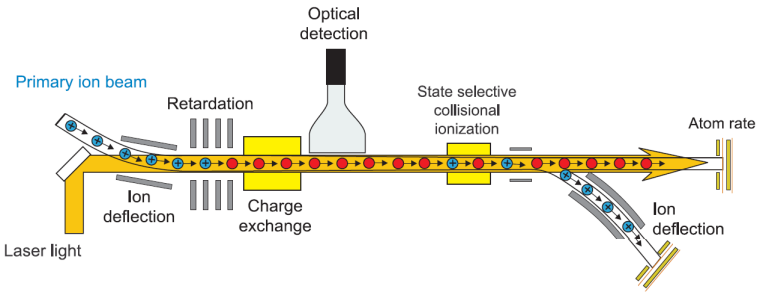

Figure 2: Sketch of the experimental setup used for state-selective resonance ionization. Figure modified from Ref. [36].

Collinear laser spectroscopy from F^- ion beams? (Working plan III)

As the most electronegative element, fluorine is highly reactive and tends to capture an electron to fill outer atomic shell (L). Hence, fluor's extraction as a negative ion could enhance the yields for neutron rich-isotopes, with the additional advantage of being extracted as a pure ion beam [31]. Electron detachment of F^- by collisions with He and Ne gases has been studied at ion beam energies up to 8 keV, with detachment cross sections for the reactions

$$F^- + He \rightarrow \begin{cases} F^* + He + e, \\ F + He^* + e, \end{cases} \tag{2}$$

$$F^- + Ne \rightarrow \begin{cases} F^* + Ne + e, \\ F + Ne^* + e, \end{cases} \tag{3}$$

of the order of 10^{-16}-10^{-15} cm^2 [37]. A fraction of the population into excited states of F^* is expected to populate the meta-stable state $F^*(3s\ ^4P_{5/2})$, from which laser spectroscopy can be performed. To our knowledge, such studies have not been reported at ion beam energies of 30-40 keV. Therefore, if the yield of negative ions proves to be considerably higher than for F^+, studies of electron dectachment of F^- will be motivated to quantify the percentage of population into the meta-stable state. This could be a highly sensitive route to study very neutron-rich F isotopes.

3 Beam-time request

The details of the required shifts for this letter of intent are summarized in Table 2. Only the production yield of ^{17}F has been reported at the PSB (1.1x10^5 ions/s) using a SiC target. Due to the relatively long half-life of ^{18}F ($\sim$110 m) a yield higher than 10^5 ions/s is expected for this isotope. Therefore, at this stage the physics cases towards the proton-drip line (^{17}F and ^{18}F) can be addressed. These measurements will provide the magnetic and quadrupole moments of ^{18}F, and the change in the rms charge radii for ^{17,18,19}F. As fluorine has only one stable isotope, measurements with radioactive isotopes are needed to test the sensitivity of the isotope shifts for different atomic transitions.
Both neutron-deficient and neutron-rich F isotopes can be produced with a SiC target, but the existing yield data for neutron-rich is only available for the SC. Yield measurements are required for neutron-rich isotopes $^{20-25}$F.
Summary of requested shifts: 7 shifts of radioactive beams and 6 shifts of stable beams are required.

References

[1] Lu, Z.-T. *et al. Colloquium* : Laser probing of neutron-rich nuclei in light atoms. *Rev. Mod. Phys.* **85**, 1383–1400 (2013).

[2] Epelbaum, E., Hammer, H.-W. & Meißner, U.-G. Modern theory of nuclear forces. *Rev. Mod. Phys.* **81**, 1773–1825 (2009).

[3] Hammer, H.-W., Nogga, A. & Schwenk, A. Three-body forces: From cold atoms to nuclei. *Rev. Mod. Phys.* **85**, 197 (2013).

Table 2: Technical questions that are expected to be answered for the study of fluorine isotopes. The number of shifts required is shown in the last column. * In brackets the number of shifts required for stable beams. Work would be shared between COLLAPS and CRIS to find the most appropriate solution.

Working plan	Physics case /technical questions	Shifts
I	Yield measurements of F^+ exotic isotopes	—
I	ISCOOL bunching efficiency of F^+	—
I	Charge radii and gs moments of ^{18}F (N=Z=9)	
	$->$ Probe of sensitivity for different atomic transitions	3
I	Charge radius of the proton halo nucleus ^{17}F	2
I	Study of isotope shifts for ^{17,18,19}F by collinear resonance ionization	
	$->$ Probe of ionization schemes and study of systematic errors	
	$->$ Test of sensitivity of resonance ionization	2
II	Hyperfine structure measurements for ^{19}F by	
	state-selective re-ionization with a continuous F^+ beam	
	$->$ Measurements of re-ionization cross sections	(3)*
	$->$ Test of sensitivity for the technique	stable
III	Yield measurements of exotic F^- ions	—
	Measurement electro detachment cross sections	(3)*
	and state-selective re-ionization	stable

[4] Hergert, H., Bogner, S. K., Morris, T. D., Schwenk, A. & Tsukiyama, K. The in-medium similarity renormalization group: A novel ab initio method for nuclei. *Phys. Reports* **621**, 165–222 (2016).

[5] Carlson, J. *et al.* Quantum monte carlo methods for nuclear physics. *Rev. Mod. Phys.* **87**, 1067–1118 (2015).

[6] Somà, V., Barbieri, C. & Duguet, T. *Ab initio* gorkov-green's function calculations of open-shell nuclei. *Phys. Rev. C* **87**, 011303 (2013).

[7] Nazarewicz, W. Challenges in nuclear structure theory. *Journal of Physics G: Nuclear and Particle Physics* **43**, 044002 (2016).

[8] Barrett, B., Navratil, P. & Vary, J. Ab initio no-core shell model. *Prog. Part. Nucl. Phys.* **69**, 0 (2013).

[9] Roth, R. *et al.* Similarity-transformed chiral NN+3N interactions for the ab initio description of ^{12}C and ^{16}O. *Phys. Rev. Lett.* **107**, 072501 (2011).

[10] Lahde, T. *et al.* Lattice effective field theory for medium-mass nuclei. *Phys. Lett. B* **732**, 110 (2014).

[11] Jansen, G. Ab initio coupled-cluster effective interactions for the shell model: Application to neutron-rich oxygen and carbon isotopes. *Phys. Rev. Lett.* **113**, 142502 (2014).

[12] Lepailleur, A. *et al.* Spectroscopy of ^{26}**F** to probe proton-neutron forces close to the drip line. *Phys. Rev. Lett.* **110**, 082502 (2013).

[13] Kanada-En'yo, Y. & Kobayashi, F. Mixing of parity of a nucleon pair at the nuclear surface due to the spin-orbit potential in ^{18}F. *Phys. Rev. C* **90**, 054332 (2014).

[14] Masui, H. & Kimura, M. Deuteron-like neutronproton correlation in 18f studied with the cluster-orbital shell model approach. *Progress of Theoretical and Experimental Physics* **2016** (2016).

[15] Cáceres, L. *et al.* Nuclear structure studies of ^{24}F. *Phys. Rev. C* **92**, 014327 (2015).

[16] Otsuka, T., Suzuki, T., Holt, J. D., Schwenk, A. & Akaishi, Y. Three-body forces and the limit of oxygen isotopes. *Phys. Rev. Lett.* **105**, 032501 (2010).

[17] Ekström, A. *et al.* Accurate nuclear radii and binding energies from a chiral interaction. *Phys. Rev. C* **91**, 051301 (2015).

[18] Langevin, M. *et al.* Production of neutron-rich nuclei at the limits of particles stability by fragmentation of 44 Mev u ^{40}Ar projectiles. *Physics Letters B* **150**, 71 – 74 (1985).

[19] Sakurai, H. *et al.* Evidence for particle stability of ^{31}F and particle instability of ^{25}N and ^{28}O. *Physics Letters B* **448**, 180 – 184 (1999).

[20] Pastore, S. *et al.* Quantum monte carlo calculations of electromagnetic moments and transitions in $A \leq 9$ nuclei with meson-exchange currents derived from chiral effective field theory. *Phys. Rev. C* **87**, 035503 (2013).

[21] Volya, A. & Zelevinsky, V. Discrete and continuum spectra in the unified shell model approach. *Phys. Rev. Lett.* **94**, 052501 (2005).

[22] Hagen, G., Hjorth-Jensen, M., Jansen, G. R., Machleidt, R. & Papenbrock, T. Continuum effects and three-nucleon forces in neutron-rich oxygen isotopes. *Phys. Rev. Lett.* **108**, 242501 (2012).

[23] Ekström, A. *et al.* Effects of three-nucleon forces and two-body currents on gamow-teller strengths. *Phys. Rev. Lett.* **113**, 262504 (2014).

[24] Lapoux, V. *et al.* Radii and binding energies in oxygen isotopes: a puzzle for nuclear forces. *Submitted to Phys. Rev. Lett.* **arXiv:1605.07885** (2016).

[25] Hagen, G. *et al.* Neutron and weak-charge distributions of the ^{48}Ca nucleus. *Nature Physics* **12**, 186 (2016).

[26] Garcia Ruiz, R. F. *et al.* Unexpectedly large charge radii of neutron-rich calcium isotopes. *Nature Physics* **Advance online publication**, doi:10.1038/nphys3645 (2016).

[27] Hagen, G., Papenbrock, T. & Hjorth-Jensen, M. *Ab Initio* computation of the ^{17}**F** proton halo state and resonances in A= 17 nuclei. *Phys. Rev. Lett.* **104**, 182501 (2010).

[28] Morlock, R. *et al.* Halo properties of the first $1/2^+$ state in ^{17}F from the $^{16}\mathrm{O}(p,\gamma)^{17}\mathrm{F}$ reaction. *Phys. Rev. Lett.* **79**, 3837–3840 (1997).

[29] Bardayan, D. W. *et al.* Observation of the astrophysically important 3^+ state in ^{18}Ne via elastic scattering of a radioactive ^{17}F beam from ^{1}H. *Phys. Rev. Lett.* **83**, 45–48 (1999).

[30] Stone, N. J. Table of nuclear magnetic dipole and electric quadrupole moments. *Atomic Data And Nuclear Data Tables* **90**, 75–176 (2005).

[31] Stora, T. *Private communication* (2016).

[32] Levy, C. *et al.* Feasibility study of in-beam polarization of fluorine. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **580**, 1571 – 1577 (2007).

[33] Shimizu, M. *et al.* Lifetime measurement of metastable fluorine atoms using electron cyclotron resonance plasma source. *Journal of Vac. Sci and Techn.* **24**, 2133 (2006).

[34] Neugart, R., Klempt, W. & Wendt, K. Collisional ionization as a sensitive detection scheme in collinear laser-fast-beam spectroscopy. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* **17**, 354 – 359 (1986).

[35] Geithner, W. *et al.* Masses and charge radii of $^{17-22}$Ne and the two-proton-halo candidate ^{17}Ne. *Phys. Rev. Lett.* **101**, 252502 (2008).

[36] Marinova, K. *et al.* Charge radii of neon isotopes across the *sd* neutron shell. *Phys. Rev. C* **84**, 034313 (2011).

[37] Poulsen, J. *et al.* Electron detachment and excitation processes in F^- - He, Ne collisions: electron and optical emissions from excited F^- and F states. *Journal of Physics B: Atomic, Molecular and Optical Physics* **23**, 457 (1990).

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
COLLAPS, 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: no 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]