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

IS471: Collinear resonance ionization spectroscopy of rare francium isotopes

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Abstract: We propose to study the neutron-deficient ($^{201-206}$Fr) and neutron-rich ($^{218,219,229-232}$Fr) francium isotopes with high-resolution collinear resonance ionization spectroscopy. Extraction of the quadrupole moments will provide information on the nature of the deformation in the neutron-deficient nuclei and the octupole deformation suggested in the neutron-rich nuclei. The presence of the decay spectroscopy station will allow identification of any overlapping hyperfine structures. The high sensitivity of the CRIS technique will allow measurement of isotopes with low production yields, towards ^{199}Fr and ^{233}Fr.

Requested shifts: 34 shifts

The present Addendum follows the status report INTC-SR-031.

Motivation, experimental setup and technique

The Collinear Resonance Ionization Spectroscopy (CRIS) experimental beam line is now fully commissioned and in operation [1]. Two successful experimental campaigns last year have resulted in the publication of a Physical Review Letter [2], multiple conference proceedings [3–11] and a technical paper [12]. Collinear resonance ionization spectroscopy was performed on the rare francium isotopes $^{202-206,218m,219,229,231}$Fr [13] and laser assisted nuclear decay spectroscopy performed on ^{202,204,218m}Fr [14], providing data for the theses of three Ph.D. students [15–17]. This represents the first demonstration of isomeric beam separation in a collinear geometry.

The CRIS technique studies the hyperfine structure of nuclei, using laser light to stepwise excite and ionize an atomic beam in a particular nuclear (ground or isomeric) state. Deflection of this selectively ionized beam, from the remaining neutral contaminants, allows ultra-sensitive detection of rare isotopes and nuclear-structure measurements in background-free conditions. Detection of the resonant ions with an MCP allows spins, moments and change in mean-square charge radii to be deduced. Deflection of the ions to the decay spectroscopy station (DSS) allows for identification of the hyperfine components from their characteristic alpha decay with the installed silicon detectors.

The combination of high detection efficiency and ultra-low background available at CRIS provides the unique opportunity to measure the rare francium isotopes, providing information on the nuclear structure in this region of the nuclear chart. This addendum to the IS471 proposal aims to push the limits of the CRIS technique further, measuring the francium isotopes towards ^{199}Fr and ^{233}Fr. In the initial phase of this project, a low-resolution laser system was used which was able to resolve the lower-state (7s $^2S_{1/2}$) splitting, allowing extraction of the magnetic moments and isotope shifts. However, the resolution was not sufficient to measure the quadrupole moment, which requires a laser linewidth of <100 MHz. In 2013, high-resolution tests with chopped CW laser light demonstrated a RIS linewidth of 26(2) MHz, enough to measure the upper-state (8p $^2P_{3/2}$) splitting.

With the physics motivation of the IS471 experimental campaign already endorsed by the INTC [1], the additional measurements of the quadrupole moments will provide important information on the evolution of the nuclear shape in the neutron-deficient francium isotopes towards ^{199}Fr. Furthermore, the study of the neutron-rich francium isotopes (towards the recently-discovered isotope ^{233}Fr) will contribute to the knowledge of this little-known region, and the suggested presence of octupole deformations can be investigated. Finally, the unknown and tentative spin assignments for the francium isotopes measured will be determined, whereby the $1/2^+$ ground state (of ^{229,231}Fr) is the proton-intruder state observed in the neutron-deficient (^{201,203}Fr) isotopes [18, 19].

Addendum

Future plans with available shifts

It is proposed to study the neutron-deficient ($^{201-206}$Fr) and neutron-rich ($^{218,219,229-232}$Fr) francium isotopes with high-resolution collinear resonance ionization spectroscopy. Any overlapping hyperfine structures of low-lying states (present in the neutron-deficient isotopes) will be identified by their radioactive decay with the DSS. This alpha-tagging technique allows the separation of the hyperfine structure of the nuclear states, providing extracted hyperfine factors with better accuracy and reliability.

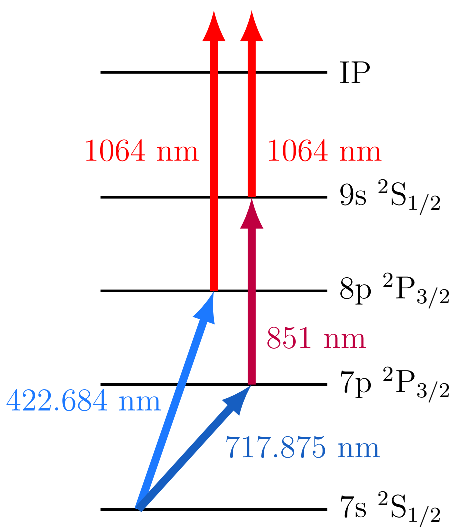

Figure 1: The two possible ionization schemes of francium.

Doppler-free resonant ionization tests were performed in 2013, optimizing the temporal overlap of the excitation and ionization laser pulses with the atomic bunch when the RIS scheme was saturated. These tests achieved a linewidth of 26(2) MHz by delaying the ionization step by 200 ns, suggesting that this resolution is possible on-line. The two resonant ionization schemes for francium are illustrated in Figure 1. The experimental campaign in 2012 utilised the 7s $^2S_{1/2}$ → 8p $^2P_{3/2}$ resonant transition. The hyperfine structure of the 7p $^2P_{3/2}$ state is almost three times larger than that of the 8p $^2P_{3/2}$ state, and would potentially provide higher sensitivity to the quadrupole moment, but requires a three-step process. Further off-line tests with rubidium atoms in early 2014 will be performed to determine the more sensitive ionization process.

Envisaged measurements and requested isotopes

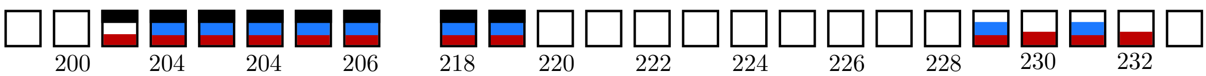

Figure 2: Francium isotopes (black) originally proposed, (blue) measured, and (red) submitted in this addendum to be measured.

Beam time for the high-resolution collinear resonance ionization spectroscopy of the neutron-deficient and neutron-rich francium isotopes is requested. Figure 2 presents the francium isotopes (black) originally proposed, (blue) measured in 2012, and (red) submitted for measurement in this addendum. High-resolution laser spectroscopy will provide the quadrupole moments and determination of the nature of the deformation of the francium isotopes towards ^{199}Fr and ^{233}Fr. Alpha-decay spectroscopy will be performed on pure beams of ground and isomeric states, allowing identification of overlapping hyperfine structures and a more accurate extraction of nuclear observables.

Have these studies been performed in the meantime by another group?

High-resolution collinear laser spectroscopy has been performed on the ground states of $^{204-206}$Fr with fluorescence detection [20]. The experiment was carried out with yields down to 10^4 atoms/s (^{204g}Fr). A re-measurement of the low-lying states of ^{204,206}Fr has also been performed and is currently under analysis. The combination of high-detection efficiency and ultra-low background at CRIS makes it possible to study francium isotopes produced at a rate that is at least 2 orders of magnitude lower than required for fluorescence-based techniques [2]. The presence of the DSS allows the hyperfine-structure resonances to be identified with decay spectroscopy and attributed to the correct isomeric state.

Number of shifts (based on newest yields) required for each isotope

Isotope	Yield (ions/μC)	Target	Ion source	Shifts
^{201}Fr	1	UC_x	Surface	6
^{202}Fr	$1.0 \times 10^{2\dagger}$	UC_x	Surface	3
^{203}Fr	1.0×10^3	UC_x	Surface	6
^{204}Fr		UC_x	Surface	1
^{205}Fr	1.7×10^5	UC_x	Surface	1
^{206}Fr	2.4×10^6	UC_x	Surface	1
^{218}Fr	4.3×10^3	UC_x	Surface	1
^{219}Fr	8.9×10^3	UC_x	Surface	1
^{229}Fr	1.0×10^3	UC_x	Surface	3
^{230}Fr	3.8×10^4	UC_x	Surface	4
^{231}Fr		UC_x	Surface	3
^{232}Fr		UC_x	Surface	4
Total				**34**

Table 1: Requested radioactive beams and shifts to study the spins and moments of the neutron-deficient ($^{200-206}$Fr) and neutron-rich ($^{218,219,229-232}$Fr) francium isotopes. Francium isotope yields from ISOLDE database unless otherwise stated.

A total experimental efficiency of 1% was determined for ^{202}Fr with a yield of 100 atoms/s†. A hyperfine-structure scan of ^{202}Fr was performed at this efficiency, with a background rate of $\sim 2\times10^{-3}$ counts/s. With a frequency step every proton super-cycle (30-40 s) and the quoted efficiency, a scan of ^{201}Fr would take 20 hours (3 shifts). Therefore, a total of 6 shifts each for ^{201}Fr and ^{203}Fr is requested to study their ground ($t_{1/2}$=53 ms and 0.53 s) and isomeric $1/2^+$ states ($t_{1/2}$=19 ms and 43 ms), respectively. With the reproducible yields at ISOLDE (even with an old target), the rare francium isotopes represent a low risk and easy to schedule experiment.

†Independent yield measurement at LA1

References

[1] J. Billowes et al., CERN-INTC-2008-010 INTC-P-240 (Jan 2008), CERN, Geneva

[2] K.T. Flanagan et al., Phys. Rev. Lett. **111**, 212501 (2013)

[3] T.E. Cocolios et al., CERN-INTC-2013-010 INTC-P-375 (2013), CERN, Geneva

[4] K.T. Flanagan, Proceedings from ICFN5 (2013)

[5] K.T. Flanagan, Acta Phys. Pol. B **44**, 95 (2013)

[6] K.M. Lynch, T.E. Cocolios, M.M. Rajabali, Hyperfine Interact. **216**, 95 (2013)

[7] T.J. Procter, K.T. Flanagan, Hyperfine Interact. **216**, 89 (2013)

[8] K.M. Lynch et al., J. Phys.: Conf. Ser. **381**, 012128 (2012)

[9] T.J. Procter et al., J. Phys.: Conf. Ser. **381**, 012070 (2012)

[10] K.T. Flanagan et al., Hyperfine Interact. (2013), (In press)

[11] K.M. Lynch et al., EPJ Web of Conferences (2013), (In press)

[12] M.M. Rajabali et al., Nucl. Instrum. Methods Phys. Res. A **707**, 35 (2013)

[13] I. Budinčević et al. (2014), (In preparation)

[14] K.M. Lynch et al., Phys. Rev. X (2014), (Submitted)

[15] T.J. Procter, Ph.D. thesis, The University of Manchester (2013), https://cds.cern.ch/record/1551521?ln=en

[16] K.M. Lynch, Ph.D. thesis, The University of Manchester (2013), http://cds.cern.ch/record/1606787?ln=en

[17] I. Budinčević, Ph.D. thesis, IKS, KU Leuven (2015)

[18] M. Borge et al., Nuc. Phys. A **539**, 249 (1992)

[19] L. Fraile et al., Nuc. Phys. A **686**, 71 (2001)

[20] A. Voss et al., Phys. Rev. Lett. **111**, 122501 (2013)