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# EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and N-ToF Experiments Committee (INTC)

## Collinear resonant ionization laser spectroscopy of rare francium isotopes.

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*This programme requests in total 33 shifts of radioactive beam, which will be spread over several runs for a period of two years, commencing 2009.*

### Introduction

We propose a programme of collinear resonant ionization spectroscopy (CRIS) of the francium isotopes up to and including $^{201}$Fr and $^{218,219}$Fr. This work aims at answering questions on the ordering of quantum states, and effect of the $(\pi s_{1/2}^{-1})1/2^+$ intruder state, which is currently believed to be the ground state of $^{199}$Fr. This work will also study the edge of the region of reflection asymmetry through measurement of the moments and radii of $^{218,219}$Fr. This proposal forms the first part of a series of experiments that will study nuclei in this region of the nuclear chart. Based on the success of this initial proposal it is the intention of the collaboration to perform high resolution measurements on the isotopes of radium and radon that surround $^{201}$Fr and $^{218}$Fr and thus providing a comprehensive description of the ground state properties of this region of the nuclear chart. Recent in-source spectroscopy measurements of lead, bismuth and polonium have demonstrated an extremely high detection sensitivity, ultimately measuring $^{182}$Pb with a yield of 10 atoms/μC [1]. This technique is limited by the full Doppler broadening of the hot ion source and is therefore unable to resolve the quadrupole moments from the atomic structure of these isotopes. The CRIS method outlined in this proposal, suppresses the associated Doppler broadening and operates with a resolution of more than 1 order of magnitude better than in-source laser spectroscopy. This will allow quadrupole moment measurements and spin assignment to be made on the lead, bismuth and polonium isotope chains. The high resolution associated with CRIS extends its application down to rare isotopes in the A=50 mass region.

CRIS represents a new innovation in laser spectroscopy, which can overcome the low sensitivity of current techniques and allow measurements to be performed on very low ion rates. An early attempt to realize such a scheme was limited by the duty cycle of the pulsed laser and the associated loss in efficiency when working with a continuous ion beam [2]. It is now possible to achieve high detection efficiency (up to 50%), high resolution and an ultra-low background, by performing resonant ionization spectroscopy (RIS) on a fast atomic bunch. The feasibility of this method has been demonstrated off-line at the IGISOL facility in Jyväskylä, with an increase in detection efficiency of nearly 4 orders of magnitude compared to fluorescence-photon detection [3]. This scheme was foreseen in the LoI for the

RFQ cooler (CERN-INTC-2003-028) and is also part of the seventh framework programme. This technique also provides a method to efficiently purify the ion beam for other applications such as decay spectroscopy experiments.

In order to realize this technique at ISOLDE a new semi-permanent beam line will be introduced and a low repetition rate pulsed laser laboratory established. A dedicated laser beam line is essential in order to meet the UHV requirements to perform this experiment. The beam line has been designed and will have a total length of 3.2m with some additional space at the end of the beam line for a $1m^2$ optical bench required for overlapping and launching the laser beams. An enclosed area of approximately $12m^2$ will be required to house the pulsed lasers.

**Physics Motivation**

Considerable attention has been given to the region below Z=82 shell closure and near the N=104 mid-shell, due to the phenomenon of shape-coexistence, first observed in the Hg chain and more recently in $^{186}$Pb, which has a triplet of differently shaped spin-zero states (see Fig. 1 and [4]). The observed phenomena are driven by valence nucleons, which occupy intruder orbitals that polarize the nucleus towards a deformed configuration. This has motivated recent magnetic moment and isotope shift measurements on Pb, Bi and Po. Although extremely sensitive, the in-source RIS method used, did not have the resolution to measure the quadrupole moment [1]. The CRIS method proposed here will be able to measure the quadrupole moments of the isotopes below N=110 and provide a full description of their deformed nature.

Systematic trends of the single particle quantum states in the region above the Z=82 shell closure, show a decrease in excitation energy of the $(\pi i_{13/2})13/2^+$, $(\pi f_{7/2})7/2^+$, $(\nu i_{13/2})13/2^+$and $(\pi s_{1/2}^{-1})1/2^+$ states with decreasing neutron number. It has been shown that the $(\pi s_{1/2}^{-1})1/2^+$ deformed intruder state is in fact the ground state of $^{195}$At and $^{185}$Bi [5,6]. Decay studies of neutron deficient $^{201,203}$Fr also show strong evidence for the presence of a $(\pi s_{1/2}^{-1})1/2^+$ isomeric intruder state [7] (and listed in table 1). The observed systematic trend suggests an inversion in the ground-state at N=112, implying the onset of considerable deformation. This proposal will study the ordering of quantum levels and the evolution of the nuclear shape in the francium isotopes near $^{199}$Fr, by measuring the magnetic and electric moments, spin and charge radius of these isotopes.

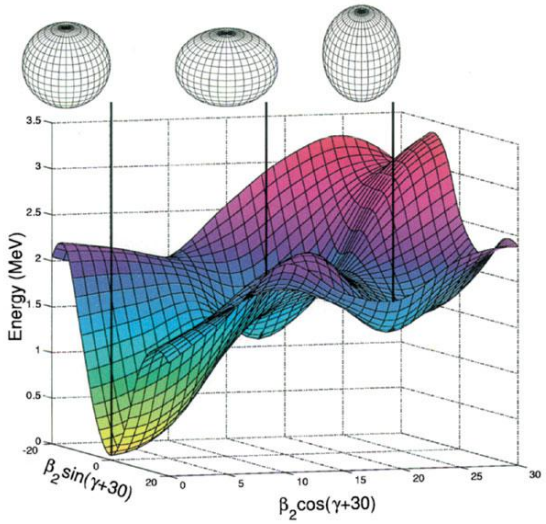


**Figure 1** Potential energy surface of $^{186}$Pb, showing spherical, oblate and prolate deformed minima with corresponding shapes. The $\beta_2$ and $\gamma$ parameters refer to the degree of elongation in the symmetry axis and triaxial deformation respectively [4].

Additionally this proposal will study the shape transition of the nucleus from spherical to octupole-quadrupole deformed in the region of reflection symmetry breaking centred at the N=137 isotone chain. This region is characterized by almost degenerate doublets of the same spin but different parities in the odd-even nuclei and an alternating spin and parity band sequence ($0^+$ $1^-$ $2^+$ $3^-$…) that are connected by enhanced E1 matrix elements in the even-even nuclei [8]. This has been attributed to either the presence of an octupole deformation or alpha clustering. The presence of octupole deformation is alluded to by the dramatic reversal in the odd-even staggering of the isotope shifts and a vanishing magnetic moment in the laboratory frame [9]. In-beam spectroscopy using alpha-gamma-gamma coincidence techniques on mass separated $^{223}AcF_2$, have shown an interleaved band structure of alternating parity states in both $^{218}$Fr and $^{219}$Fr [10,11]. The close proximity of the double closed shell of $^{208}$Pb to these two nuclei places them at a transitional point between systems of quadrupole-octupole

deformation and spherical symmetry and is therefore an important testing point for modern nuclear models.

**Methodology**

We will measure nuclear observables by studying the atom and the associated coupling between the nuclear spin with the atomic total angular momentum vectors. This coupling introduces a perturbation term to the atomic Hamiltonian that results in a hyperfine splitting of the energy levels. By measuring this substructure and with just angular momentum considerations, the nuclear moments and spin are extracted without nuclear model dependence. As the structure of the nucleus evolves across an isotope chain from highly dilute to neutron rich matter, the associated change in the nuclear charge distribution adjusts the binding energy of the atomic electrons, which modifies the magnitude of the transition frequency, denoted as the isotope shift.

This work will build on previous experience gained from fluorescent photon detection in a collinear geometry, which utilizes the accelerated ion beam to suppress the thermal Doppler broadening [11]. The laser and ion beams are overlapped collinearly to maximize the resolution and efficiency of these measurements. The application of the original technique is limited to yields greater than $10^6$ions/μC due the low efficiency of photon detection and the high background from scattered light. The introduction of efficient particle detection techniques, such as β-asymmetry detection and state-selective collisional ionization do not sufficiently reject background signals and are in general limited to yields of greater than $10^3$ions/μC. High detection efficiency and selectivity can be achieved by using pulsed lasers to step-wise excite the atom into the continuum. This technique, known as resonant ionization spectroscopy (RIS), is currently used to measure nuclei with yields down to 10 ions/μC, but with a resolution that is three orders of magnitude lower than possible with collinear laser spectroscopy [1]. Such measurements cannot resolve the nuclear quadrupole moment or unambiguously assign the nuclear spin.

The limitations of the RIS technique can be overcome by performing it in a collinear geometry on a fast atomic beam, thus benefiting from the associated Doppler suppression. In order to perform high resolution measurements, it is necessary to use a pulsed amplified continuous wave (CW) laser. The resolution is Fourier limited by the pulse width of the amplifying laser. The ability to detect ions with almost 100% quantum efficiency and still maintain the high resolution associated with traditional collinear laser spectroscopy makes this technique a unique tool to probe far from stability.

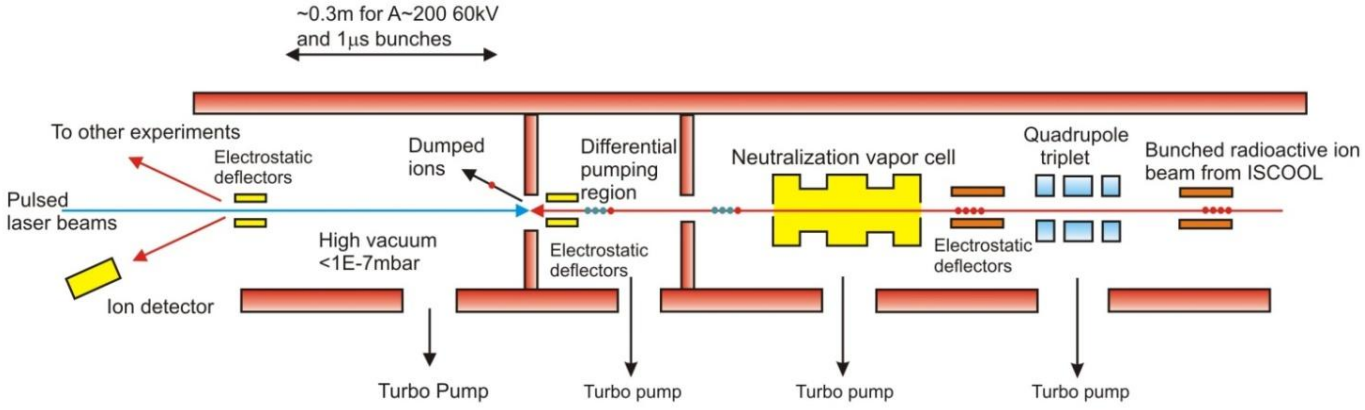


**Figure 2** Schematic layout of beam line, showing an anti-collinear overlap between pulsed lasers and bunched ions.

This proposal will install a new experimental setup that combines the benefits of the collinear geometry with the detection efficiency and selectivity of the RIS technique and will provide unprecedented precision far from the line of stability. The production of bunched ion beams is central to this new method and has been made possible with the new RFQ ion cooler and Paul trap at ISOLDE (ISCOOL). The device allows ions to be collected and trapped for up to one second and then released and accelerated within 1μs. The ion bunch is neutralized by an alkali vapor cell and the fast-atomic bunch is then ionized by collinearly and temporally overlapped pulsed lasers. The ionization scheme for francium (figure 3) will require two steps; a pulsed amplified tunable laser will excite the first step and a high-power pulsed laser will subsequently ionize the system. To measure the hyperfine structure a scanning voltage is applied to the neutralization cell, which Doppler tunes the velocity of the atom bunch onto resonance with the laser. The resonantly produced ions are then deflected on to a particle detector. The bunched beam avoids losses in efficiency due to the duty-cycle of the pulsed lasers. The region where the ionization process occurs must be maintained at UHV (better than $10^{-8}$mbar) to reduce non-resonant collisional ionization associated with the rarefied gas molecules. This requires differential pumping between the neutralization vapor cell and the ionization region (outlined in Fig. 2). Under these conditions, only the isotope of interest will be ionized, any isobaric contamination will remain neutral or deflected immediately after the neutralization region. In the initial test of this technique a detection efficiency of one atom in thirty was demonstrated [3]. This method has the potential to detect up to 50% of the atoms in the beam with almost no background, which would permit exotic nuclei with yields below 1 ion/μC to be studied.

The two possible ionization schemes available for francium are shown in figure 3. The HFS of the 7p $^2P_{3/2}$ state is almost three times larger than the 8p $^2P_{3/2}$ state, and therefore better suited to this work. The Fourier limited line widths range from 8-50MHz (depending on pulse length and amplifying medium), and therefore able to easily resolve the HFS of the francium isotopes. The second step into the continuum is achieved using the third harmonic of a Nd:YAG laser, which has an extremely high power and can easily ionize the entire excited ensemble.

Since francium has a long history of production at ISOLDE and the neutron deficient cases are especially clean, this proposal requires little or no further beam development. The preparation required perform measurements on $^{201\text{-}206}$Fr automatically allows $^{218,219}$Fr to be measured with no additional experimental investment, therefore the two regions can combined into one experimental campaign.

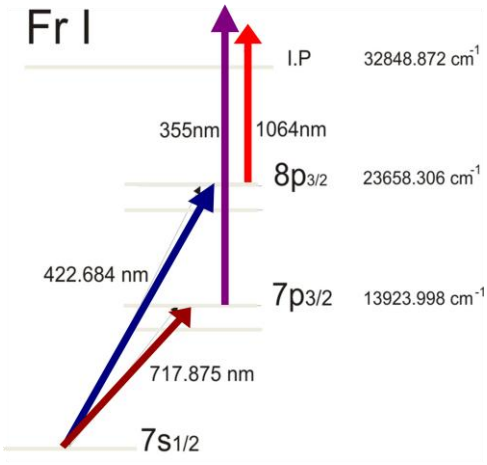

**Figure 3.** Ionization scheme for francium

## Experimental Requirements

The proposed beam line that will be installed into the ISOLDE hall is shown in figure 4. The beam line will have total length of 3.2m and will require an additional 1m of space at the end of the line for a small optical table. This is the necessary to overlap the laser beams before launch into the beam line. Due to the requirement of UHV the beam line needs to remain in place for the duration of this project. Therefore the collaboration would require a semi-permanent location for this equipment. It would also be favorable to locate the pulsed lasers relatively close to the experimental setup, but not essential. The

lasers again will require an enclosed location of $12m^2$ that will remain unchanged throughout the entire extent of this project .

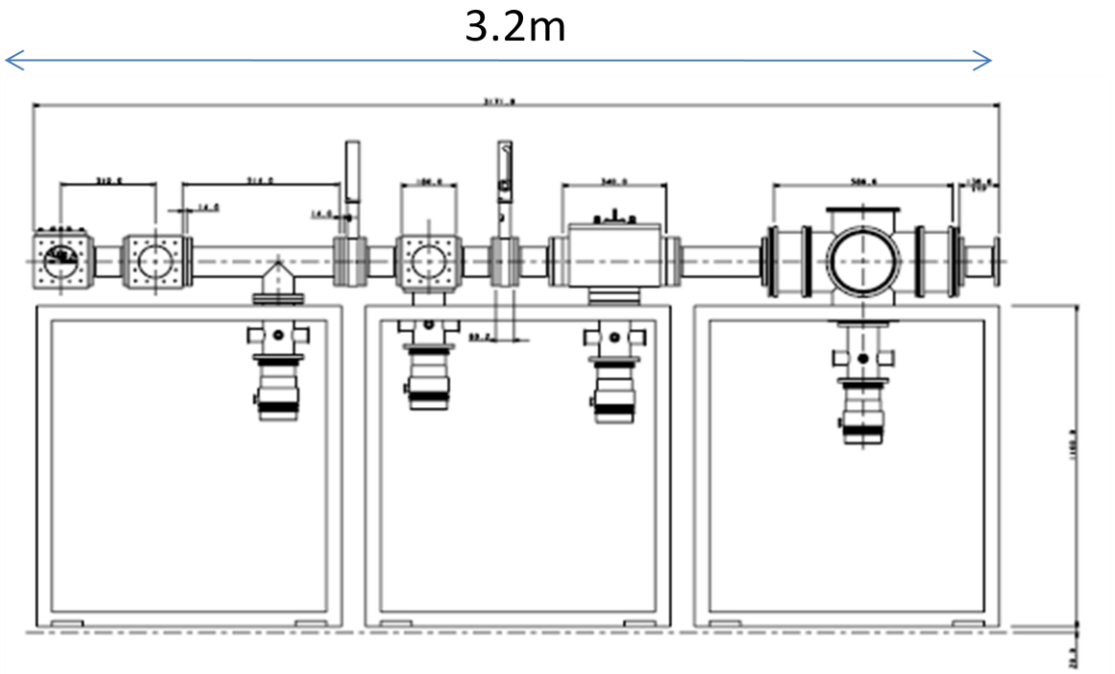


**Figure 4: Technical** drawing showing new beam line that will be installed as part of this experiment.

**Beam time request and programme of work**

The project will be spread out over three years, with work in the first year chiefly concerned with the setting up of the beam line and laser lab. During this initial installation period off-line stable alkali beams from the RFQ cooler will be required. This beam time is essential to optimize the ion bunch length and overlap within the interaction region of the setup. For this reason it is important that access to stable ion beams from the RFQ cooler is granted during the off-line period.

The detection limit of this experiment is determined by the efficiency, the background rate and required time to perform a measurement. Given the efficiency already demonstrated, and rejection of non-resonant collisional ionization within the interaction region at an attainable UHV of $10^{-9}$mbar it will be possible to perform measurements down to yields of 1 atom/μC . The known yields at ISOLDE of the francium ground states are listed in table 1, which shows that $^{201}$Fr is currently the limit for CRIS measurements. The data in table 1 suggests that the ThC target is the more suitable for this work and therefore would be requested in preference to the UCx target, in the absence of more recent yield measurements. This project does not require the RILIS setup for francium production.

The project will be broken up into three on-line runs, each with specific goals. The first run of 12 shifts will study the francium isotopes $^{206\text{-}203}$Fr. Although the ground states are produced with high yields for this work the isomeric states may have significantly lower yields and require more time to resolve. A second run of 9 shifts will then study $^{218,219}$Fr and possibly the isomeric state in $^{218}$Fr. A final run of 12 shifts will be used to study $^{201,202}$Fr. The extremely low yields and the possible large deformed structure of these nuclei will necessitates extended running time to measure the ground and isomeric states in these two isotopes.

The laser equipment required for this project currently exists within the collaboration. Required turbo pumps and cryo-pumps are also available. The designs for the vacuum chambers are currently under review and will be constructed at the University of Manchester workshop.

**Table 1.** Isotopes isomers considered in this proposal

| Francium isotope | Half life | Spin | Yield (atoms/μC) | Target |
|---|---|---|---|---|
| 219 | $21ms$ | $9/2^-$ | 8900 | UCx |
| 218m | $18ms$ | | - | |
| 218g | $1ms$ | $1^-$ | 4300 | UCx |
| 206m2 | $0.7s$ | $(10^-)$ | - | |
| 206m1 | $15.9s$ | $(7^+)$ | - | |
| 206g | $15.9s$ | $(3^+, 2^+)$ | $2.4 \times 10^6$ | UCx |
| 205 | $3.9s$ | $(9/2^-)$ | $1.7 \times 10^5$ | UCx |
| | | | $2 \times 10^7$ | ThCx |
| 204m2 | $1s$ | $(10^-)$ | - | |
| 204m1 | $2.6s$ | $(7^+)$ | - | |
| 204g | $1.7s$ | $(3^+)$ | $1.9 \times 10^6$ | ThCx |
| 203m | $60ms$ | $(1/2^+)$ | - | |
| 203g | $0.56s$ | $(9/2^-)$ | $2.1 \times 10^5$ | ThCx |
| | | | 1000 | UCx |
| 202m | $0.34s$ | $(10^-)$ | - | |
| 202g | $0.34s$ | $(3^+)$ | 71 | UCx |
| 201m | $19ms$ | $(1/2^+)$ | - | |
| 201g | $53ms$ | $(9/2^-)$ | 1 | UCx |

**Summary**

*2008/2009*

- Installation of beam line, including assembly and testing of vacuum components and data acquisition equipment into experimental area.
- Preparation of pulsed lasers, optical tables, environmental controls for laser room, laser beam transport to the interaction region, the long term stabilization of the lasers.
- Testing of laser ionization and detection systems with off-line ion beams and optimization of bunched ion beams from ISCOOL.

*2009/2010*

- An initial on-line run to study $^{203\text{-}206}$Fr of 12 shifts will be requested.
- A second run of 9 shifts will study $^{218,219}$Fr.
- A third run of 12 shifts will study $^{202,201}$Fr.

**A total of 33 shifts is requested over the three year running period 2008-2010 with access to stable alkali beams from ISCOOL during the shutdown periods.**

**References**


[1] H. De Witte *et al*., Phys. Rev. Lett., **98**, 112502 (2007).
[2] Ch. Schulz *et al.*, J. Phys. B, **24,** 4831 (1991).
[3] K. T. Flanagan, Ph.D Thesis, Nuclear Group, University of Manchester, 2004.
[4] A.N. Andreyev *et al*., Nature **405**, 430, (2000).
[5] H. Kettunen *et al.*, Eur. Phys. J. A **16**, 457 (2003).

[6] C.N. Davids *et al.*, Phys. Rev. Lett. **76**, 537 (1996).
[7] J. Uusitalo *et al.*, Phys. Rev. C **71**, 024306 (2005).
[8] E. W. Otten, Treatise on heavy-ion science, vol. 8. Ed. D. Allan Bromley (Plenum, New York, 1989) p. 597.
[9] M. E. Debray *et al.*, Phys. Rev. C **62**, 024304 (2000).
[10] C.F. Liang *et al*., Phys. Rev. C **44**, 676 (1991).
[11] K.-R. Anton *et al.*, Phys. Rev. Lett, **40**, 642 (1978).