EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Benchmarking of a Multi Ion Reflection Apparatus for Collinear Laser Spectroscopy of radionuclides

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Abstract: Supported by an ERC Starting Grant, we are developing a new experimental technique to enhance the sensitivity of collinear laser spectroscopy (CLS) by a factor 20-600 in order to probe rare isotopes currently out of reach due to their low production yields at radioactive ion beam (RIB) facilities. This novel approach is based on a multi-reflection time-of-flight apparatus (or also called electrostatic ion beam trap) which provides extended observation times while preserving the high resolution of conventional CLS. This research program will strongly benefit from stable beams during the long shutdown LS2 by efficiently coupling the new apparatus to the ISOLDE facility and by benchmarking its performance under realistic conditions of ISOLDE beam delivery.

Requested shifts: Letter of Intend. No shifts are requested at this time.

1 A Multi Ion Reflection Apparatus for Collinear Laser Spectroscopy of radionuclides

Collinear laser spectroscopy (CLS), as performed at COLLAS/ISOLDE since 1980 [1], is a powerful technique to study ground-state properties of short-lived radionuclides which provides insight into a wide range of contemporary questions in nuclear physics [2].
In CLS, the radioactive ion (or atom) beam is overlapped with a laser beam. On resonance, the laser-excited atoms or ions emit fluorescence photons which are detected by photomultiplier tubes (PMT). Hence, by scanning the laser frequency the hyperfine structure (HFS) of rare isotopes can be mapped out with high resolution. As the HFS is a consequence of the interaction of the atomic nucleus with its surrounding electron cloud, these measurements allow one to determine spin, charge radius or electromagnetic moments of the nuclide under investigation.
In the last decade, CLS has benefited from the advent of ion traps in rare isotope science [3, 4, 5, 6] . The bunched beams released from these traps, e.g. from ISCOOL at ISOLDE [7], have led to an increase in sensitivity by several orders of magnitude due to an improved signal-to-background ratio when gating on the passing ion bunch.
Our new project introduces another type of ion trap, a Multi-Reflection Time-of-Flight (MR-ToF) apparatus [8] or also called Electrostatic Ion Beam Trap (EIBT) [9], which has the potential to significantly enhance the sensitivity of CLS further. Recently, MR-ToF devices have entered the field of rare isotope science very successfully as fast and efficient mass separators or mass spectrometers [10, 11],. Their strength to extend precision mass measurements to nuclides previously out of reach has been first demonstrated at ISOLTRAP/ISOLDE, e.g. by measurements of ^{53,54}Ca right at the intensively studied and debated (sub-)shell closures N=32/34 [12].
Given the opportunities offered by these devices, we aim to establish an MR-ToF setup as a Multi Ion Reflection Apparatus for Collinear Laser Spectroscopy of radionuclides (MIRACLS) by employing this novel technique for nuclides hitherto not accessible to CLS given its sensitivity limitation: In conventional CLS the ion bunch passes the laser interaction and fluorescence detection region once within several μs and is subsequently lost for further use although the lifetime of the radioactive ions is at least in the order of a few ms. In MIRACLS, however, the ion bunch is reflected back and forth between two electrostatic mirrors. Hence, the ions pass the interaction region with the laser once per

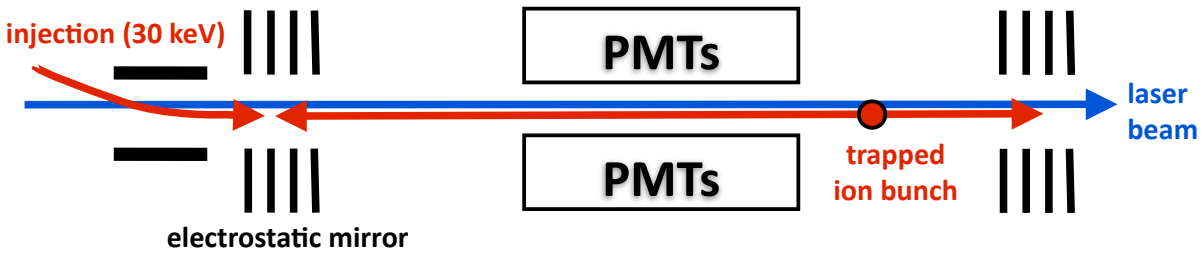

Figure 1: Schematics of a Multi Ion Reflection Apparatus for Collinear Laser Spectroscopy of radionuclides.

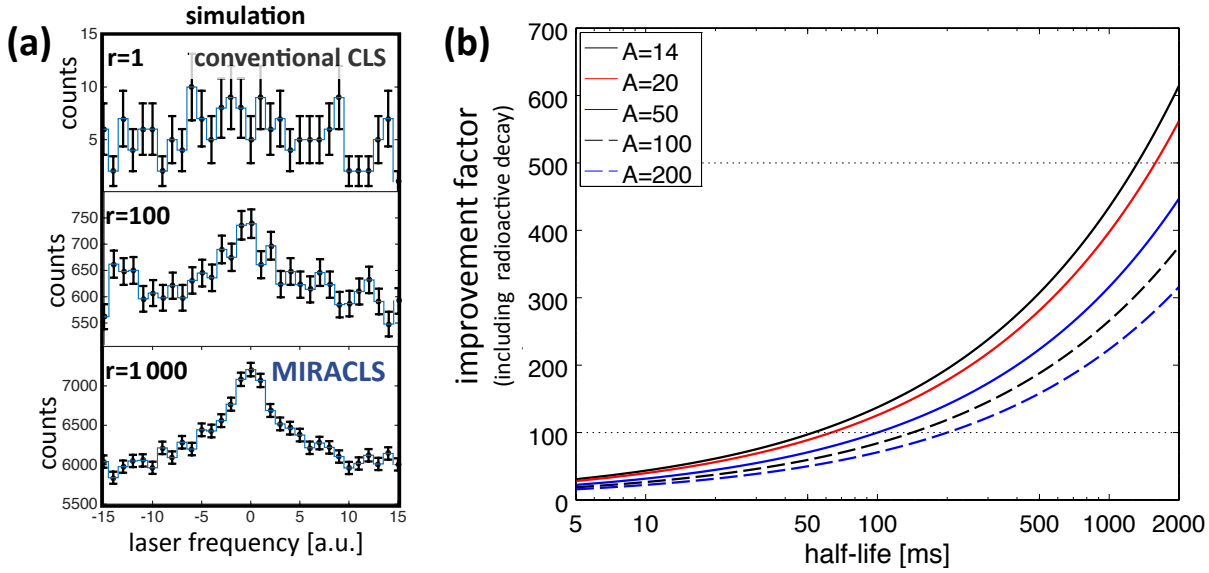

Figure 2: Improvement in experimental sensitivity compared to conventional CLS:
(a) Simulated PMT counts in the optical detection region around a resonant transition in conventional CLS compared to MIRACLS with 100 and 1000 revolutions r in the MR-ToF apparatus. While the detected counts are dominated by background for conventional CLS in this simulation, the signal is well above background in MIRACLS.
(b) Improvement factor in experimental sensitivity as a function of a nuclide's half-life $T_{1/2}$ and mass number A. The optimal storage time in MIRACLS is $t_{trap} \approx 1.8 \cdot T_{1/2}$.

revolution extending the effective observation time by a factor identical to the number of revolutions. At the same time, the ion beam energy of typically a few keV in today's MR-ToF devices will be increased to 30 keV in our concept (see Figure 1) in order to maintain the high resolution of conventional CLS. In the absence of universal and fast cooling techniques, this is an MR-TOF device decisive advantage for laser spectroscopy of short-lived radionuclides over other types of ion traps which would otherwise also confine ions over long observation times.
Compared to the conventional in-beam use of CLS, MIRACLS allows gains in experimental sensitivity by a factor of 20 to 600, typically limited by the half-life of the nuclide under study and hence the storage time of the ions in the trap. Consequently, it promises to extend CLS to nuclides presently out of reach given their low yields of typically <1000 ions/s at RIB facilities which approaches the single-ion detection limit, i.e. the limit where yields of a few ions/s delivered to the experiment are sufficient for a successful measurement. Figure 2 illustrates these improvements in experimental sensitivity of MIRACLS compared to conventional CLS.

2 Stable ISOLDE beam for MIRACLS

The ERC Starting Grant supports the present project since January 2017 and we are currently working on a proof-of-principle experiment with an existing MR-ToF setup op-

erating at $\sim$ 1.3 keV. Simultaneously, a device with a beam energy of 30 keV is designed and will be built and commissioned for the purpose of collinear laser spectroscopy. This work is done in close collaboration with a new project at ISOLDE to build a general purpose MR-ToF apparatus serving the ISOLDE community as a mass separator to suppress undesired isobaric contamination in the ISOLDE beam.
In addition to the MR-ToF ion optics, the MIRACLS setup will consist of a reference and test ion source delivering stable beam and a buffer-gas filled Paul trap for beam preparations. Hence, the full apparatus will be first commissioned with stable beam from its own ion source prior to its coupling to ISOLDE. However, the full commissioning requires access to ISOLDE beam. Considering the tight time constraints at ISOLDE under regular online operation and the limited access to stable beam for technical developments, the time period during LS2 in 2019/20 hence provides an excellent opportunity to prepare the beam transfer from ISOLDE and to benchmark the performance of MIRACLS without sacrificing precious ISOLDE online time. In detail, we intend to request stable beam from ISOLDE in 2019/20 for the following work packages

- Optimisation of beam transfer from ISCOOL to MIRACLS
  Due to the small length of MIRACLS' Paul trap, ISCOOL will be used to cool and bunch the ISOLDE beam as in regular CLS at ISOLDE. Consequently the beam needs to be efficiently transferred from ISCOOL to MIRACLS. We intend to use stable ISOLDE beam (of different masses) in order to establish and optimise this transfer for different mass regions. This will also allow us to investigate whether it is possible or more advantageous to inject ISCOOL beam directly into MIRACLS' MR-ToF apparatus or whether the ion bunch is first transfered into MIRACLS' own Paul trap.

- Benchmark measurement
  Once the efficient ion transfer is established, we intend to perform a first benchmark measurement of optical isotope shifts between the Mg isotopes ^{24,26}Mg. Even-even Mg isotopes are chosen as particularly well suited cases for the MIRACLS technique because of their closed two-level systems, in which laser excited ions decay back into their initial ionic state and are not pumped into other hyperfine or metastable fine structure states. The measurement results can be directly compared to existing data. Hence, they allow to benchmark the accuracy of the technique under realistic conditions of ISOLDE beam delivery in addition to the study of individual systematic effects with the beam from MIRACLS' offline ion source.

- Mass resolving power within MIRACLS
  While not yet explored for laser spectroscopy, MR-ToF devices are celebrated for their superb mass resolving power. Naturally, the capability to suppress isobaric contamination is also beneficial for laser spectroscopy of radionuclides and its use for this purpose is also considered. MIRACLS' MR-ToF setup will be optimised in its design for laser spectroscopy and not necessarily for mass resolving power. For instance, while CLS requires a low energy spread to minimize Doppler broadening, high mass resolving powers in an MR-ToF apparatus are obtained by a focus in the time domain resulting to a larger energy spread. As an example. ISOLTRAP's

MR-ToF mass spectrometer is typically operated with an energy spread of 60 eV [11]. Hence, we would to study the achievable mass resolving power in MIRACLS in CLS mode.

Summary of requested shifts: Letter of Intend. No shifts are requested at this time.
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References

[1] R Neugart, et al. Collinear laser spectroscopy at ISOLDE: new methods and highlights. *Journal of Physics G: Nuclear and Particle Physics*, 44(6):064002, 2017.

[2] Klaus Blaum, et al. Precision atomic physics techniques for nuclear physics with radioactive beams. *Physica Scripta*, 2013(T152):014017, 2013.

[3] A. Nieminen, et al. On-Line Ion Cooling and Bunching for Collinear Laser Spectroscopy. *Phys. Rev. Lett.*, 88:094801, Feb 2002.

[4] A. Nieminen, et al. Cooling and bunching of ion beams for collinear laser spectroscopy. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 204:563 – 569, 2003.

[5] E. Mané, et al. An ion cooler-buncher for high-sensitivity collinear laser spectroscopy at ISOLDE. *The European Physical Journal A*, 42(3):503–507, 2009.

[6] E. Mane, et al. Collinear laser spectroscopy with reverse-extracted bunched beams at TRIUMF. *Hyperfine Interactions*, 199:357–363, 2011. 10.1007/s10751-011-0331-7.

[7] H. Franberg, et al. Off-line commissioning of the {ISOLDE} cooler. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 266:4502 – 4504, 2008.

[8] H. Wollnik et al. Time-of-flight mass spectrometers with multiply reflected ion trajectories. *International Journal of Mass Spectrometry and Ion Processes*, 96(3):267 – 274, 1990.

[9] D. Zajfman, et al. Electrostatic bottle for long-time storage of fast ion beams. *Phys. Rev. A*, 55:R1577–R1580, Mar 1997.

[10] R.N. Wolf, et al. On-line separation of short-lived nuclei by a multi-reflection time-of-flight device. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 686(0):82 – 90, 2012.

[11] R.N. Wolf, et al. ISOLTRAP's multi-reflection time-of-flight mass separator/spectrometer. *International Journal of Mass Spectrometry*, 349-350:123 – 133, 2013. 100 years of Mass Spectrometry.

[12] F. Wienholtz, et al. Masses of exotic calcium isotopes pin down nuclear forces. *Nature*, 498(7454):346–349, 06 2013.