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

In-source laser spectroscopy of mercury isotopes

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A. N. Andreyev[5], A. E. Barzakh[2], J. Billowes[4], T. E. Cocolios[4], J. Cubiss[5], V. N. Fedosseev[3], R. Ferrer[1], K. T. Flanagan[4], L. P. Gaffney[1], T. D. Goodacre[3,4], A. Gottberg[3], M. Huyse[1], D. G. Jenkins[5], Yu. Kudryavtsev[1], B. A. Marsh[3], R. Raabe[1], S. Raeder[1], E. Rapisarda[3], R. E. Rossel[3], S. Rothe[3], M. Seliverstov[2,3], T. Stora[3], I. Strashnov[4], P. Van Duppen[1], R. Wadsworth[5], G. L. Wilson[5]

[1]*KU Leuven, Belgium*; [2]*PNPI, Gatchina, Russia*; [3]*CERN-ISOLDE, CH*; [4]*University of Manchester, U.K.*; [5]*University of York, U.K.*

Spokespersons: Liam Paul Gaffney [Liam.Gaffney@fys.kuleuven.be], Maxim Seliverstov [seliver@pnpi.spb.ru], Andrei Andreyev [Andrei.Andreyev@york.ac.uk]
Contact person: Bruce Marsh [Bruce.Marsh@cern.ch]

Abstract: This Letter of Intent proposes to address issues surrounding the possible in-source laser spectroscopy measurements of Hg isotopes with RILIS. Key to these studies is the successful, and so far untested, coupling of a molten Pb target to the RILIS ion-source cavity, due to the increase in production yield it affords over the UC_x target. At the moment, the ionisation scheme for Hg is inefficient and should be improved and tested inline with the target–cavity enhancements. It is also expected that the issues addressed by this letter will have consequnces for future planned experiments, e.g. transfer reactions on isomeric beams of ^{183,185}Hg.

Requested shifts: 3 shifts

1 Introduction and physics case

Nuclei in the neutron-deficient lead region are famed for their manifestation of shape coexistence [1]. It all began at ISOLDE with the discovery of a large jump in the mean-squared charge radius between ^{187}Hg and ^{185}Hg in isotope shift measurement [2]. This was interpreted as a dramatic change in shape from a weakly-deformed oblate shape in the heavier isotopes to a more-strongly deformed prolate shape in calculations based upon the Strutinsky shell-correction method [3]. Another striking example of shape coexistence occurs in ^{186}Pb where the ground state plus the first two excited states are interpreted as the 0^+ band heads of three differently-shaped configurations: spherical, oblate and prolate [4]. In the case of the Pb isotopic chain, the isotope shifts [5, 6] indicate that the ground state remains spherical, whereas the Hg isotopes [7] exhibit a more interesting odd-even staggering around the neutron mid-shell (see Fig. 1). This region of the nuclear chart has recently become a hotbed of experimental activity, yet the isotope shift has been measured down to only $A = 181$ ($N = 101$) for the Hg isotopes [7]. The observed odd-even staggering is expected to vanish as one moves beyond the mid-shell region, but it is yet to be determined whether this indeed happens and at which point it occurs. As the latter is dependent on the interplay between single-particle and collective behaviour, its determination can give new insight. At minimum, ^{179}Hg needs to be measured and potentially ^{177}Hg. In addition to the Hg and Pb isotopic chains, isotope shifts have been measured at ISOLDE for Po down to $N = 107$ [8], the Pt chain to $N = 100$ [9] and the odd-Z chains of Tl and Au.
At the other end of the Hg isotopic chain, beyond the $N = 126$ shell closure, no data on the isotope shift exists so far. Extending these studies to the neutron-rich isotopes, ^{207,208}Hg, would provide the first data in even-Z nuclei below $Z = 82$.

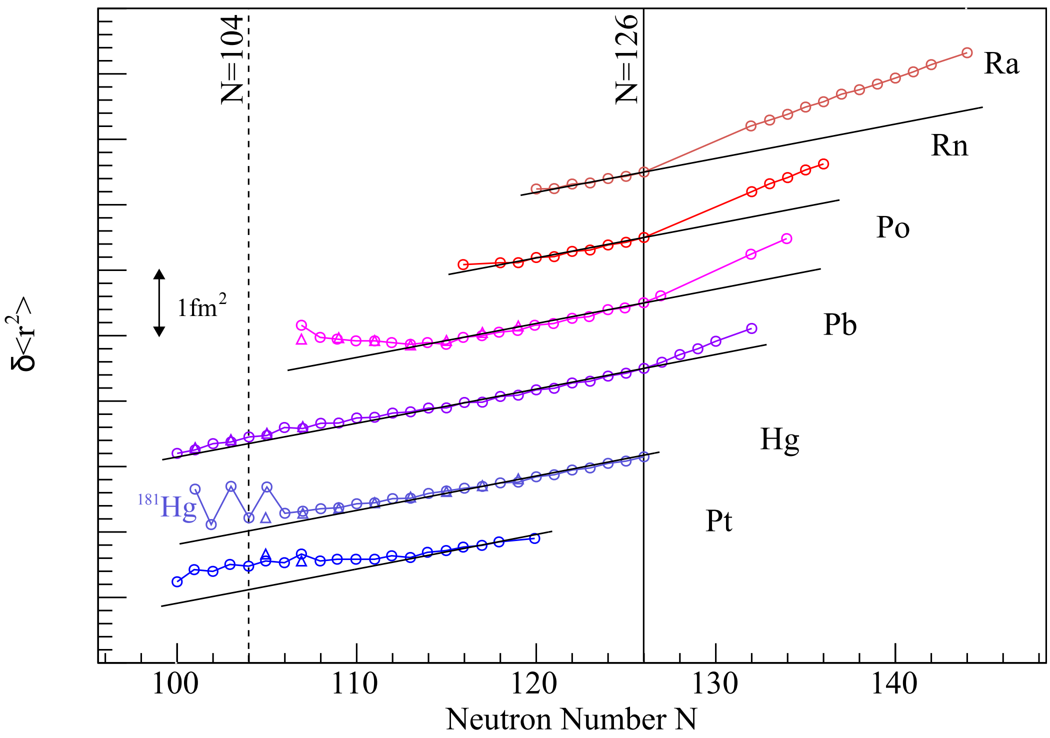

Figure 1: Relative changes in mean-square charge radii for the isotopic chains of the even Z elements from Pt to Ra. Reproduced from Ref. [8].

2 Experimental technique

The Hg nuclei will be ideally produced in a molten Pb (see Section 3) target connected to the Resonance Ionisation Laser Ion Source (RILIS) cavity of the ISOLDE mass separator to perform the laser spectroscopy studies. Extraction of the reaction products from the target material relies on diffusion. This is known to be slow for molten Pb targets, which will have a significant impact on the yield of the shorter lived Hg isotopes. The large gain in production cross-section in the molten Pb target over the UC_x target counteracts this, and the available data indicates that, at least down to ^{177}Hg, the molten Pb target is better suited. For the neutron-rich isotopes, the molten Pb target is again expected to outperform the UC_x target (see Fig. 2). The coupling of a molten Pb target with a laser ion source is so far untested, but yields have been obtained using the MK3 and VARDIS ion sources (see Fig. 3), which can be used in combination with the RILIS ionisation efficiency to give estimations of the expected yields.

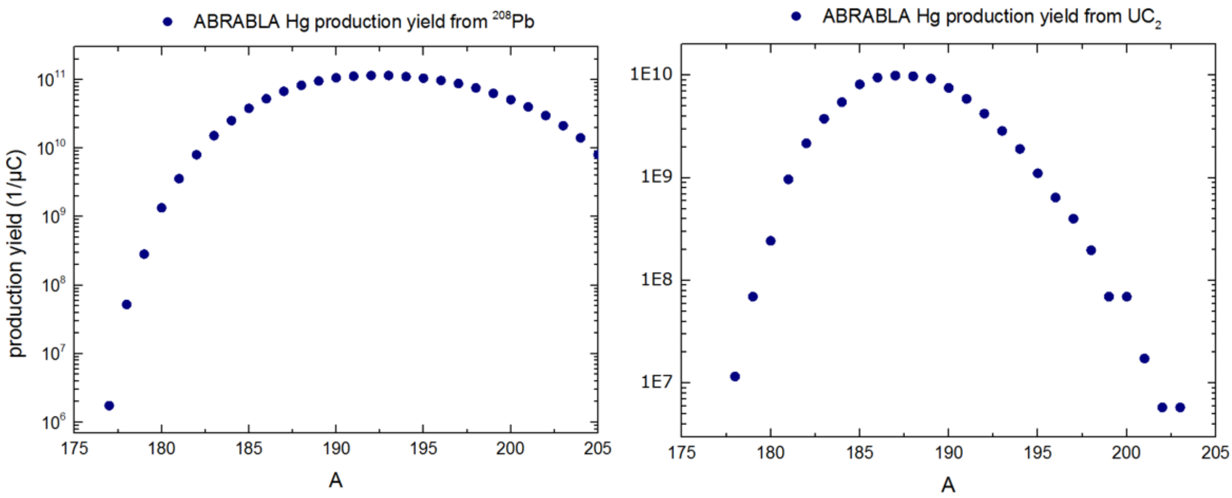

Figure 2: Comparison of the production yields calculated with the ABRABLA code for the production of Hg istopes from a Pb target (left) and UC_2 target (right). For the longer-lives isotopes above $A = 180$, the Pb target is expected to perform much better than the UC_2 target.

Currently, the efficiency of the ionisation scheme for Hg (see left-hand side of Fig. 4) is measured to be as low as 0.1%. Improvements to the efficiency are possible following the upgrade of RILIS, with the addition of three Ti:Sa lasers. With the combined benefit of an optimal ionisation scheme and the improved spectral overlap of the laser line-width with the Doppler-broadened hyperfine-structure (HFS) lines, it is reasonable to expect an efficiency improvement of at least an order of magnitude.

The laser-ionised Hg ions will be transmitted to the windmill setup where their α decay will be detected over a set period of time for a given laser frequency, a technique described in Refs [5, 11]. Scanning the laser frequency in steps, the HFS is revealed in the variation of α-decay count rate. Simulations (see right-hand side of Fig. 4) reveal that, although the line width is expected be large ($\sigma \lesssim 5$ GHz) due to Doppler broadening and laser bandwidth, it is possible to resolve all 3 components of the hyperfine structure of the 253.7-nm $6s^2\ ^1S_0 \rightarrow 6s6p\ ^3P_1$ transition. In addition, since the isotope shift is large, i.e. 3.7 GHz between the neighbouring ^{186}Hg and ^{188}Hg and 24 GHz between the g.s. and isomer in ^{185}Hg, it can still be accurately measured under these conditions. It has been demonstrated in the past that laser spectroscopy can be performed on even-even nuclei with production

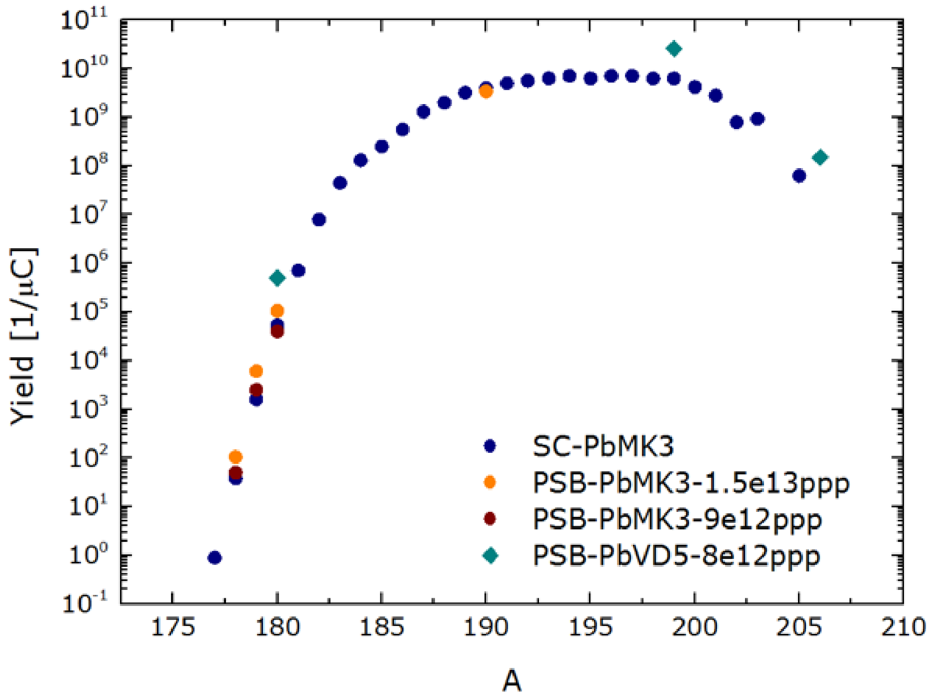

Figure 3: Production yields measured for the Hg isotopes with various ion-sources at the SC and PS-Booster. The red dots of the 'PSB-PbMK3-9e12ppp' data represent an ionisation efficiency of 10% with the MK3 ion source. The RILIS efficiency should be at least 1% (i.e. one order of magnitude less) after the improvements mentioned in this LOI.

rates as little as 1 atom per second [5, 8]. For the neutron-rich isotopes, the small α-decay branching ratio means that alternative tagging is required, such as β-tagging or γ-tagging for the isomeric states in the odd-mass nuclei. For this, the new, flexible ISOLDE Decay Station (IDS) would be put to use.

3 Request for beam development

The coupling of the RILIS cavity to a molten Pb target is non-trivial and its compatability must be tested before we can propose measurements using this configuration. In this LOI, **we are requesting 3 shifts** to investigate the performance of the molten lead target with improved RILIS ionisation scheme:

- to find optimal operating conditions/parameters of the target and ion source cavity
- to measure the yields and release time of neutron-deficient mercury isotopes

Moveover, the laser ionisation scheme for Hg must be further optimised in order to increase the current ionisation efficiency beyond the current 0.1%.

3.1 Transferable outcomes

In addition to the new possibility of laser spectroscopy of the Hg isotopes with $N \leq 101$, use of the molten Pb target coupled with an improved ionisation scheme will also allow for pure and intense beams of the mid-shell, $102 \leq N \leq 106$, Hg isotopes. Although the

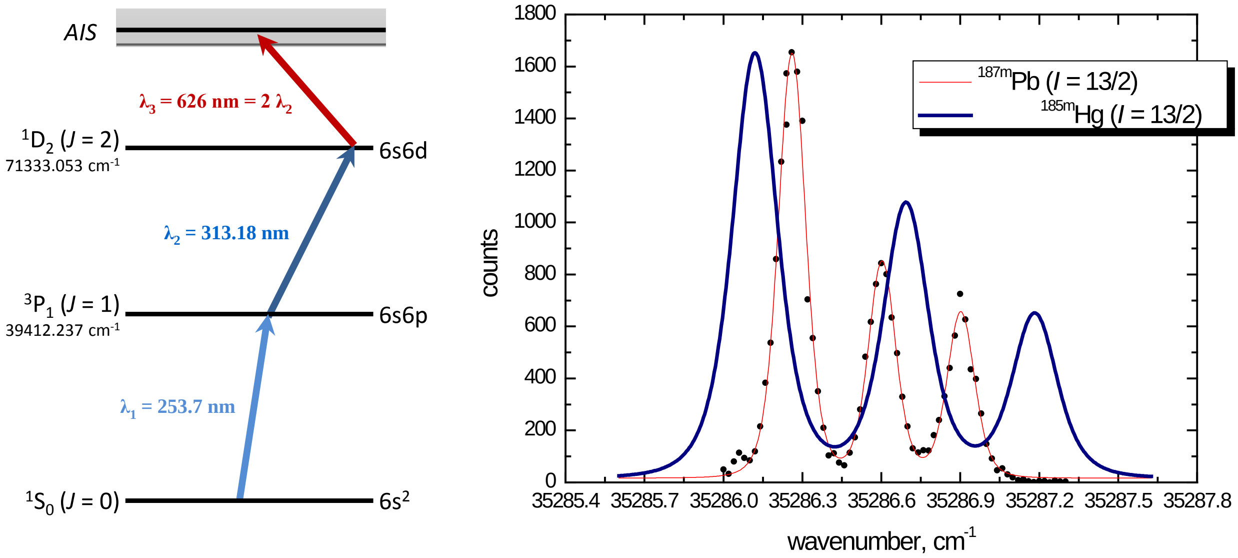

Figure 4: Proposed laser scheme for photoionisation of Hg atoms (left) and a simulation of the HFS in ^{185m}Hg compared to the experimental data of the isotone ^{187m}Pb [6, 10].

current level of purity and intensity is sufficient for the previous [12, 13] and future Coulomb-excitation experiments [14], a higher intensity is required for the intended low cross-section transfer experiments [15]. Another critical feature in LOI-I-110 for the Coulomb excitation and one- and two-neutron transfer reactions of odd-mass nuclei [15], is the availability of isomeric beams, i.e. $13/2^+$ and $1/2^-$ shape isomers in ^{185}Hg. Future hyperfine structure scans of the neutron-deficient Hg isotopes would determine the optimal laser frequencies for isomer-selective ionisation.

Utilising the new ISOLDE Decay Station (IDS) during the laser ionisation experiments for α-tagging, it is possible to run a concurrent decay experiment. This has been utilised successfully before in experiments involving, e.g. Tl beta-decay [16] and beta-delayed fission studies [17]. The interesting possibility of garnering information on beta-delayed proton emission in ^{179,181,183}Hg [18] provides an additional motivation to study these isotopes with the IDS.

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