Towards an Australian Atom-Trap Trace-Analysis (ATTA) Facility

P.S. Light^a, R.D. Glover^a, M.A. Dakka^a, G.Tsiminis^a, A.J. Palmer^b, D. Chetty^b, I. Litvinyuk^b, R.T. Sang^b and A.N. Luiten^{a*}

^aInstitute for Photonics and Advanced Sensing (IPAS), University of Adelaide, SA 5005, Australia

^bCentre for Quantum Dynamics and School of Natural Sciences, Griffith University, Brisbane, QLD 4111, Australia

ABSTRACT

Atom-Trap Trace-Analysis (ATTA) is a technique aimed at measuring the relative (in comparison to the common isotope) abundance of exceedingly rare noble gas radio-isotopes (Ar-39, Kr-81 and Kr-85), for the purposes of dating water, ice and other materials that contain trapped gases. These isotopes exist with an extremely low natural abundance and require measurement capability down to parts in 10^{17} . The noble gas dating protocol is similar to that of radio-carbon dating but, the three isotopes together, allow dating of materials in complementary ranges to that possible with the radio-carbon technique. In a facility jointly created by CSIRO, Griffith and Adelaide Universities, we use laser guidance, cooling and trapping to perform isotopic separation using the isotopic dependence of atomic energy levels. The facility is currently undergoing construction but has been shown to be able to produce metastable Ne and Ar, which can then be laser cooled and trapped. When combined with the existing gas separation facility at the CSIRO Waite facility, which efficiently extracts pure noble gases from those dissolved in water or ice samples, we should be in a position to start measuring the age of real-world samples in the early part of 2020. In addition, to describing the current state of construction, we will also discuss two more efficient approaches for creating metastable atoms that can reduce samples size and avoid unwanted cross-contamination between samples.

Keywords: Laser cooling, atom-trapping, radio-isotopes, radio-dating.

1. INTRODUCTION

We are currently constructing a facility that will offer the capability to measure the relative abundance of several noble-gas radio nuclides compared with the stable isotope abundance, for the purposes of dating water and ice samples in a technique similar to radio-carbon dating.

The measurement facility will use the recently developed Atom-Trap Trace-Analysis (ATTA) technique, which allows measurements to be performed using gas extracted from small water samples, orders of magnitude smaller than is required for existing techniques such as low-level counting (LLC) or accelerator mass spectrometry (AMS). The facility will be able to measure three target isotopes: Kr-81, Kr-85 and Ar-39. Because these isotopes are noble gases and thus chemically inert they are considered as ideal environmental tracers.

The facility will provide the ability to accurately date water and ice core samples using the natural radio-isotopes incorporated within the samples. This will allow a detailed understanding of water and gas movement in underground reservoirs, provide analysis of changes in atmospheric composition over the long-term, and assess the impact of unconventional gas extraction on water systems. The wide range of half-lives provides dating capability over decades (Kr-85), centuries (Ar-39) and beyond millennia out to one million years (Kr-81). Further, it will be capable of detection of manmade emissions of Kr-85, which can aid in determination of compliance with nuclear non-proliferations treaties.

In addition to describing the anticipated capabilities of the facility, we will introduce new laser-based techniques that can offer greater sample through-put and measurement precision compared with the few existing ATTA systems worldwide.

2. EXPERIMENTAL DESIGN

The atom-trap trace analysis (ATTA) technique [1] for measuring noble-gas radio-isotope abundance requires that the noble-gas sample is first excited into the metastable state, from which laser-cooling is readily achievable. A picture of

the current apparatus is shown in Fig 1. On the left-hand end is a DC discharge for producing a hot metastable noble gas beam. The metastable atoms are then accessible for interaction/manipulation using near-IR light ($\sim 810\text{nm}$ for Kr and Ar). The atom beam passes through a pinhole and is then collimated through a 2D optical molasses to increase the atomic beam brightness. The beam then enters into a Zeeman slower to decrease the average beam velocity before it enters into a 3D magnetic-optic trap (MOT) on the right-hand end of the apparatus. The MOT is observed with an electron-multiplied CCD camera to count the number of trapped atoms.

Figure 1. ATTA apparatus at the IPAS, University of Adelaide. See text for description of parts.

The CSIRO Gas separation facility (at the CSIRO Waite campus) can provide the ATTA with pure single-species noble gas samples derived from water or ice samples of interest. These are then fed into the ATTA apparatus: by tuning the laser frequencies used in the collimator, the Zeeman slower and MOT we can selectively trap an isotope of interest. When counting the rare radio-isotope we expect to only have a single trapped atom at a rate of between a few per minute and a few per hour (depending on the specific isotope); in the case of the common isotope we expect a large MOT. By ratioing the rate of capture of the rare isotope to the loading rate of the common isotope we can accurately estimate the relative abundance of the uncommon isotope.

3. PLANNED UPGRADES

Current ATTA systems use DC or RF discharges to excite atoms into the metastable state. In addition to being inherently inefficient ($\sim 10^{-4}$ excited to the metastable level at best), this approach leads to cross-sample contamination because high kinetic energy ions produced in the discharge end up in the walls of the vacuum chamber, and then leak out during subsequent samples. A more efficient and cleaner metastable production technique could reduce measurement time, increase throughput, and allow measurement of smaller samples. While optical lamp-based excitation techniques have been considered before [2], here we explore two innovative laser excitation techniques:

Multi-photon Excitation: We have experimentally measured two-photon transitions for optical excitation into the metastable level [3]. A two-photon excitation into krypton $2p_6$ state decays directly into the $1s_5$ metastable state with favourable ($\sim 75\%$) branching ratio, and we have demonstrated efficiencies of 2% per pulse, using a broad-bandwidth excitation source at 215nm. Modelling suggests efficiencies up to 30% are possible under optimal conditions [3].

Frustrated Tunnel Ionization: We use a strong-field excitation technique [4,5] which takes advantage of a neutral exit channel available in the tunneling regime of strong-field ionization. By modifying the pulse shape and duration, we are currently attempting to optimize excitation into the desired metastable state. We will present our preliminary results on metastable production using frustrated tunnel ionization.

References

- [1] Z. T. Lu et al., Earth-Science Rev., **138** 192-214 (2014)
- [2] H. Daerr et al., Rev. Sci. Instrum. **82** 073106 (2011)
- [3] M. A. Dakka et al., Phys. Rev. Lett **121** 093201 (2018)
- [4] T. Nubbemeyer et al., Phys. Rev. Lett. **101** 233001 (2008)
- [5] H. Zimmermann et al., Phys. Rev. Lett. **114** 123003 (2015)