EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Status Report to the ISOLDE and Neutron Time-of-Flight Committee

Beta-delayed fission and in-source laser spectroscopy in the lead region (experiments IS456, IS466, IS511, IS534)

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The Windmill Collaboration*

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Abstract

The Windmill collaboration joins together expertise on selective resonance laser ionization and detailed decay spectroscopy to address nuclear and atomic structure, fission and nuclear astrophysics questions involving nuclei around the Z=82 shell closure, both on the neutron-deficient and neutron-rich sides. During the last decade, the shape coexistence present in the long isotopic chains of the elements from Au (Z=79) to At (Z=85) has been extensively studied (IS407, IS456, IS466, IS511, IS534) via their charge radii, electromagnetic moments, E0 transitions, etc. As the second major strand of the experiments, the β-delayed fission studies in the neutron-deficient isotopes of Tl, At and Fr have been successfully performed (IS466, IS534). These experiments require preliminary developments with the RILIS (I057, I086, I153), which in return have yielded important atomic information, such as the ionisation potential of astatine.

* Students currently analysing data from those experiments are underlined.

Experiments and remaining shifts: IS456 – **4.5 shifts**, IS534 – **21.5 shifts** (3.5 shifts from 2012 + 18 shifts approved in June 2013 in the Addendum for gold isotopes)

IS407 - Study of the neutron deficient Pb and Bi isotopes by simultaneous atomic- and nuclear-spectroscopy, J. Lassen & S. Franchoo, successfully completed, closed.
http://cds.cern.ch/record/533810?ln=en
http://cds.cern.ch/record/707297?ln=en

I057 – In-source laser spectroscopy of Po, S.R. Lesher & V.N. Fedosseev, successfully completed, closed.
http://cds.cern.ch/record/816374?ln=en

IS456 - Study of polonium isotopes ground state properties by simultaneous atomic- and nuclear-spectroscopy, T.E. Cocolios & Yu. Kudryavtsev, **4.5 shifts remaining.**
http://cds.cern.ch/record/1009761?ln=en
http://cds.cern.ch/record/1100220?ln=en
http://cds.cern.ch/record/1642843?ln=en

IS466 - Identification and systematical studies of the electron-capture delayed fission (ECDF) in the lead region - Part I: ECDF of ^{178,180}Tl and ^{200,202}Fr isotopes; Part II: ECDF of ^{178,182}Tl; Part III: detailed bDF studies of ^{202}Fr and a search for bDF of ^{204}Fr, A.N. Andreyev, successfully completed, closed.
http://cds.cern.ch/record/1080150?ln=en
http://cds.cern.ch/record/1132637?ln=en
http://cds.cern.ch/record/1319032?ln=en

IS511 - Shape coexistence in the lightest Tl isotopes studied by laser spectroscopy, A.N. Andreyev & A.E. Barzakh, successfully completed, closed.
http://cds.cern.ch/record/1319031?ln=en

I086 - Development of astatine ion beams with RILIS, A.N. Andreyev & V.N. Fedosseev, successfully completed, closed.
http://cds.cern.ch/record/1232260?ln=en

IS534 - I: Beta-delayed fission, laser spectroscopy and shape-coexistence studies with radioactive At beams. II: Delineating island of deformation in light Au isotopes by means of laser spectroscopy, A.N. Andreyev, P. Van Duppen & V.N. Fedosseev, **21.5 shifts remaining**.
http://cds.cern.ch/record/1410652?ln=en
http://cds.cern.ch/record/1551259?ln=en
http://cds.cern.ch/record/1643088?ln=en

I153 - In-source laser spectroscopy of mercury isotopes, L.P. Gaffney, M.D. Seliverstov & A.N. Andreyev, endorsed by the INTC.
http://cds.cern.ch/record/1603156?ln=en

Experimental setup/technique

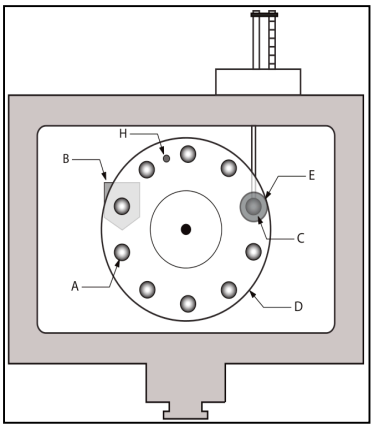

Fig.1 : Layout of the Windmill setup. A. Carbon foil. B. Decay detectors. C. Implantation detectors. D. Wheel. E. Faraday cup. H. ^{241}Am sources.

Setup: The Windmill is an α-decay spectroscopy setup from IKS-KU Leuven, designed and built in the '80s for use at the LISOL separator (CRC, Louvain-La-Neuve, Belgium) [Dendooven92]. It consists of a rotatable aluminium wheel that holds 10 thin carbon foils (20(1) μg/cm^2 thick) on copper rings of 10-12 mm diameter [Lommel02] and two ^{241}Am α sources (<50Bq, Fig. 1, H). After mass separation, the 30-60 keV beam is implanted through the central hole of a silicon annular detector into one of the carbon foils (Fig. 1, C). A second silicon detector is placed closely behind the carbon foil. The two silicon detectors cover a solid angle of 50-66% [Andreyev10, Elseviers13]. This geometry allows effective measurements of both singles and coincident particle decays of implanted activity, e.g. α, electrons, fission fragments. Two additional detectors are placed off-axis (Fig. 1, B) to study the decay of the longer-lived daughter products. Two high-purity germanium detectors typically surround the Windmill in a 90° arrangement to measure the energy of γ rays, offering 3% efficiency at 1 MeV. **At ISOLDE**, the Windmill setup may be placed at LA1, LA2 or GLM, although LA1 is favored. Beam transport efficiency to the setup is typically >95%. The setup comes with its own support, beam collimators, a Faraday cup, and vacuum diagnostics. ISOLDE provides the vacuum pumps. The germanium detectors are set on tables from ISOLDE. A dedicated shielding for the germanium detectors is brought with the setup (lead and copper cylinders). The DAQ is based on the XIA DGF-4C modules + IGOR system from LISOL.

Beta-delayed fission (βDF, IS466, IS534): A major part of the Windmill programme is the study of β-delayed fission in the neutron-deficient lead region. In the βDF process, if the Q_{EC} value of the β-decaying precursor is greater than the fission barrier of the daughter nucleus, the β-decay process can populate excited states in the vicinity of the top of the fission barrier, which may then fission. By measuring the fission fragments with the silicon detectors, it is possible to extract βDF branching ratios, total kinetic energy and fission fragment mass distribution. We identified several new βDF cases in the lead region. Overall, we have studied the βDF of ^{178,180,182}Tl [Liberati13, Andreyev10, Elseviers13], ^{194,196}At, ^{200,202}Fr. A recent review [Andreyev13] summarizes the status of βDF studies across the nuclear chart. Several papers are in preparation. Two PhD theses by L. Ghys (KU Leuven) and V. Truesdale (University of York) are also in preparation.

In-source laser spectroscopy (IS407, IS456, IS466, IS511, IS534): The other major strand of the Windmill programme is the study of the ground-state properties of nuclei with laser spectroscopy using the RILIS. By scanning the laser frequency and measuring the ionization yield of isotopes of interest (via the detection of particle or γ decays), it is possible to observe the hyperfine structure and isotope shift of atomic transitions, from which nuclear spin, electromagnetic moments and changes in the mean-square radii may be deduced [Cheal10, Fedosseev12, Blaum13]. The Windmill setup is used as a counting station, alongside Faraday Cup FC490, the ISOLDE Tape Station, or the MR-ToF-MS at ISOLTRAP [Kreim13]. This technique has been successfully applied to the isotopic chains $_{79}$Au, $_{81}$Tl, $_{82}$Pb, $_{83}$Bi, $_{84}$Po, and $_{85}$At [Marsh13]. To allow the astatine HFS and βDF measurements, a dedicated request for astatine beam development was made (I086), which was successfully completed in 2011-2012 [Rothe13].

Alpha- and beta-decay studies: During the HFS and βDF measurements, particle and γ-ray decay spectroscopy data are collected. These are systematically analyzed to address shape coexistence in nuclei [Heyde11]. Results have been published on the decays of ^{178,179,180}Tl [Liberati13, Andreyev13, Elseviers11], ^{185,189,215}Pb [Andreyev02, Sauvage09, DeWitte13], ^{215,218}Bi [DeWitte04, DeWitte13], ^{195,199}Po [Cocolios10, Cocolios12], and ^{200,201,203,205}Fr [DeWitte05]. Several papers are in preparation.

Future prospects:

βDF studies. The βDF studies of Tl and Fr are now completed and the experiments IS466/IS511 are closed. However, we still need to complete the βDF of ^{194}At from the IS534 proposal, especially addressing the question whether βDF is observed after the ground-state or isomeric-state β decay. This is essential as it sheds light on the influence of the spin of the involved levels on the βDF process (isomer separation is required). We have 3.5 shifts remaining from 2012, and the respective Addendum to IS534 will be submitted in January 2014 (also for HFS of At isotopes, see below). In the future, we wish to proceed with the βDF studies of ^{186,188}Bi and of the *neutron-rich* Fr and Ac isotopes. The respective proposals will be prepared in 2014-2015. The higher γ-ray detection efficiency and better particle/fission detection possibilities at the ISOLDE Decay Station (IDS), being presently developed by our collaboration, motivate that the Windmill programme be moved to the IDS once the appropriate ancillary detectors become available.

HFS/IS, shape coexistence studies. This programme is still on-going. We have an approved Addendum to IS534 to complete the HFS studies of Au isotopes (18 shifts), while another Addendum to IS534 to complete the HFS studies of At isotopes will be submitted in January 2014 (16.5 additional shifts). Following the success of the LIST beam time with Po, an addendum to complete IS456 is in preparation for the INTC in January 2014 (13.5 additional shifts). Furthermore, LoI I153 for the development of mercury beams was endorsed by INTC in 2013. Provided this development is successful, we will proceed with a dedicated proposal for HFS measurements of the most neutron-deficient and neutron-rich Hg isotopes. Depending on the readiness, some of these experiments will be performed at IDS.

Status report for IS456

Title: Study of polonium isotopes ground state properties by simultaneous atomic- and nuclear-spectroscopy
Spokespersons: Thomas Elias COCOLIOS & Yuri KUDRYAVTSEV
Accepted isotopes: polonium-193-212,216-218
Performed studies: **polonium-191-211,216-219**

Experiment IS456 has received beam over three runs in 2007, 2009, and 2012.

2007 campaign: **17 shifts**. The experiment was focused on the even-A isotopes and the study of $^{194-204}$Po was completed successfully. A high level of contamination originating from francium isobars and the tails of nearby francium masses was identified for the neutron-rich isotopes ^{216,218}Po at GLM and that part of the programme was abandoned for that run. The rest of the beam time was then used to study the odd-A isotopes $^{193-199}$Po. Unexpected features were observed in the α decay of ^{195}Po and the β decay of ^{199}Po revealed inconsistencies with the literature data [Cocolios12].

2009 campaign: **23 shifts**. The experiment aimed at completing the previous study by re-measuring the isotopes $^{205-210}$Po with our atomic transition of interest in order to help with determination of the atomic parameters necessary for the extraction of the changes in the mean-square charge radii. In order to avoid the contamination from isobaric francium isotopes, studies were performed in the absence of proton irradiation, using the β decay of isobaric astatine in the target matrix as a precursor: $^{206,208-210,211g}$Po were successfully produced, as well as ^{216,218}Po from the α decay of long-lived radon and radium isotopes. During the periods of irradiation, additional data were acquired on ^{193,195}Po, as well as new data on ^{191,192,201,203}Po. The anomalies in the α decay of ^{195}Po were also addressed and combined with β-decay data from LISOL to resolve the low-lying structure of ^{191}Pb [Cocolios10].

By combining the data sets from the 2007 and 2009 campaigns, it was possible to establish a King plot between two transitions in Po-I which allowed to test the large-scale atomic calculations by S. Fritzsche [Cheal12]. The changes in the mean-square charge radii of the even-A polonium isotopes were found to depart increasingly from the prediction of the FRDM for N<116, unlike the mercury isotopes, which is the mirror isotopic chain across the Z=82 shell closure, where the even-A isotopes are found to remain on a near-spherical trend [Cocolios11] (see Fig 2). The quadrupole and magnetic moments of odd-A polonium isotopes can be explained only when a substantial mixing of spherical and deformed configurations in ground and isomeric states is supposed [Seliverstov13, Seliverstov14]. The resolution of this study was however not sufficient to determine unambiguously the spin of the odd-A isotopes and that of ^{191}Po is questioned in particular.

2012 campaign: **1.5 shifts**. During the 2012 LIST development beam time, additional shifts were used to attempt the study of the isotopes that could not be achieved previously due to the isobaric francium contamination: ^{211m,212m}Po. The suppression factor at those masses was however insufficient to complete the programme and the isotopes $^{216-219}$Po were studied instead. Laser spectroscopy of ^{217}Po was performed for the first time, as well as the first α-decay spectroscopy of ^{219}Po [Fink13].

Status report for IS534 (28 shifts approved in 2012, 3.5 remaining and 18 new shifts were approved in June 2013 for the gold Addendum)

Title: I: βDF, laser spectroscopy and shape-coexistence studies with radioactive At beams. II: Delineating island of deformation in light Au isotopes by means of laser spectroscopy.
Spokespersons: A.N. Andreyev, P. Van Duppen and V.N. Fedosseev
Accepted isotopes: $^{177\text{-}183}$Au, $^{194\text{-}224}$At
Performed studies: $^{177\text{-}183}$Au, ^{194,196,197,201,203,205,207,209,211,217}At

The initial experiment IS534 (28 shifts approved in 2012) aimed at β-delayed fission and laser spectroscopy of astatine beams. Following I086, the pioneering development of the ionization scheme for astatine was completed in 2011-2012 [Rothe13] and two successful campaigns were performed in 2012: May 2012 – βDF studies of ^{194,196}At at GPS in broadband mode, and October 2012 – laser spectroscopy studies of ^{197,198,203,205,207,209,211,217}At at HRS. The respective data are under analysis. The draft of a Letter on the multi-modal fission of ^{194,196}At is available (L. Ghys, PhD student, KU Leuven). Our preliminary charge radii data for At isotopes are shown in Fig 2. An onset of deformation is observed in ^{197}At, along with the kink when crossing the N=126 shell closure. Due to technical issues during the October 2012 experiment, not all planned astatine isotopes could be measured (see Fig 2), which is why we will proceed with an Addendum to complete these measurements (submitted to January 2014 INTC).

In the October 2012 period, a part of the beam time (4.5 shifts) was also used for the initial HFS measurements of the light isotopes $^{177\text{-}183}$Au in narrowband mode. This was motivated by the very interesting pattern of charge radii for these isotopes, measured by us in June 2012 during the Au RILIS beam development, which was performed in parallel with REX-tuning. The analysis of the Au data is in progress (J. Cubiss, PhD student, University of York), and the preliminary status is given in Fig 2. Specifically, the first ever HFS measurements for $^{177\text{-}182}$Au were performed. It shows that $^{180\text{-}182}$Au continue the trend of strongly-deformed $^{183\text{-}186}$Au isotopes, observed in an earlier experiment. In contrast, ^{177,179}Au follow the trend of the heavier (A>187) gold isotopes, which are nearly spherical. In ^{178}Au, the second (and possibly, the third) isomeric state was found, however more data are needed to understand this complex case. Following the approved Addendum to IS534 (June 2013), we will extend these data to lighter masses.

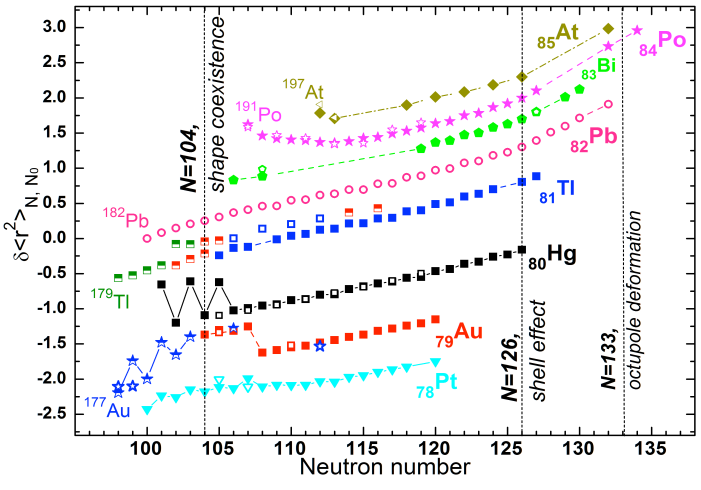

Fig.2 Charge radii in the lead region. The Au, Tl, Pb, Po and At data, measured by our collaboration within IS407, IS456, IS511, IS534 are from: Pb data [DeWitte07], Po data [Cocolios10, Selivestov13], Tl data (IS511, in preparation); At and Au data (IS534, in preparation).

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Appendix

I057/IS456:

Publications

1. [Cocolios08] T.E. Cocolios, B.A. Marsh, V.N. Fedosseev, S. Franchoo,G. Huber, M. Huyse, A.M. Ionan, K. Johnston, U. Köster, Yu. Kudryavtsev, M. Seliverstov, E. Noah, T. Stora, and P. Van Duppen. *Resonant laser ionization of polonium at RILIS-ISOLDE for the study of ground- and isomer-state properties*. Nuclear Instruments and Methods in Physics Research **B 266**, 4403-4406 (2008). Proceedings to the EMIS conference (Deauville, France, June 2007).
2. [Cocolios10] T.E. Cocolios, A.N. Andreyev, S. Antalic, A. Barzakh, B. Bastin, J. Büscher, I.G. Darby, W. Dexters, D.V. Fedorov, V.N. Fedosseev, K.T. Flanagan, S. Franchoo, G. Huber, M. Huyse, M. Keupers, U. Köster, Yu. Kudryavtsev, E Mané, B.A. Marsh, P. Molkanov, R.D. Page, M.D. Seliverstov, A.M. Sjoedin, I. Stefan, J. Van de Walle, P. Van Duppen, M. Venhart, and S. Zemlyanoy. *Structure of ^{191}Pb from α- and β-decay spectroscopy*. Journal of Physics **G 37**, 125103 (2010).
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