| **TRIUMF - EEC SUBMISSION**<br>Draft Submission<br>*Progress Report* | | **Exp. No.**<br>S1241 - *In Preparation*<br><br>**Date Created:**<br>2009-06-04 05:56:15 |
|---|---|---|

**Title of Experiment:**

Mass measurements of astatine isotopes

**Name of group:**

**Spokesperson(s) for Group**

D. Lunney, J. Dilling

**Current Members of Group:**
(name, institution, status, % of research time devoted to experiment)

| | | | |
|---|---|---|---|
| D. Lunney | Universite de Paris Sud | Senior Research | 10% |
| J. Dilling | TRIUMF | Research Scientist | 10% |
| A. Lapierre | TRIUMF | Research Associate | % |
| C. Andreoiu | Simon Fraser University | Assistant Professor | % |
| F. Ames | TRIUMF | Research Scientist | % |
| G. Gwinner | University of Manitoba | Associate Professor | % |
| J. Lassen | TRIUMF | Research Scientist | % |
| M. Brodeur | University of British Columbia | Student (PhD) | % |
| M. Dombsky | TRIUMF | Senior Research | % |
| M.R. Pearson | TRIUMF | Research Scientist | % |
| P. Bricault | TRIUMF | Senior Research | % |
| P.P.J. Delheij | TRIUMF | Research Scientist | % |

| | | | |
|---|---|---|---|
| R. Ringle | NSCL | Research Scientist | % |
| S. Ettenauer | University of British Columbia | Student (PhD) | % |
| T. Brunner | T.U. Munich | Student (PhD) | % |

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**New Beam Requests:**

8 shifts

**Beam Shifts Used:**

**Beam Shifts Remaining:**

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**Basic Information:**

*Date Created:* 2009-06-04 05:56:15

*Date Experiment Ready:* 2009-06-04

*Summary:*

We propose measuring the masses of the neutron-rich astatine isotopes $^{221\#224}$At since they are unknown and lie very close to a possible nucleosynthesis path of the *r*-process. In particular, the mass of $^{223}$At would accurately determine the $Q_{\#}$ value and yield complementary information and constraints concerning octupole deformation. The newly-commissioned Penning-trap spectrometer TITAN, at TRIUMF-ISAC is an excellent choice for these measurements due to the possibility of encountering unknown isomeric states. We request 8 shifts of beam time.

*Plain Text Summary:* Weighing radioactive nuclides determines their binding energy, as a famous equation goes (E = mc2). Not only is the binding energy important for nuclear structure, it also determines the amount of energy available for reactions and decays. The aim of this experiment is two-fold: (1) by determining the masses of unknown astatine isotopes we hope to constrain the processes by which they are used to create even heavier elements in the stars and (2) by which they decay into isotopes of radon, which exhibit a particular nuclear structure effect called octupole deformation that allows a test of fundamental interactions.

*Primary Beam Line:* ISAC-1

*TRIUMF Support (Resources Needed):*

ISAC beam delivery

*NSERC:*

*Other Funding:*

*Safety Issues:*

A full suite of safety reports exist for the TITAN installation.

*EEC Reader:*

TRIUMF SUB-ATOMIC PHYSICS EEC NEW RESEARCH PROPOSAL

Detailed Statement of Proposed Research for Experiment # S1241

**Title:** Mass measurements of astatine nuclides

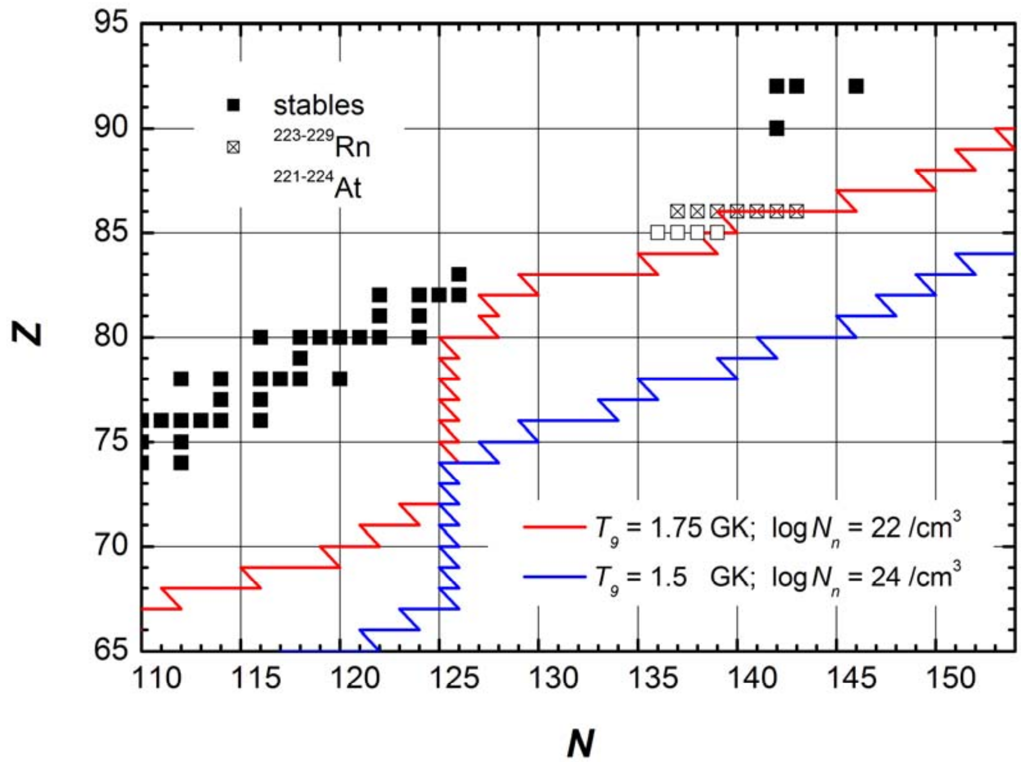
**Spokespersons:** D. Lunney and J. Dilling, for the TITAN collaboration

**Abstract:** We propose measuring the masses of the neutron-rich astatine isotopes $^{221\text{-}224}$At since they are unknown and lie very close to a possible nucleosynthesis path of the *r*-process. In particular, the mass of $^{223}$At would accurately determine the $Q_\beta$ value and yield complementary information and constraints concerning octupole deformation. The newly-commissioned Penning-trap spectrometer TITAN, at TRIUMF-ISAC is an excellent choice for these measurements due to the possibility of encountering unknown isomeric states. We request 8 shifts of beam time.

(a) **Scientific value of the experiment**: Describe the importance of the experiment and its relation to previous work and to theory. All competitive measurements at other laboratories should be mentioned. Include examples of the best available theoretical calculations with which the data will be compared.

A recent forum was convened by the US National Research Council to define the most important unanswered questions in physics. The resulting list was published in Discovery magazine [Has02] and third amongst the “top eleven” questions was the origin of the heavy elements. Since the pioneering work of Burbidge, Burbidge, Fowler and Hoyle in 1957 [B2FH], it has been generally accepted that elements heavier than iron are produced by neutron capture. This process can happen relatively slowly or else in a hot, neutron-rich environment where neutron captures occur very rapidly, as do the beta decays that move the flow to heavier elements. The site of this so-called *r* process is still very much debated however, with leading contenders being type-two supernovae and merging neutron stars [Arn07].

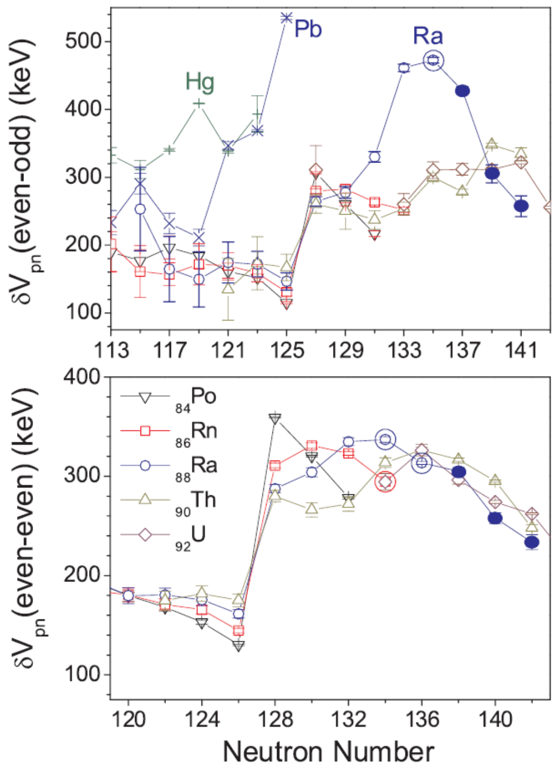
The *r* process involves practically all neutron-rich nuclides from iron to uranium. As such, modeling the r process requires the use of mass models since most of the involved nuclides have never been produced in the laboratory. The choice of mass model therefore plays a large role. The figure below illustrates the chart of the nuclides in the region north-west of $^{208}$Pb and shows three possible *r*-process paths calculated using the canonical model and the waiting-point approximation in which the neutron captures are assumed to be in equilibrium with photodisintegrations. The astrophysical conditions respect the so-called waiting-point validity conditions, as explained by Goriely and Arnould [Gor96]. This high-mass region is particularly important due the process of fission that can allow the *r* process to recycle, greatly affecting the abundance distributions. This point is discussed at length by [Mart06] who reached the interesting conclusion that mass models not predicting shell quenching do not produce robust abundances faced with the occurrence of nuclear fission during the *r* process. Mass measurements are therefore important as input data for modeling and for adjusting the parameters of different mass models (see discussion and comparisons in [Lun03]).

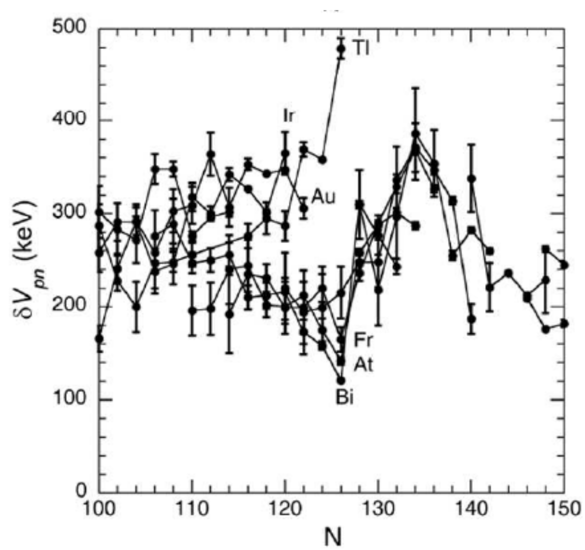



*The area of the nuclear chart north-west of $^{208}$Pb showing stable nuclides (black squares) and two possible r-process paths corresponding to astrophysical conditions that respect the waiting-point validity approximation [Gor96]. Shown as boxes with an "x" are radon nuclides that were measured by the Penning-trap mass spectromer at ISOLDE: ISOLTRAP [Neid09]. Shown as empty boxes are the At isotopes of this proposal.*

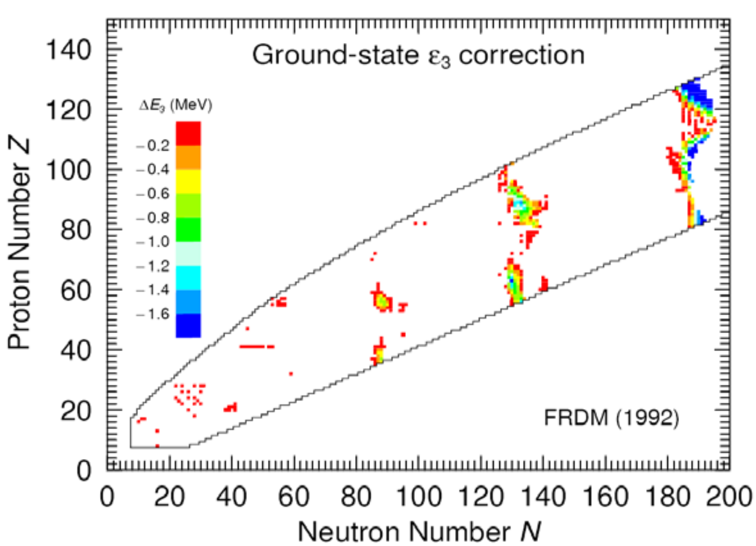
The above figure shows recent measurements from the pioneering Penning-trap mass spectrometer ISOLTRAP at CERN-ISOLDE that produced first mass values for seven radon isotopes one of which, $^{229}$Rn, had never been observed [Neid09]. This was the first observation of a new isotope with a Penning trap, and a nice illustration of the flexibility and performance of these devices. The consequences of these masses on the prediction of models (and on the r process) are currently being studied [Mina09]. Having an adjacent isotope chain would add beta-decay energies which are important for the evaluation of beta-decay half-lives that greatly influence the *r* process.

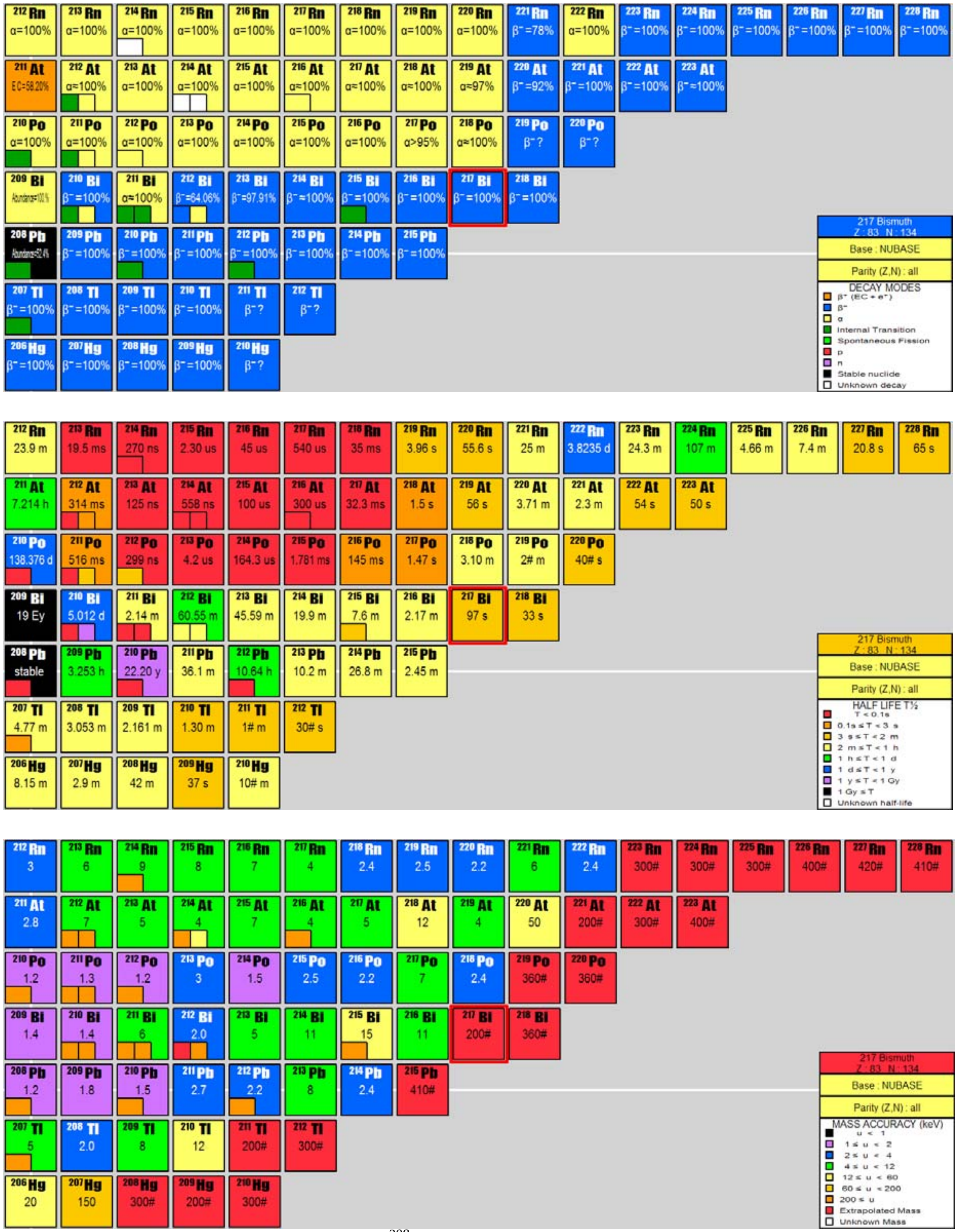
In addition to nucleosynthesis, the masses of the new neutron-rich At isotopes are interesting for nuclear structure, specifically the valence nucleon or $\delta V_{pn}$ interaction – nicely illustrated by the recent mass measurement of $^{208}$Hg by the ESR at GSI [Chen09]. The $\Delta V_{pn}$ values were also discussed in the context of the ISOLTRAP radon results [Neid09]. There, a very interesting anomaly was illustrated for the case of radium (which requires the mass of two radon isotopes). The figure is reproduced below and shows the change in valence nucleon energy as a function of neutron number. In the case of Rn (left, top), the structure seen may be an indication a sub-shell closure or more interestingly, of octupole deformation. The odd-Z cases (right) are less clear-cut since the uncertainties of the points for At are too large.




The case of a possible octupole deformation is intriguing. The Finite Range Droplet Model (FRDM) of Moller and Nix [Moll95] predicts rare octupole deformation in the region concerned by this proposal (see figure below). Through the mass, the binding energy reflects changes from nuclide to nuclide in nuclear structure, with shell effects and deformation being nicely highlighted. As seen in the figure (left), the effects of octupole deformation are much smaller, requiring mass measurements of particularly high accuracy to render them visible. Precision mass measurements of $^{221\text{-}224}$At would not only put constraints on the decay schemes but may also allow a model-dependent extraction of an octupole component from the ground-state energy. This may be interesting for efforts devoted to Electric Dipole Moment (EDM) studies in $^{223}$Rn where octupole deformation is expected to enhance the existence of possible EDMs. The mass measurements of this proposal would therefore be an interesting complement to the beta-decay studies of the Radon-EDM experiment S929 presently underway at ISAC.

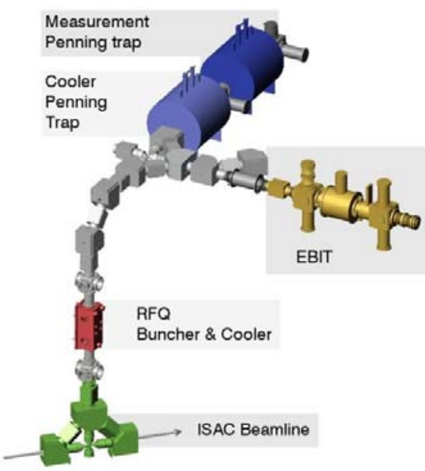





*The area of the nuclear chart north-west of $^{208}$Pb shown as a function of (top) decay mode; (middle) half-life and (bottom) mass uncertainty. Uncertainties marked with # (red) derived from extrapolation [Aud03]. The key nuclides for this proposal are: $^{221-223}$At and heavier.*

(b) **Description of the experiment**: Techniques to be used, scale drawing of the apparatus, measurements to be made, data rates and background expected, sources of systematic error, results and precision anticipated. Compare this precision with that obtained in previous work and discuss its significance in regard to constraining theory. Give a precise list of targets to be used in order of their priority.

These measurements would be performed with the TITAN setup (left), requiring only the RFQ buncher and the measurement Penning trap [Dil06].




To make a mass measurement, an ion is injected into the homogeneous field of the TITAN Measurement Penning Trap (MPET) where its cyclotron frequency $f_c = qB/2\pi m$ is probed and determined using a time-of-flight detection of the ejected ions. The cyclotron frequency is compared to that of a well-known reference mass (generally, a stable species of similar mass) to provide a measurement. TITAN was commissioned in August, 2007 at which point the masses of the short-lived radioactive nuclides $^{8}$Li and $^{9}$Li were measured. Since then, several high-quality measurements have been published: $^{8}$He [Ryjkov08]; $^{11}$Li [Smith08]; $^{11}$Be [Ringle09]. From efficiencies derived from these measurements, yields of less than 100/s are sufficient to measure the nuclides in this proposal. A relative mass uncertainty of $10^{-8}$ is possible in all cases, given statistics.

Use of the new uranium oxide (UO) target coupled with the successful FEBIAD ion source should provide very comfortable rates for $^{221\text{-}223}$At and should also offer the possibility of discovering the new isotope $^{224}$At.

(c) **Experimental equipment**: Describe the purpose of all major equipment to be used.
Details of all equipment and services to be supplied by TRIUMF must be provided separately on the Technical Review Form available from the Science Division Office.

Aside from the TITAN setup itself, the only TRIUMF equipment necessary could be the yield station in order to map out the magnetic profile of some of the isobaric contamination in the case of the FEBIAD source, notably from francium and radon. Since the masses are unknown, it is difficult to say if the mass separator will have sufficient resolving power.

(d) **Readiness**: Provide a schedule for assembly, construction and testing of equipment. Include equipment to be provided by TRIUMF.

The TITAN setup is currently in running mode. TITAN has already run using all three types of ion sources, measuring masses in the same region. **Since the proposed measurements can be made as of today, we request stage-two approval at this time.**

(e) **Beam time required**: State in terms of number of 12-hour shifts. Show details of the beam time estimates, indicate whether prime-user or parasitic time is involved, and distinguish time required for test and adjustment of apparatus.

We request a total of 8 shifts using the UO target and FEBIAD source with the breakdown shown below. Reference masses would be either $^{202}$Hg or $^{204}$Hg, performed every 3-4 hours.

| | |
|---|---|
| **$^{220}$At** | **0.5** |
| **$^{221}$At** | **1.0** |
| **$^{222}$At** | **1.5** |
| **$^{223}$At** | **2.0** |
| **$^{224}$At** | **3.0** |
| **Total** | **8 shifts** |

(f) **Data analysis**: Give details and state what data processing facilities are to be provided by TRIUMF.

All the necessary software tools are now operational for analyzing TITAN data.

## References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