EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Extending and Refining the Mass Surface around ^{208}Pb by High-Precision Penning-Trap Mass Spectrometry with ISOLTRAP

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S. Kreim[1], D. Beck[2], K. Blaum[1], Ch. Böhm[1], Ch. Borgmann[1], M. Breitenfeldt[3] R. B. Cakirli[1,4], T. E. Cocolios[5], F. Herfurth[2], A. Herlert[6], M. Kowalska[5], D. Lunney[7], S. Naimi[7,a], M. Rosenbusch[8], L. Schweikhard[8], S. Schwarz[9], J. Stanja[10], T. Stora[5], F. Wienholtz[8], R. N. Wolf[8], K. Zuber[10]

[1] *Max Planck Institute for Nuclear Physics, Heidelberg, Germany*
[2] *GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany*
[3] *IKS Leuven, Belgium*
[4] *Department of Physics, University of Istanbul, Istanbul, Turkey*
[5] *CERN, Geneva, Switzerland*
[6] *University of Manchester, School of Physics and Astronomy, United Kingdom*
[7] *CSNSM-IN2P3-CNRS, Université de Paris Sud, Orsay, France*
[8] *Ernst-Moritz-Arndt-University, Greifswald, Germany*
[9] *NSCL, Michigan State University, East Lansing, USA*
[10] *Technical University, Dresden, Germany*

Spokesperson: Susanne Kreim, skreim@cern.ch
Contact person: Susanne Kreim, skreim@cern.ch

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Abstract: We propose high-precision mass spectrometry of nuclides around the doubly magic ^{208}Pb. On the neutron-rich side, we aim to extend the knowledge of Fr, At, Hg, and Au masses to study the robustness of the $N = 126$ shell closure and to provide mass data necessary for modeling the rapid-neutron-capture process. On the proton-rich side, we aim at high-resolution mass spectrometry of selected Au, At, and Fr isotopes to verify the predicted existence of very low-lying isomeric states. The proposal will make use of newly-available laser-ionization schemes for Au and At. Finally, the recently implemented multi-reflection time-of-flight mass separator for auxiliary isobaric purification now allows measurements which were not feasible before.

Requested shifts: This is a long-term measurement program that would stretch over 3-4 years and require 85 shifts.

[a] Present address: RIKEN Research Facility, Japan

1 Introduction

Experiments carried out in the heavy-mass region are very suitable to investigate mainly topics related to nuclear structure and the rapid-neutron-capture process. Special interest lies also in phenomena which are not seen in lighter nuclei, such as octupole deformation or which are dramatically pronounced, like the triple shape coexistence of ^{186}Pb [1] or the exception example of shape staggerin in the Hg isotopes [2].
Shell structure development and evolution constitute pressing questions in nuclear physics. Nuclei around the magic proton and neutron numbers of 2,8,20,50 and even 82 have been studied extensively and structural changes have been well observed. For the neutron shell $N = 126$, however, not much data exist. Thus, input for the further development of nuclear structure models in the heavy-mass region is critically lacking in this important region. This proposal aims to investigate the robustness of the $N = 126$ closed shell for more exotic species concerning the nature of the shell gap, residual interaction, isomerism or octupole correlations and intends to study structural changes such as shape coexistence upon filling of the neutron shell towards $N = 126$. The proposed studies nicely complement the already performed measurements at ISOLTRAP in this region of the nuclear chart [3, 4]. Moreover, the experiments carried out under IS 463 and the new proposal INTC-P-293 also aim to probe this heavy-mass region.
Furthermore, mass measurements in the quadrant $N > 126, Z > 82$ allow to investigate a possible nucleosynthesis path of the r-process. Since the r-process involves practically all neutron-rich nuclides from iron to uranium, mass models are needed to model the r-process since most of the involved nuclides have never been produced in the laboratory.

2 Physics Interest and Experimental Program

Within this section, a more detailed physics motivation and the experimental program will be introduced together with the foreseen mass measurements using the ISOLTRAP Penning-trap mass spectrometer.

2.1 Stability of the $N = 126$ and $Z = 82$ Shell Closures

The evolution of shell strength - especially the possibility that it may quench to the point of disappearing - is one of the foremost questions of nuclear structure today. As pointed out by Bender, Bertsch and Heenen [5] (effective) single-particle energies cannot be treated as experimental observables, unlike two-nucleon separation energies that are derived from mass measurements. Therefore, new mass data for more exotic nuclides along shell closures are important for testing state-of-the-art mean field approaches as well as helping to define interaction parameters (see the discussions of shell gaps in [5] as well as Goriely et al. [6]). In addition, High-precision mass measurements at $N = 126 \pm 2$ and $Z = 82 \pm 2$ deliver valuable input for shell model calculations, as explained in detail in [7], by helping to determine the monopole part of the residual interaction. As can be seen from fig. 1, the envisaged measurements lie in the two quadrants below $Z = 82$. Taking into account the known mass accuracy, improved mass values for isotopes of Au,

and Hg (marked with black crosses) will help to investigate the robustness of the $N = 126$ neutron and $Z = 82$ proton shell closure.

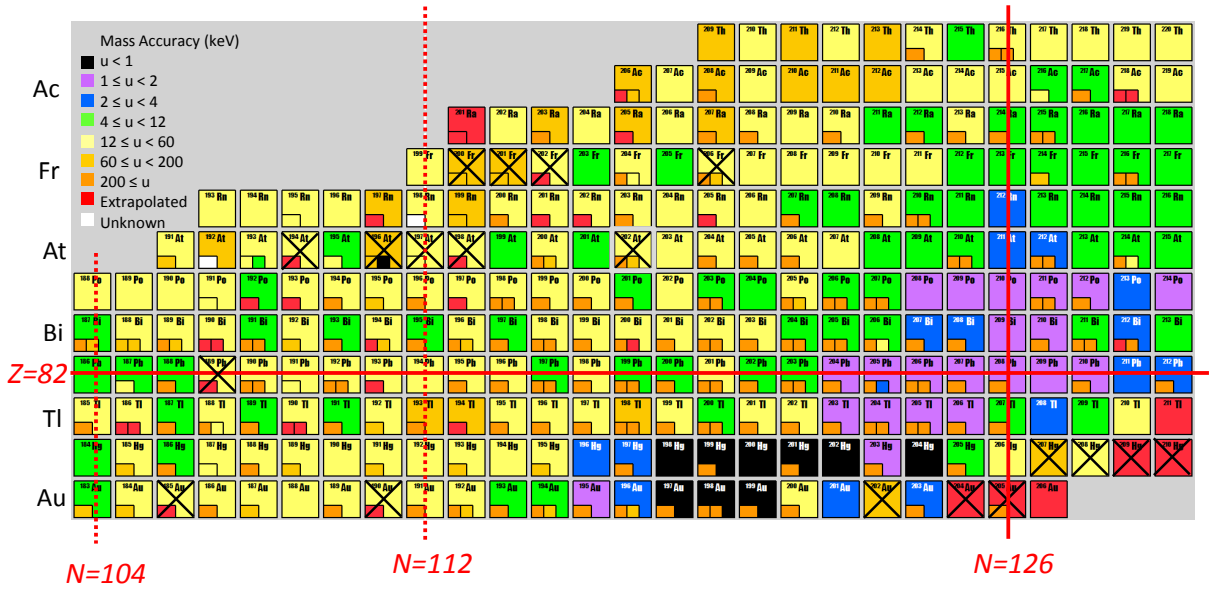

Figure 1: Area of the nuclear chart around the $Z = 82$ proton shell closure displayed with the known mass accuracy [8]. Nuclei of interest for concerning the topics of stability of the $N = 126$ shell closure, mid-shell behavior above and below $Z = 82$, and partly isomerism are marked with black crosses.

- ^{202,204,205}**Au:** With the neutron-rich isotopes of gold the neutron shell closure $N = 126$ will be examined, especially how the nuclear binding energies develop upon reaching and crossing the closed shell. The nucleus ^{204}Au is giving input into calculations for particle-hole excitations, and ^{205}Au is of particular importance since it is a closed-shell nucleus. The masses of ^{204,205}Au are up to now only extrapolated.

- $^{207-210}$**Hg:** With the already quite well known mass of ^{206}Hg as a starting point the robustness of the $N = 126$ shell closure will be examined. Largely improved masses of $^{207-210}$Hg will help investigating the behavior of two-neutron separation energies beyond $N = 126$ in search of signe of shell closure and deformation. Furthermore, with the current uncertainty reachable by ISOLTRAP it is possible to look for the existence of not yet known isomeric states in the Hg isotopes. From the trend in the Hg isotopes, one would expect an isomer in ^{207,209}Hg. In addition, the two isotopes ^{207,208}Hg can be used to calculate particle-hole excitation and two-body matrix elements. The value of ^{208}Hg has recently been measured using the Schottky mass-measurement technique with an uncertainty of 31 keV [9], therefore no shifts will be requested for this nucleus. For ^{209,210}Hg only extrapolated masses are known at present.

2.2 Mid-Shell Behavior

By studying a selected property across the isotopic chain, transitional regions in the chart of nuclei can be identified. Since high-precision mass measurements yield sufficiently small uncertainties on binding energies, they can be used as input parameters for investigating transitional regions, as has been shown by Garcia-Ramos and colleagues for the isotopic chain of platinum [10]. Empirical studies for signatures of transitional nuclei can be found in [11] and the development of collectivity in heavy nuclei is treated in [12]. Within this proposal, we intend to look for an onset of deformation beyond the $Z = 82$ proton shell closure by measuring the isotopic chains of neutron-deficient At and Fr as shown in fig. 1. The mass values of all proposed nuclei will be improved by up to an order of magnitude to less than 20 keV uncertainty which – for nuclei with $A > 180$ – is a prerequisite to access such minute nuclear binding energy effects to probe onsets of deformation or shape coexistence (see e. g. discussion in [4]). Establishing onsets of deformation will moreover give insight into higher-order nucleon interactions.
Mass measurements can guide the adjustment of mass models as it occurred in the refinement of the Skyrme-Hartree-Fock-Bogoliubov mass formulas [6]. Here, the experimental data on binding energies lead to the inclusion of weakened pairing into the mass formulas (e. g. HFB-13), thus reproducing nicely the experimental results. As the shell gap at $N = 126$ has been studied by Goriely and colleagues with very little experimental data, the envisaged measurements on the closed-shell nuclei will expand the experimental knowledge and help to further refine these mass formulas.

- $^{194,196-198,202}$**At:** The mass measurements on the isotopic chain of astatine in the region of the nuclear chart north-west of ^{208}Pb help to look for the onset of deformation which is expected in this heavy-mass region. It can be probed by looking at the neutron and proton separation energies which can be obtained from mass measurements. In addition, the partly only extrapolated values for excitation energies of isomeric states can be improved thus yielding valuable input for spectroscopy experiments. In addition, the available charge radii for At isotopes can be compared with S_{2n} values resulting from the proposed measurements, in search for correlations in these two observables (for more details, see [4]). The masses of ^{195,199,201,203}At are already known well below 20 keV and will aid to complete the isotopic chain.

- $^{200-202,206}$**Fr:** Together with the already existing mass values of uncertainties below 10 keV, it is aimed to study the isotopic chain of francium around $N = 112$. With the improved mass values, the neutron and proton separation energies can be studied regarding onset of deformation north-west of the $N = 126$ and $Z = 82$ shell closures.

2.3 Nucleosynthesis Path for the r-Process

The heavy-mass region is of particular interest due to the process of fission that can allow the r-process to recycle. Mass measurements are important as input data for modeling and for adjusting the parameters of different mass models [13]. Fig. 2 shows two possible r-process paths in the quadrant $N > 126, Z > 82$ corresponding to astrophysical conditions that respect the waiting-point validity approximation [14]. Recently, the radon isotopic

chain was measured at ISOLTRAP producing seven new or improved values [15]. Having an adjacent isotope chains of At and Fr would add beta-decay energies which are important for the evaluation of beta-decay half-lives that greatly influence the r-process.

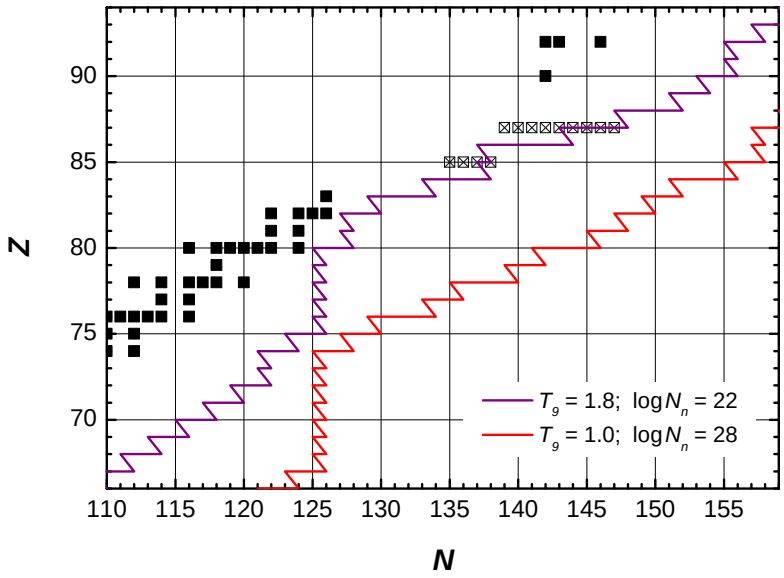

Figure 2: The nuclear chart around ^{208}Pb showing stable nuclides (black squares) and two possible r-process paths. Shown as boxes with an "x" are the At isotopes and Fr isotopes of this proposal. For details, see text.

- **$^{220-223}$At, $^{226-234}$Fr:** The neutron-rich Fr and At isotopes can be used to fill in the rather limited knowledge of precise mass values in this region and thus deepening our knowledge about the evolution of binding energies close to the r-process path. The masses of ^{228,231,232}Fr and $^{221-223}$At would be determined for the first time and for ^{233,234}Fr even the half-lives are not known. The proposed isotopes will help the development of microscopic mass models to consolidate the nucleosynthesis path for the r-process and complement the recently measured radon isotopes [15].

2.4 Octupole Deformation

One of the (many) remarkable features of the nucleus is that it can readily change shape, at apparently little cost in internal energy. Early work by Moller and Nix [16] lead to the elaboration of shape parametrizations within the so-called Macroscopic-Microscopic approach to nuclear masses (FRDM). Despite the simple microscopic component and rather large set of parameters, it is still true that the FRDM gives an accurate fit to the ensemble of experimental mass data. The richness of shapes is manifested by the changes in ordering of the excited states but its cause is found in the small changes

in binding energy between the different shapes. Shown in fig. 3 is a prediction of the octupole component from the FRDM. Though small compared to the total mass, it is very localized. The At and Fr mass measurements proposed here would provide extremely accurate mass values over the entire region of where the predicted octupole effect would begin, peak, and disappear. This may allow us to gather knowledge about the presence and conditions association with octupole shapes. These studies add to the investigations already performed with ISOLTRAP concerning Xe and Rn isotopes [15, 17].

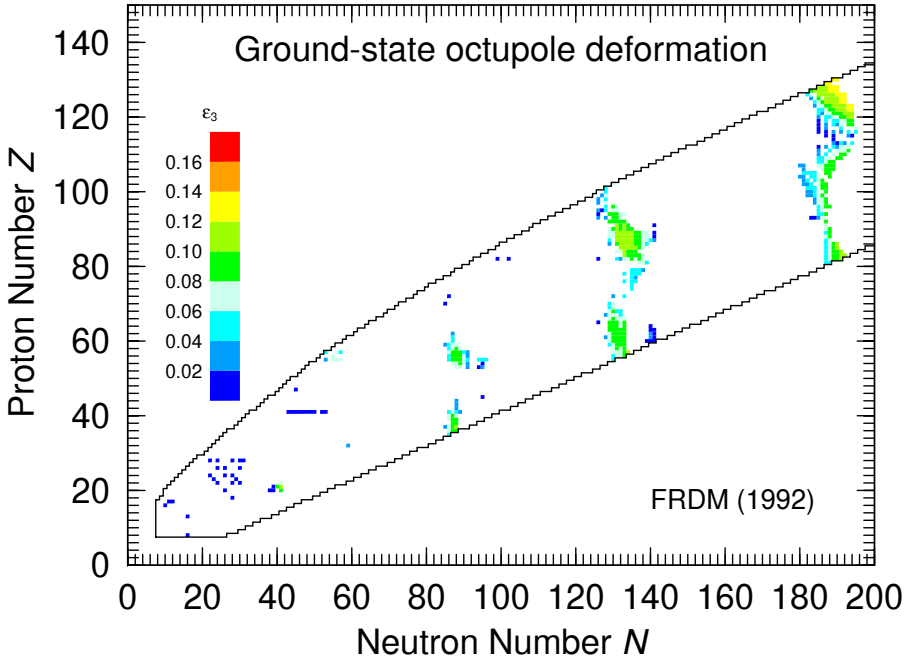

Figure 3: Prediction of octupole deformation across the nuclear chart [16]. The effects in the region $N > 126, Z > 82$ are very small compared to the total binding energy and require mass measurements of particularly high accuracy to render them visible.

2.5 Isomerism

Isomers are important beacons that signal preferable nuclear configurations. The heavy proton-rich region is rife with particularly low-lying isomeric states. The same nuclides are known to exhibit a rich variety of shape coexistence and transformations, see for example Andreyev and colleagues for the case of ^{186}Pb [1] and the famous shape staggering of the Hg isotopes from Dabkiewicz and colleagues [2]. Many of the predicted isomers have so small excitation energies that they are very difficult to determine using conventional nuclear spectroscopy. ISOLTRAP has demonstrated that superior mass resolving power can be brought to bear allowing mass spectrometry to yield a result where nuclear spectroscopy could not (see Schwarz [3] and Van Roosbroeck [18]). We have identified several cases where such isomers could be examined. The determination of excitation energies of isomeric states, which were formerly only extrapolated or not known altogether, also provide necessary input for further spectroscopy experiments.

- ^{185,190}**Au:** In ^{185,190}Au the excitation energies for the isomeric states are only extrapolated and will be determined via mass measurements. Together with the already well-known ground-state masses of ^{185,190}Au, the evolution of nuclear binding energies towards mid-shell can be further examined, south-west of the doubly-magic ^{208}Pb.

- ^{183}**Hg,** ^{185,189}**Pb:** In these three isotopes, not only the excitation energy but also partly the half-lives are extrapolated. The Penning-trap mass measurements will determine the excitation energies, which will lead to a better identification of those nuclides in combination with spectroscopy experiments.

- ^{194,197,198,202}**At,** $^{200-202,206}$**Fr:** Along the At and Fr chain, ground and isomeric states will be studied, where many of the excitation energies are only extrapolated, as marked in table 1. The two nuclides ^{202}At and ^{206}Fr have to be mentioned explicitly, because it is aimed to resolve and determine both isomeric states with ISOLTRAP.

2.6 Nuclei Accessible via α-Decay Chains

Since many of the francium, astatine, and lead nuclei belong to α-decay chains, these mass measurements can provide improved mass values for other nuclei linked via the decay. Whenever the uncertainty in the Q_α-value is smaller than the known mass accuracy, the mass value of daughter, granddaughter, mother or grandmother nuclei can be improved. Therefore, the mass values of ^{181}Hg and ^{189}Po can be improved by measuring ^{185}Pb, the masses of ^{186,189}Tl and ^{194}Bi can be improved through the mass measurements of ^{194,197}At and ^{198}At, respectively. The nuclides ^{196,198,200}At and ^{201,202}Fr are also linked via α-decay chains the respective Fr and At isotopes and their mass values could be improved.

3 Mass Measurements at ISOLTRAP

The Penning-trap mass spectrometer has been performing mass measurements with high-precision for many years giving input to many physical topics reaching from nuclear structure studies to astrophysical applications, which can be monitored by the substantial publication record, see www.cern.ch/isoltrap.

3.1 Experimental Setup

Precision mass measurements have been performed at the Penning-trap mass spectrometer ISOLTRAP for many years with a relative uncertainty routinely reaching 10^{-8} [19]. Up to recently, ISOLTRAP consisted of three parts: a radio-frequency quadrupole (RFQ) ion trap for beam preparation and two Penning traps [19]. A recent summary of all measured masses since 2006 is given in [20]. The linear, gas-filled RFQ ion trap cools the 60 keV continuous ISOLDE beam via buffer gas cooling. Furthermore, the ions are accumulated and leave the so-called buncher as ion bunches towards the preparation Penning trap where contaminants are removed with a resolving power of up to 10^5. The ions are then transferred to the second, precision Penning trap for the mass measurement.

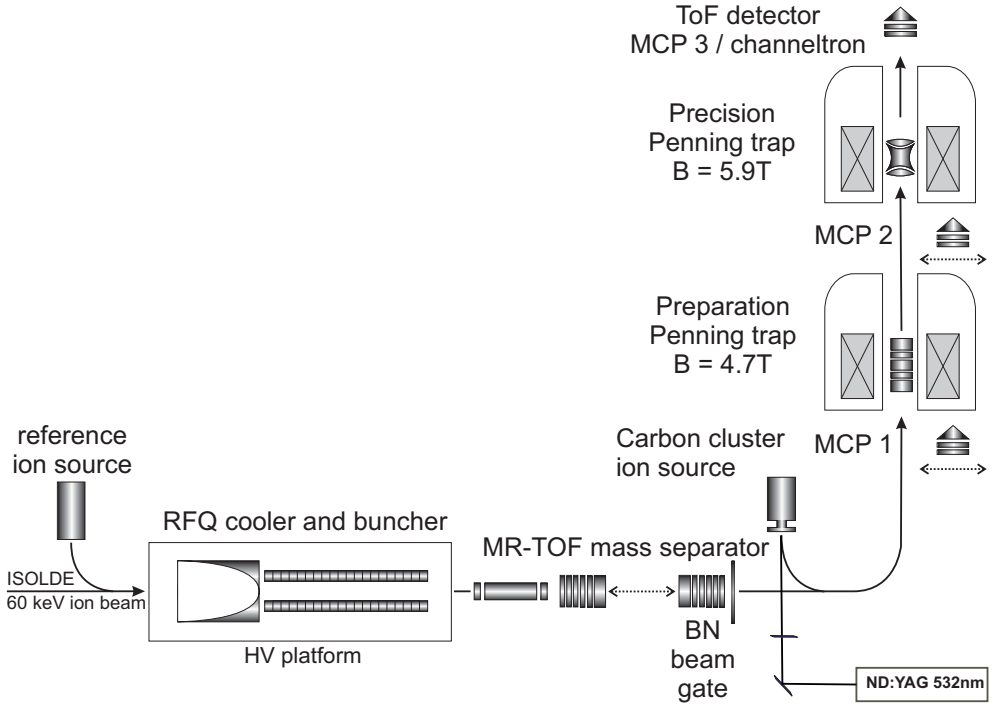

Figure 4: Schematic view of ISOLTRAP.

The time-of-flight detection technique is employed to determine the frequency of an ion stored in a Penning trap, from which the mass can be extracted in conjunction with a reference mass measurement. ISOLTRAP has studied nuclides with half-lives below 100 ms and production yields of only a few hundred ions per second. During the year 2010, a multi-reflection time-of-flight (MR-ToF) mass separator was installed and successfully commissioned [21]. The MR-ToF mass separator acts as an auxiliary device for isobaric purification of rare-isotope ensembles, which not only conserves a high ion-of-interest throughput – in the case of strong contamination, but also works on shorter time scales than the preparation trap thus enhancing the capabilities of ISOLTRAP significantly. Fig. 4 shows the current experimental setup which can be used without modifications for all of the proposed mass measurements.

3.2 Current Performance of ISOLTRAP

The Penning-trap mass spectrometer is able to perform high-precision mass measurements over the whole nuclear chart. The relative, mass-dependent systematic error over a wide mass range of 250 u was determined as an upper limit to $8 \cdot 10^{-9}$ [22]. At room temperature and a pressure of roughly $1 \cdot 10^{-8}$ mbar, the overall efficiency for short-lived nuclei lies around $0.3\,\% - 3\%$ depending on the half-life or charge-exchange losses of the nuclide of interest. The system has adressed nuclei with half-lives down to 65 ms [23] with yield of some few hundred ions per second. Isomeric states can be resolved well below 100 keV excitation energy [24]. With the newly installed MR-ToF mass separator with a pressure of $5 \cdot 10^{-9}$ mbar and usual trapping times of 30 ms one can reach a resolving power of 200,000 and a suppression factor of four orders of magnitude by using a Bradbury-Nielsen

beam gate, which considerably enhances the performance of ISOLTRAP when dealing with large contamination ratios [21].

4 Beam Time Requests

The beam time request of 85 shifts is detailed in the table below. For all cases a uranium carbide (UCx) target can be used but with different ion sources. Below, the isotopes are discussed regarding the feasibility of producing the desired radioactive ion beams.

- **Neutron-rich Au isotopes:** The newly developed RILIS ionization scheme succeeded in providing neutron-rich $^{201-205}$Au isotopes from a UCx target for the first time in 2010. In spite of RILIS lasers, no Hg or Pb isotopes should be present [25]. Unofficial yield estimates by IS447 are $4 \cdot 10^4/1.6\,\mu$A for ^{201}Au and $2 \cdot 10^3/1.6\,\mu$A for ^{202}Au.

- **Hg and Pb isotopes:** The contamination of Tl and Fr can in the meantime be suppressed with a quartz transfer line due to further development of the ISOLDE Target Group, thus relatively pure beams should be deliverable [25]. The yield for neutron-rich Hg isotopes are expected to lie in the same range as the ones for the n-rich Au isotopes, however not well estimated and produced so far. Since some target beam time is needed for extracting the desired radioactive beam, it is planned to couple the technical developments to the proposed physics cases. Further developments might also include laser ionization but this would have to be tested on a time scale not taken into account by this proposal. It also could be investigated to what respect ThO is a possible target, since it could offer interesting gain in terms of production cross section, using 1 GeV protons, and in terms of release properties. As gold has been seen in 2010, it is proposed to first perform mass spectrometry on neutron-rich Au isotopes. The outcome of these measurements should then be used toward target development with ThO. To this end, we ask also for target-development beam time to push forward the production of ThO targets. The neutron-deficient ^{183}Hg is best produced with molten lead target coupled to a VADIS ion source. As for the neutron-deficient Pb isotopes, the current state-of-the are targets are sufficient.

- **Neutron-deficient Au isotopes:** Mass spectrometry on neutron-deficient gold isotopes will profit from using a RILIS ionization scheme as in the case of neutron-rich isotopes. However, a hot plasma ion source could also be used for isotopes with $A \leq 185$ since the yield will be higher as compared to laser ionization. Here, the yields for ^{194,197}Au are $4 \cdot 10^4/\mu$C and $2 \cdot 10^6/\mu$C, respectively [25]. In that case, it has to be checked whether isobaric contamination from Hg and Tl isotopes can be handled by the ISOLTRAP purification systems. Here, the ISOLTRAP setup could aid target development within the scope of a few years. Alternatively, the newly-developed VADIS arc-discharge ion source could be used to further enhance the yield. Mass spectrometry for neutron-deficient Au could also be performed on molecules produced in a FEBIAD ion source. This, however, would need serious

target development and should be regarded as a medium-term enhancement (not covered by the time line of this proposal).

- **At isotopes:** ISOLDE has successfully delivered negative ion beams of astatine with a ThO target, however, these beams cannot be used at ISOLTRAP for mass spectrometry. With the RILIS ionization scheme successfully tested in 2010, positive At ion beams are now available. However, since the tests were not done with a traditional ISOLDE target, target developments would be needed to produce reliable beams of At isotopes, which could be scheduled in one of the next runs of the running period 2011. Again, ISOLTRAP can be used as a monitoring tool to document the target development. In the meantime, a three-step resonant ionization scheme for astatine was successfully tested at TRIUMF yielding about a factor of 50 more in efficiency compared to the first results at ISOLDE. Unofficial yields using the three-step ionization scheme at TRIUMF were quoted for ^{199,218}At to be $5 \cdot 10^4$/s and $3 \cdot 10^3$/s, respectively. The Fr contamination starting around $A = 203$ could be cleaned away using a beam gate for the long-lived isomers. In the other cases, the MR-ToF mass separator is expected to cope with the contamination of Fr and Ra isotopes because resolving power and expected contamination ratio seem feasible. For the Tl contamination on the neutron-deficient side, the required resolving power lies more than one order of magnitude below the demonstrated value.

- **Fr isotopes:** Compared to measurements undertaken by ISOLTRAP in 2002, the isobaric contamination of Ra isotopes can now be estimated with a yield not higher than the Fr isotopes themselves when using a Ta or Nb surface ion source [25]. The newly installed MR-ToF mass separator can achieve a resolving power to the full-width-half-maximum (FWHM) of 200,000 and a suppression of the separated ion beams by four orders of magnitude, see fig. 4 [21]. Taking the required resolving power for Fr ions into account which lies for all isotopes of interest well below the present limit of the MR-ToF mass separator, the current ISOLTRAP setup will be able to deal with the Ra contamination due to this improvement in selectivity.

- **Isomeric States:** The present limit for resolving isomeric states with the ISOLTRAP Penning-trap mass spectrometer lies below 100 keV excitation energy. Isomeric states are proposed with an excitation energy sufficient for isomeric separation with the Penning-trap mass spectrometer. To summarize, the proposed measurements include studies on isomeric states of ^{185,190}Au, ^{183}Hg, ^{185,189}Pb, ^{194,197,198,202}At, $^{200-202,206}$Fr as well as the search for isomerism in the neutron-rich isotopes of gold and mercury. In ^{185,190}Au and ^{200}Fr the assignment of states is uncertain. The isotopes are included in table 1.

Table 1 shows all isotopes for which shifts are requested with their half-lives and the current mass uncertainty, taken from [8]. Extrapolated values are marked with #. The expected yields were taken from the ISOLDE yield database or communicated by Thierry Stora. The numbers marked with $ are extrapolated. Isotopes, where the isomeric states shall be studied, are indicated by ^{m}. Moreover, the target-ion-source combination is listed for the different isotopes.

- For astatine, the yields given were produced with a ThO target, which produces negative ion beams. Although negative ion beams cannot be utilized by ISOLTRAP, the yields for a target producing positive ion beams should be comparable [25]. The yield estimate for ^{190gs}Au is $7 \cdot 10^7/\mu$C. This is expected to drop by several orders of magnitude for the isomer production taking into account half-life and isomer production branching, which should nevertheless provide an ion beam analyzable by ISOLTRAP. The yield for $^{221-223}$At were measured using the SC instead of the PSB. Thus, some drop from these figures must be expected. The isotopes $^{221-223}$At have been reported as measured by Chen and colleagues [26], but mass values have not been provided.

- For the proposed measurements on the Hg isotopes, we intend to use the remaining shifts of the proposal IS463.

- The MR-ToF mass separator needs to be calibrated for removal of contaminants for each mass number A, which requires 0.3 shifts per A. Since mass measurements are intended on 27 different masses, in total 9 additional shifts are needed for this calibration.

Summary of requested shifts: In summary, 85 shifts are requested, 76 shifts for the actual mass measurements, as can be seen from table 1, and 9 shifts for calibration of the MR-ToF mass separator. Additional beam time for target development will be needed (to be allocated separately to the ISOLDE Target Group).

Table 1: Beam time requests

nuclei	half-life	δm/keV	yield (ion/μC)	shifts	target	ion source
^{185m}Au	6.8 m	100#	$8{\cdot}10^{7}$\$	4	UCx	RILIS or hot plasma
^{190m}Au	125.0 ms	150#	n. a.	4	UCx	RILIS or hot plasma
^{202}Au	28.4 s	170	$2{\cdot}10^{3}$	2	UCx	RILIS
^{204}Au	39.8 s	200#	$8{\cdot}10^{2}$\$	4	UCx	RILIS
^{205}Au	32.5 s	300#	$2{\cdot}10^{2}$\$	4	UCx	RILIS
^{183m}Hg	5.0 s#	40#	$3{\cdot}10^{4}$	2	molten Pb	VADIS
^{207}Hg	2.9 m	150	$5{\cdot}10^{5}$\$	0	UCx	RILIS or hot plasma
^{209}Hg	37.0 s	150#	$5{\cdot}10^{3}$\$	0	UCx	RILIS or hot plasma
^{210}Hg	10.0 m#	200#	$5{\cdot}10^{2}$\$	0	UCx	RILIS or hot plasma
^{185m}Pb	4.07 s	40#	$5.0{\cdot}10^{2}$	2	UCx	RILIS
^{189m}Pb	1.0 m#	30	$9.2{\cdot}10^{6}$	2	UCx	RILIS
^{194m}At	250.0 ms	60	$1{\cdot}10^{2}$\$	2	UCx	RILIS
^{196}At	388.0 ms	60	$1{\cdot}10^{4}$\$	2	UCx	RILIS
^{197}At	2.0 s	50	$3{\cdot}10^{4}$\$	2	UCx	RILIS
^{197m}At	388.2 ms	50	$3{\cdot}10^{4}$\$	2	UCx	RILIS
^{198}At	4.06 s	50	$1{\cdot}10^{6}$\$	2	UCx	RILIS
^{198m}At	1.0 s	90#	$1{\cdot}10^{6}$\$	2	UCx	RILIS
^{202}At	184.0 s	28	$3{\cdot}10^{5}$	1	UCx	RILIS
^{202m}At	182.0 s	40	$3{\cdot}10^{5}$	1	UCx	RILIS
^{202m}At	460.0 ms	40	$3{\cdot}10^{5}$	1	UCx	RILIS
^{220}At	3.71 m	50	$7.7{\cdot}10^{3}$	2	UCx	RILIS
^{221}At	2.3 m	200#	$4.5{\cdot}10^{3}$\$	2	UCx	RILIS
^{222}At	54.0 s	300#	$1{\cdot}10^{3}$\$	3	UCx	RILIS
^{223}At	50.0 s	400#	$1{\cdot}10^{2}$\$	4	UCx	RILIS
^{200}Fr	49.0 ms	80	$1{\cdot}10^{1}$	2	UCx	Ta or Nb
^{200m}Fr	190.0 ms	110	$1{\cdot}10^{1}$	1	UCx	Ta or Nb
^{201}Fr	62.0 ms	70	$1{\cdot}10^{0}$	2	UCx	Ta or Nb
^{201m}Fr	27.0 ms	90	$1{\cdot}10^{0}$	1	UCx	Ta or Nb
^{202}Fr	300.0 ms	50	$1{\cdot}10^{5}$	2	UCx	Ta or Nb
^{202m}Fr	290.0 ms	90#	$1{\cdot}10^{5}$	1	UCx	Ta or Nb
^{206}Fr	16.0 s	28	$1{\cdot}10^{8}$	1	UCx	Ta or Nb
^{206m}Fr	15.9 s	40	$1{\cdot}10^{8}$	1	UCx	Ta or Nb
^{206m}Fr	700.0 ms	40	$1{\cdot}10^{8}$	1	UCx	Ta or Nb
^{226}Fr	49.0 s	100	$1.1{\cdot}10^{9}$	1	UCx	Ta or Nb
^{227}Fr	2.47 m	100	$4.2{\cdot}10^{8}$	1	UCx	Ta or Nb
^{228}Fr	38.0 s	unknown	$4.2{\cdot}10^{8}$	1	UCx	Ta or Nb
^{229}Fr	50.2 s	40	$1{\cdot}10^{8}$\$	1	UCx	Ta or Nb
^{230}Fr	19.1 s	30	$1{\cdot}10^{7}$\$	1	UCx	Ta or Nb
^{231}Fr	17.6 s	unknown	$1{\cdot}10^{6}$\$	1	UCx	Ta or Nb
^{232}Fr	5.0 s	unknown	$1{\cdot}10^{5}$\$	2	UCx	Ta or Nb
^{233}Fr	not known		$1{\cdot}10^{4}$\$	3	UCx	Ta or Nb
^{234}Fr	not known		$1{\cdot}10^{3}$\$	3	UCx	Ta or Nb

References

[1] A. Andreyev, et al., *Nature* **405**, 430 (2000).

[2] P. Dabkiewicz, et al., *Phys. Lett. B* **82**, 199 (1979).

[3] S. Schwarz, et al., *Nucl. Phys. A* **693**, 533 (2001).

[4] C. Weber, et al., *Nucl. Phys. A* **803**, 1 (2008).

[5] M. Bender, G. F. Bertsch, P.-H. Heenen, *Phys. Rev. C* **78**, 054312 (2008).

[6] S. Goriely, M. Samyn, J. M. Pearson, *Nucl. Phys. A* **773**, 279 (2006).

[7] O. Sorlin, M.-G. Porquet, *Porgr. Part. Nucl. Phys.* **61**, 602 (2008).

[8] G. Audi, A. H. Wapstra, C. Thibault, *Nucl. Phys. A* **729**, 337 (2003).

[9] L. Chen, et al., *Phys. Rev. Lett.* **102**, 122503 (2009).

[10] J. E. Garcia Ramos, C. DeCoster, R. Fossion, K. Heyde, *Nucl. Phys. A* **688**, 735 (2001).

[11] R. B. Cakirli, R. F. Casten, *Phys. Rev. C* **78**, 041301(R) (2008).

[12] R. F. Casten, D. S. Brenner, P. E. Haustein, *Phys. Rev. Lett.* **58**, 658 (1987).

[13] D. Lunney, J. M. Pearson, C. Thibault, *Rev. Mod. Phys.* **75**, 1021 (2003).

[14] S. Goriely, M. Arnould, *Astronomy and Astrophysics* **312**, 327 (1996).

[15] D. Neidherr, et al., *Phys. Rev. Lett.* **102**, 112501 (2009).

[16] P. Möller, J. R. Nix, W. D. Meyers, W. J. Swiatecki, *Atomic Data and Nuclear Data Tables* **59**, 185 (1995).

[17] D. Neidherr, et al., *Phys. Rev. Lett.* **102**, 112501 (2009).

[18] J. Roosbroeck, et al., *Phys. Rev. Lett.* **92**, 112501 (2004).

[19] M. Mukherjee, et al., *Eur. Phys. J. A* **35**, 1 (2008).

[20] M. Kowalska, et al., *Hyp. Int.* **196**, 199 (2010).

[21] N. R. Wolf, M. Eritt, G. Marx, L. Schweikhard, *Hyp. Int.* (2010), submitted.

[22] A. Kellerbauer, et al., *Eur. Phys. J. D* **22**, 53 (2003).

[23] A. Kellerbauer, et al., *Phys. Rev. Lett.* **93**, 072502 (2004).

[24] C. Weber, et al., *Phys. Lett. A* **347**, 81 (2005).

[25] T. Stora, private communication (2010).

[26] L. Chen, et al., *Phys. Lett. B* **691**, 234 (2010).

Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT
The experimental setup comprises: ISOLDE central beam line and ISOLTRAP setup. The preliminary safety file is the WORD document "safety-requirements-ISOLDE-ISOLTRAP" with the corresponding attached documents dealing with the different hazards: acetone, cadmium, ethanol, helium, isopropanol, nitrogen, and noise. Furthermore, the existing ISIEC EXCEL file "ISIEC_ISOLTRAP_2010-11-18" is also part of the safety documents made available for the ISOLTRAP experiment.

Part of the	Availability	Design and manufacturing
ISOLTRAP setup	☒ Existing	☒ To be used without any modification

HAZARDS GENERATED BY THE EXPERIMENT (if using fixed installation:) Hazards named in the document relevant for the fixed ISOLTRAP installation.

Additional hazards:

Hazards	[Part 1 of experiment/ equipment]	[Part 2 of experiment/ equipment]	[Part 3 of experiment/ equipment]
Thermodynamic and fluidic			
Pressure	[pressure][Bar], [volume][l]		
Vacuum			
Temperature	[temperature] [K]		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid	[fluid], [pressure][Bar], [volume][l]		
Electrical and electromagnetic			
Electricity	[voltage] [V], [current][A]		
Static electricity			
Magnetic field	[magnetic field] [T]		
Batteries	☐		
Capacitors	☐		
Ionizing radiation			
Target material [material]			
Beam particle type (e, p, ions, etc)			
Beam intensity			

Beam energy			
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	□		
• Open source	□		
• Sealed source	□ [ISO standard]		
• Isotope			
• Activity			
Use of activated material:			
• Description	□		
• Dose rate on contact and in 10 cm distance	[dose][mSV]		
• Isotope			
• Activity			
Non-ionizing radiation			
Laser			
UV light			
Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300 MHz)			
Chemical			
Toxic	[chemical agent], [quantity]		
Harmful	[chem. agent], [quant.]		
CMR (carcinogens, mutagens and substances toxic to reproduction)	[chem. agent], [quant.]		
Corrosive	[chem. agent], [quant.]		
Irritant	[chem. agent], [quant.]		
Flammable	[chem. agent], [quant.]		
Oxidizing	[chem. agent], [quant.]		
Explosiveness	[chem. agent], [quant.]		
Asphyxiant	[chem. agent], [quant.]		
Dangerous for the environment	[chem. agent], [quant.]		
Mechanical			
Physical impact or mechanical energy (moving parts)	[location]		
Mechanical properties (Sharp, rough, slippery)	[location]		
Vibration	[location]		

Vehicles and Means of Transport	[location]		
Noise			
Frequency	[frequency],[Hz]		
Intensity			
Physical			
Confined spaces	[location]		
High workplaces	[location]		
Access to high workplaces	[location]		
Obstructions in passageways	[location]		
Manual handling	[location]		
Poor ergonomics	[location]		

Hazard identification:

Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): No additional equipment needed.