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

Decay studies and mass measurements on isobarically pure neutron-rich Hg and Tl isotopes

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Abstract

We propose to perform mass measurements followed by β- and γ-decay studies on isobarically pure beams of neutron-rich Hg and Tl isotopes, which are very poorly known due to a large contamination at ISOL-facilities with surface-ionised francium. The aim is to study the binding energies of mother Hg and Tl nuclides, as well as the energies, spins and parities of the excited and ground states in the daughter Tl and Pb isotopes. The proposed studies will address a new subsection of the nuclear chart, with $Z < 82$ and $N > 126$, where only 9 nuclides have been observed so far. Our studies will provide valuable input for mass models and shell-model calculations: they will probe the proton hole-neutron interaction and will allow to refine the matrix elements for the two-body residual interaction. Furthermore, they also give prospects for discovering new isomeric states or even new isotopes, for which the half-lives are predicted in the minute- and second-range.

To reach the isobaric purity, the experiments will be performed at the ISOLTRAP setup. The mass measurements will take place in the precision Penning trap, which – for excitation energies of 100 keV or more – can even resolve isomers. The decay system will be located behind ISOLTRAP, where the mother nuclei will be implanted in a tape surrounded by detectors measuring the intensity, energy and time evolution of the emitted β and γ radiation.

For the following program we request in total 22 shifts, spread into a run on Hg isotopes and a test-run devoted to yields of Tl isotopes.

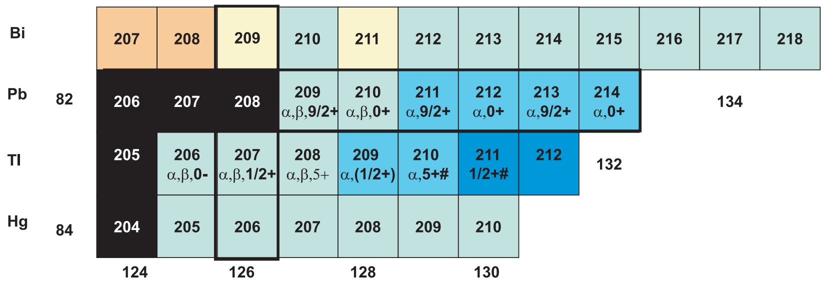

Figure 1: Fragment of the nuclear chart around ^{208}Pb. Tl and Pb isotopes with missing nuclear-structure information are indicated in darker shades of blue. α indicates that there is experimental data on states fed via α decay, β means the same for states populated via β-decay. Also the ground-state spins are presented.

1 Introduction

Studies of many interesting regions of the nuclear chart at ISOL-type facilities are hampered by large isobaric contaminations. One of such regions comprises neutron-rich nuclides in the vicinity of ^{208}Pb, which can be produced only with uranium and thorium targets, where the surface-ionised francium is an unavoidable problem. Earlier experiments at ISOLDE (IS354 [1] and IS387 [2]) already studied this region, but they aimed specifically at Tl, Pb and Bi isotopes in the mass range A=215-217, for which Fr half-lives are in the μs range.

We want to propose a solution to this contamination problem – which did not allow the previous experiments to address isotopes below $A = 215$ – by using the ISOLTRAP Penning traps to isobarically purify the beam of interest. This will allow us to study nuclides from the remaining quadrant of the nuclear chart around ^{208}Pb – with $Z < 82$ and $N > 126$ (Fig. 1), where much less data are collected than for nuclides above the Pb isotope chain. The beams of interest of this proposal are the neutron-rich Hg and Tl isotopes beyond $N = 126$, where we want to measure the masses and β- and γ-decay schemes. Thus, we will also gain insight into excited states of the daughter nuclides: Tl and Pb.

2 Physics motivation

The neutron-rich isotopes in the vicinity of ^{208}Pb have remained quite unexplored for a long time. This is the case especially for mercury and thallium, which lie in a new subsection of the nuclear chart with $50 < Z < 82$ and $N > 126$ (Fig. 1), where only 9 nuclides have been identified so far.

The study of nuclides with few valence particles or holes provides the best test ground for basic ingredients of shell-model calculations, especially concerning the matrix elements of the two-body residual interaction. In the case of neutron-rich mercury and thallium isotopes, which have been particularly successfully described by Kuo and Herling [3], new information can be gained on the interaction of proton-holes with neutron-particles. Since the data is so scarce, every new decay measurement can be used to refine and improve the existing interactions [4, 5]. It also allows to trace the evolution of the single-particle levels when going away from the doubly-magic ^{208}Pb, and to clarify to which extend the shell model with magic $Z = 82$ and $N = 126$ is upheld in this region. Also mass measurements in this area are extremely valuable, since predictions for different terms in the mass formulas, such as the isospin symmetry term, vary significantly for different models and this effect increases when going from one shell to another, as shown recently [6]. Mercury masses above $N = 126$ will also give the first values in this quadrant of the nuclear chart of δV_{pn} [7], representing the average interaction of the last two protons and the last two neutrons for even-even nuclei, which revealed a number of interesting results, such as empirical evidence for its correlation with growth rates of collectivity [8].

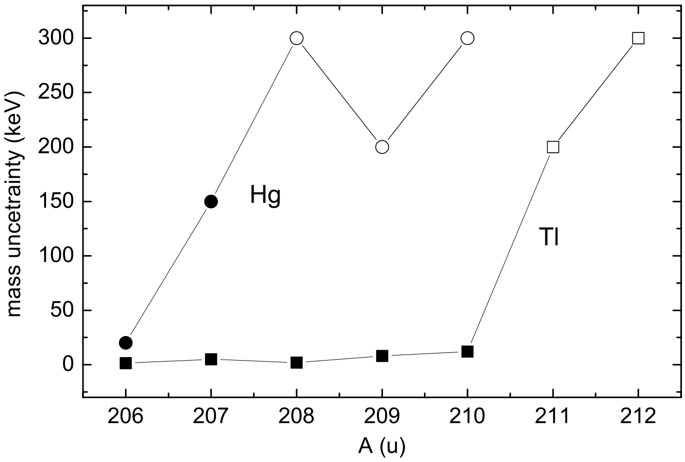

Figure 2: Experimental uncertainty in the mass of neutron-rich Hg and Tl isotopes [9]. None of these masses were measured directly. Data represented by empty circles and squares are known not from purely experimental data, but at least partly from systematic trends.

2.1 Present knowledge of the region of interest

The masses of Hg and Tl isotopes beyond $N = 126$ are not very well known [9]. Their uncertainties, with the exception of $^{206-210}$Tl, are in the range of several hundred keV, as shown in Fig. 2. None of them were measured directly and the majority is based at least partly on systematic trends.

The nuclear structure of the nearest neighbours of ^{208}Pb, with one or two proton/ neutron (particle or hole) outside the closed shell, have been studied in detail using transfer and stripping reactions on stable lead targets. Recently, in this way new excited states in ^{208}Tl were determined [10].

Deep inelastic heavy-ion reactions have been shown to populate high-spin yrast states in stable and moderately neutron-rich isotopes. By combining this method with high-resolution γ-spectroscopy detailed information was obtained e.g. for ^{208,209,210}Pb [11, 12, 13] and ^{206}Hg [14]. However, this technique cannot give access to the very neutron-rich isotopes.

The projectile fragmentation of uranium provided information on several neutron-rich isotopes in the Hg-Po region via time-of-flight, magnetic rigidity and energy loss measurements. The identified nuclides included ^{209,210}Hg and ^{211,212}Tl [15].

The most straightforward way of getting nuclear-structure information is through α decays. These, however, only feed a small part of the excited levels, and do not reach below thallium. As shown in Fig. 3 on the example of ^{207}Tl, β decay can provide much more information, thus the need to perform such measurements.

The present knowledge of the states of Tl and Pb nuclides in this region is summarised in Fig. 1, Table 1 and Table 2. In some cases no decay information is available at all, and even the ground-state half-life is not known.

2.2 Aims of the proposed studies

The proposed mass measurements will allow us to derive the binding energies and two neutron separation energies, as well as first δV_{pn} values in this subregion of the nuclear chart.

The decay studies will give access to the positions of the single-particle states and their evolution with an increasing number of protons. Thallium isotopes have 81 protons, thus their ground state should be formed by one proton hole in one of the close-lying $h_{11/2}s_{1/2}d_{3/2}$ orbits below the $Z = 82$ shell gap. For even mass – and odd neutron – isotopes beyond

Table 1: Measured nuclear-structure properties of neutron-rich Tl isotopes [10, 15, 16].

A	N	I^{π}	$t_{1/2}$ g.s./isomer	level scheme from α-decay	level scheme from β-decay
206	125	0^{-}	3.7 min/ 4.2 min	+	+
207	126	$1/2^{+}$	1.3 s/ 4.8 min	+	+
208	127	5^{+}	3.1 min	+	+
209	128	$(1/2^{+})$	2.2 min	+	-*
210	129	(5^{+}) syst.	1.3 min	-	-
211	130	(1/2+) syst.	> 300 ns	-	-
212	131	-	> 300 ns	-	-

* L. Zhang et. al [17] observed 3 new γ lines in the β decay of ^{209}Hg, which they attributed to ^{209}Tl, but no new level scheme was proposed.

Table 2: Measured nuclear-structure properties of neutron-rich Pb isotopes [16].

A	N	I^{π}	$t_{1/2}$	level scheme from α-decay	level scheme from β-decay
209	127	$9/2^{+}$	3.3 h	+	+
210	128	0^{+}	22.3 years	+	+
211	129	9/2+	36.1 min	+	-
212	130	0^{+}	10.6 h	+	-
213	131	$(9/2^{+})$	10.2 min	+	-
214	132	0^{+}	26.8 min	+	-
215	133	-	-	-	-

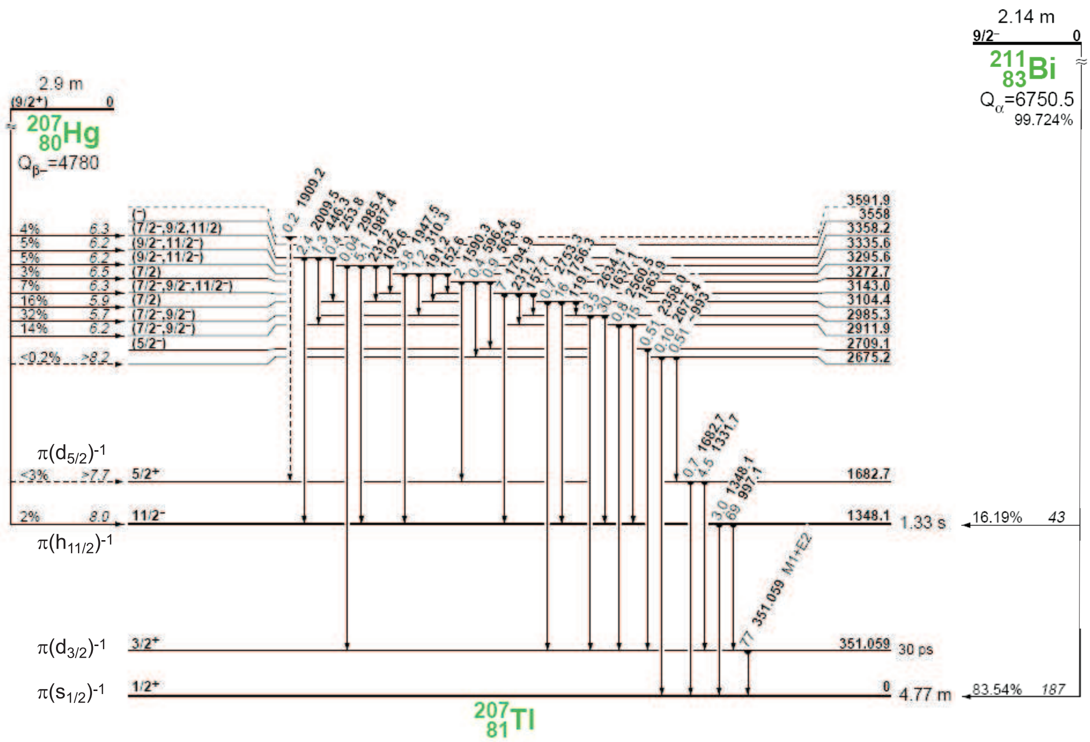

Figure 3: Measured level scheme of ^{207}Tl obtained from β decay of ^{207}Hg and α decay of ^{211}Bi [16]. For the lowest lying proton-hole states, the dominant configuration is indicated.

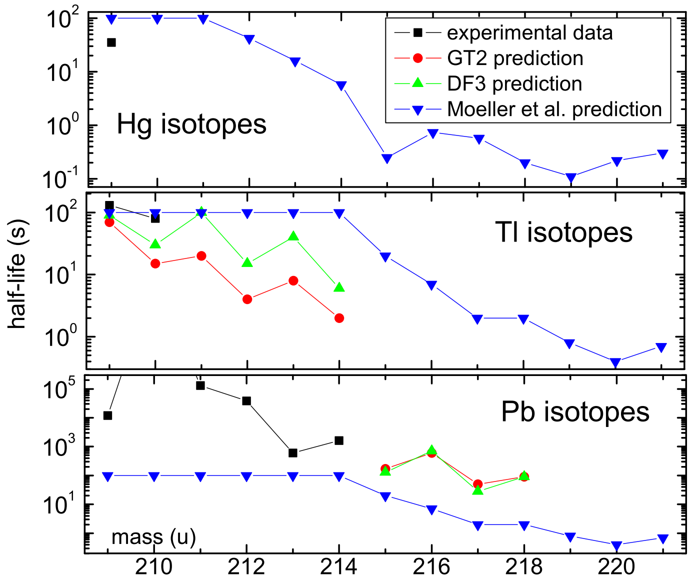

Figure 4: Measured and estimated half-lives of Hg, Tl and Pb nuclides beyond $A = 209$. For the estimates by Möller et. al [18], 100 s half-life indicated for some nuclides is only the lower limit. Results of calculations using DF3 and GT2 models – both including allowed and first forbidden transitions – taken from [19]. Experimental data taken from [16].

$A = 206$ this hole is coupled to a neutron in one of the $g_{9/2}d_{3/2}i_{11/2}$ orbits. Lead isotopes with $Z = 82$, on the other hand, are magic and their low-lying nuclear structure – beyond doubly-magic ^{208}Pb – should be governed only by valence neutrons above $N = 126$. At higher energies, also excitation of protons across $Z = 82$ may take place.

Since the proton-hole orbital $h_{11/2}$ has a much larger spin than $s_{1/2}$ and $d_{3/2}$ holes, we also hope to discover long-lived isomeric states, present for example in ^{206}Tl and ^{207}Tl, as shown in Fig. 3. The experiment has also the potential of discovering new nuclides, whose half-lives are predicted by numerous models to lie in the range of seconds or even minutes, as presented in Fig. 4.

3 Experimental procedure

The proposed mass measurements will take place at the ISOLTRAP setup [20, 21], whereas the decay studies will be performed at a tape-station system for β- and γ-decay spectroscopy located behind ISOLTRAP, as shown in Fig. 5.

The experimental procedure required for the proposed studies is the following: The linear gas-filled RFQ ion trap stops the 60-keV continuous ISOLDE beam and prepares it for transfer into the cooling Penning trap (with 15% efficiency). To this end, the ISOLDE ions are electrostatically retarded before they enter the RFQ, where they are cooled by energy loss due to collisions with the helium buffer gas. After a certain cooling time (typically 10 ms) the ions are transferred as an ion bunch into the tandem Penning trap system. In the cooling Penning-trap the ions are stored (up to 1 s) and contaminant ions are removed. This is done through a mass-selective buffer gas cooling technique, which is presently limited to a ratio of contaminants to the ions of interest not larger than around 10^3, due to space charge effects.

Next, the ions are transferred to the second, precision Penning trap, where – in the case of mass measurements – they are captured. The mass of the stored ion is determined via its cyclotron frequency. A cyclotron resonance spectrum is obtained by the time-of-flight detection method: The extra radial kinetic energy resulting from the resonant excitation

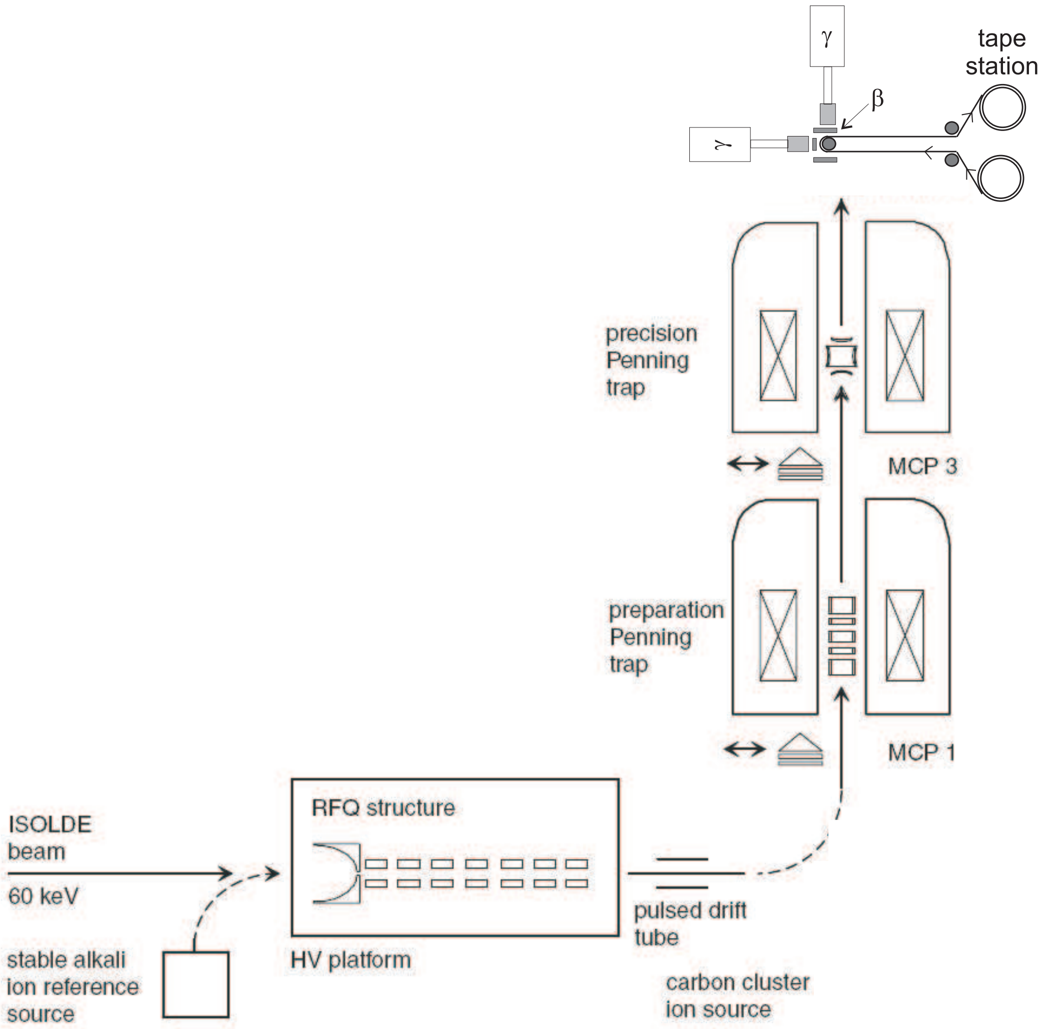

Figure 5: The triple trap mass spectrometer ISOLTRAP along with the proposed decay spectroscopy setup.

with an azimuthal rf field at the cyclotron frequency is detected by a reduction in the time of flight of the ejected ions towards a detector. Since this is a destructive detection method, no decay spectroscopy can be performed for the ion bunch used for the mass measurement.

In the case of decay studies the ions are shot through the precision trap, or – if necessary – are trapped in it for further purification. In presence of isomers in the mother nuclei, also isomeric purification can take place at this trap. This is possible if the excitation energy of the isomer is larger than a hundred keV, as it is the case for ^{206}Tl and ^{207}Tl. In the case of capture, the ions are radially ejected from the trap by use of a dipolar rf field at exactly the cyclotron frequency. On their way to the decay spectroscopy system, the ions are accelerated to around 1 keV or more and are implanted in a tape placed behind the last trap. The decay-detection system is located as close as possible to the implantation point (as shown very schematically in Fig. 5). It consists of thin plastic β-scintillators arranged in a close-to-4π geometry, behind which 2-3 Ge detectors are located, allowing efficient detection of the γ radiation. After a measurement – which takes from several hundred ms up to several minutes – the tape is moved in order to take away the daughter contamination, and a new bunch from ISOLTRAP is implanted.

4 Beam-time request

For the production of both Hg and Tl isotopes we would like to request an actinide target with resonant laser ionisation, which reduces considerably isobaric contamination present in a plasma ion source. For mercury we will also need the quartz transfer line, which was tested briefly for francium [22], and which can give up to 10^4 suppression of alkali beams [23].

The amount of the requested beam-time is determined by the estimated ISOLDE yields for the given target and ioniser, as well as the total efficiency of the ISOLTRAP and decay-spectroscopy setups. It should be noted at this point that the use of ISOLTRAP gives synergy to the project, since one can avoid doubling the time spent on beam preparations for both mass and decay studies, and furthermore decay studies can be assisted by isomeric selection performed in the precision trap.

The estimated yields take into account cross-sections for a 1.4 GeV proton impact on an actinide target, the release efficiency and laser-ionisation efficiency[1]. The cross-sections for both uranium and thorium targets[2] were calculated with the Silverberg-Tsao and EPAX codes for both neutron-deficient and neutron-rich Hg and Tl isotopes, as well as for Bi isotopes, for which experimental data above $N = 126$ exist. They were then compared to the available ISOLDE yield data for UC_x[3] (corrected for the efficiency of the used ion source) in order to extract an average release efficiency for the given isotope chain. A conservative value of this factor was finally multiplied with the RILIS efficiency and with the calculated production rates, to give the estimated yields. The used RILIS efficiency is 27% for thallium and 1% for mercury[4].

The measured and estimated yields per μC for Hg and Tl isotopes produced with a UC_x target are presented in Fig. 6, and – as mentioned before – the expected yields should be almost the same for ThC_x. They are accompanied by measured Fr yields, as well as Fr yields after the expected 10^4 suppression in the quartz transfer line, which should allow to decrease the ratio of contaminants to the ions of interest to less than 10^3 for all Hg isotopes. For Tl, this ratio might be larger than 10^3. As a check of the estimation method Fig. 7 shows measured [24] and predicted yields for neutron-rich Bi isotopes, which agree for the ThC_x target but differ by two orders of magnitude for UC_x. Such a behaviour is very surprising, since – as already mentioned – uranium and thorium should give very similar production cross-sections.

[1] No decay losses have been includes, since for Hg and Tl isotopes with $A < 215$ the predicted half-lives are in the second- or even minute- range, as shown in Fig. 4.

[2] The cross-sections are almost the same for those two target materials

[3] Much less data is available for thorium.

[4] The efficiency for mercury is only a lower limit.

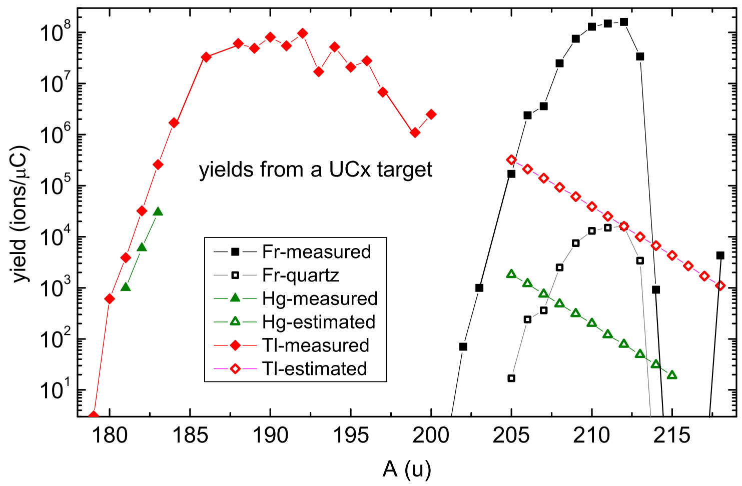

Figure 6: Measured Fr yield and estimated yields for Hg, Tl and Pb nuclides beyond $A = 205$.

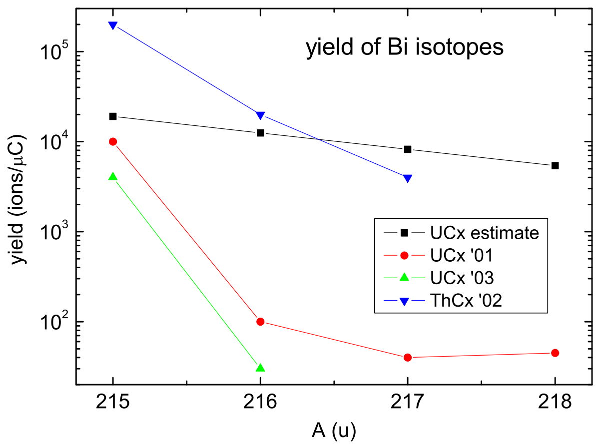

Figure 7: Measured and estimated yields of neutron-rich Bi isotopes produced with uranium and thorium targets. Experimental data taken from [24].

Based on these existing data we would like to request a ThC_x for the experiment.

Now, one also has to include the efficiency of the experimental setups. For mass measurements it is about 15%, resulting from the 15% efficiency of the buncher and close-to-100% efficiencies of the Penning traps and ion detection. For decay studies, we assume that more than 50% of the β particles will be detected in the thin ΔE_β scintillators in a close-to-4π geometry. For γ counts we will use a 70% Ge-detectors with an average 0.5% efficiency for the expected γ energies, based on the decay of Hg and Tl with known β decay energies.

Based on the above values, our requested beam-time is presented in Table 3. For mercury, we would like to request one beam-time for mass and decay measurements on $^{207-210}$Hg, where for the decay studies ^{207}Hg will serve as a reference. If the measured yields are as expected or larger, we plan to submit an addendum to the present proposal, in order to extend the measurements to even more neutron-rich Hg isotopes. In the case of thallium, we would like to request a test beam-time to check Tl and Fr yields in the mass range A=208-214. If the ratio francium/thallium is not larger than 10^3, we will include in the possible addendum also measurements on thallium.

In total, we request 22 shifts to be used in two runs: 19 shifts for mercury and 3 test-shifts for thallium.

Table 3: Requested beam-time.

isotope(s)	measurement	no. of shifts
$^{207-210}$Hg	mass determination	7
^{207}Hg	decay studies	1
$^{208-210}$Hg	decay studies	11
$^{208-214}$Tl	yield test	3
		total: 22

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