EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Penning-trap mass measurements with ISOLTRAP

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Abstract: The ISOLTRAP mass spectrometer is dedicated to determining nuclear binding energies and Q values by the Penning-trap technique. The experiments concerned by the present report have been directed at a wide range of physics subjects, of which the study of nuclear shell effects far from stability, the onset of nuclear collectivity and the modeling of astrophysical environments/processes stand out. A decisive strength of the setup is its flexibility under on-line conditions, allowing for efficient use of on-line beam time in the case of difficulties with allocated beams. To overcome the increasingly difficult task of coping with short-lived, highly-contaminated ion beams, a series of on-line and off-line technical developments have taken place at ISOLTRAP, which, in their turn, open the path to new experimental opportunities.

Experiments and remaining shifts: The ISOLTRAP experiment has at present 12 active experiments or approved proposals, as summarized in the table below:

Exp.	Approved shifts	Remaining shifts	Requested isotopes	Observations
IS463	22	4.5	$^{207-210}$Hg,$^{208-214}$Tl	
IS473	5	5	^{202}Tl	addendum approved
IS490	28	16	$^{46-48}$Ar,$^{70-72}$Kr	
IS498	8	4.5	^{168,170}Dy,^{174}Er,^{178,180}Yb	
IS513	21	21	^{193,195,197,199}Po	not yet scheduled
IS518	34	4.5		shifts transferred to IS534
IS532	21	3	$^{52-55}$Sc	addendum submitted separately
IS535	14	10	$^{76-79}$Cu	
IS542	9	9	^{32}Ar	not yet scheduled
IS565	8	8	^{23}Mg/^{23}Na, ^{21}Na/^{21}Ne	not yet scheduled
IS567	17	17	^{34}Mg	not yet scheduled
IS574	19	19	$^{129-132}$Cd	not yet scheduled

Including the already closed IS413 experiment, the experiments above have produced since 2010 a number of 14 scientific articles, of which 1 Nature Letter and 2 Physical Review Letters, as well as 5 theses.

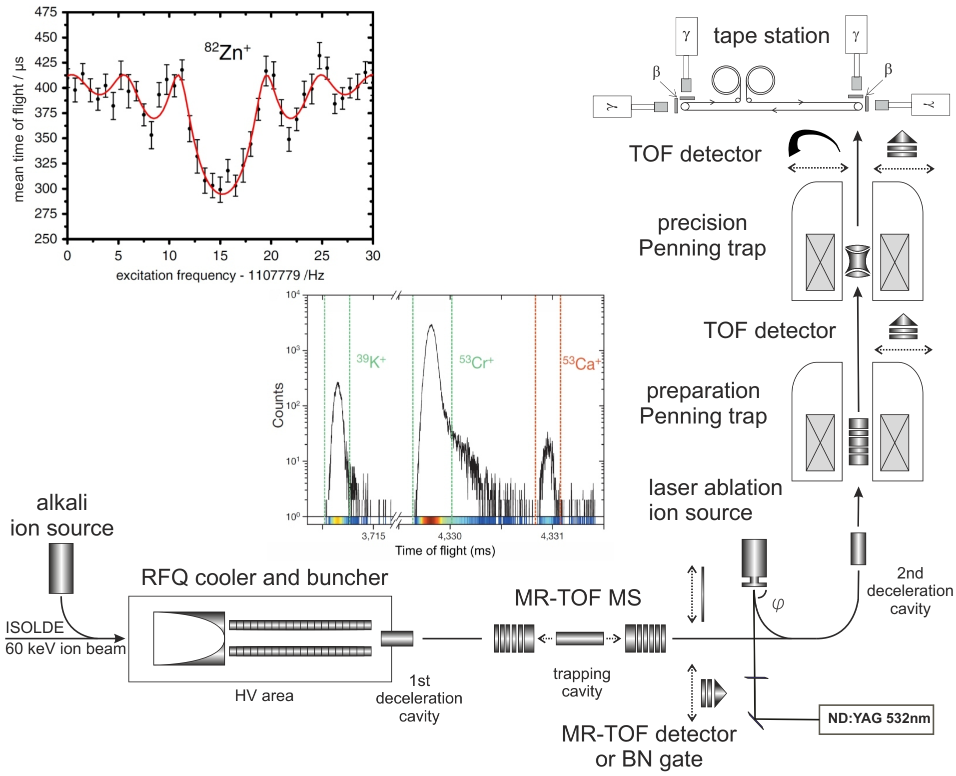

Figure 1: Schematic view of the ISOLTRAP setup. The inset on the left shows a time-of-flight ion-cyclotron resonance of $^{82}Zn^{+}$ (TOF detector above precision Penning trap), the inset on the right shows a time-of-flight spectrum of $A = 53$ (MR-TOF detector). For details, see text.

Experimental setup

Figure 1 shows the current experimental setup, which consists of four traps: a linear segmented radio-frequency quadrupole (RFQ) for ion beam cooling and bunching, a multi-reflection time-of-flight mass separator (MR-TOF MS), and two Penning traps (preparation and precision Penning trap) [1]. Details of the current setup, as well as an overview of the recent technical developments, can be found in [2]. For a historical review, showing some of the pioneering work performed at ISOLTRAP in the field of mass spectrometry, see [3].The overall efficiency from the merging switchyard of ISOLDE to the final ISOLTRAP detector is on the order of 10^{-3} to a few 10^{-2}, depending on the mass and half-life of the nuclide of interest.

The ISOLDE ion beam first enters the linear, gas-filled RFQ ion trap [4] where buffer-gas cooling is applied for $10 - 20\,$ms. After passing the first deceleration cavity, isobaric contaminants are separated due to mass-over-charge dependent flight times after repeated oscillations between the electrostatic mirrors of the MR-TOF MS [5].

With the implementation of the MR-TOF MS in 2010, new various applications have become possible. Used as a separator for beam purification, a resolving power on the order of 10^5 together with a suppression of the unwanted species of close to 10^4 can be reached within a few tens of milliseconds. This is about an order of magnitude faster

than the conventional technique employed so far with any Penning-trap mass spectrometer worldwide. This achievement opens the door for the study of nuclei even farther from stability with shorter half-lives and lower production yields or beams with a higher degree of contamination [5, 6]. As an example,a time-of-flight spectrum for $A = 53$ is shown in the right inset of Fig. 1. In the case of the mass measurement of ^{82}Zn, it was successfully employed for fast and efficient beam purification [7].
Alternatively, the MR-TOF MS can be used for mass measurements reaching uncertainties on a low 10^{-7} level. The first direct mass measurement could be demonstrated with ^{53,54}Ca [8]. Furthermore, by gating on the time of flight of the ion of interest in the isobaric spectrum, one can scan the wavelength of one of the excitation steps of the RILIS lasers and thus perform in-source laser spectroscopy either for nuclear-structure studies or for selective ionization of different nuclear states. Proof of principle measurements with the MR-TOF MS, showing the capability of isomeric selectivity by exploiting the hyperfine structure, have been performed in 2012 and recently reported in [2, 6, 9]. Finally, the purification cycle in the MR-TOF MS can be repeated at a high rate, while accumulating the ions of interest in the subsequent preparation trap, to later send the accumulated bunch only once to the precision trap for the measurement cycle. This so-called stacking technique has been demonstrated with on-line beam recently [10].
In the preparation Penning trap ions can be removed by mass-selective resonant buffer-gas centering [11] with a resolving power of up to 10^5. The so-called SIMCO scheme for purification in buffer-gas free environments has been developed recently [12]. Effects of space charge when dealing with large samples in the preparation trap have been investigated in [13]. Similarly, the possibility of mass measurements with this trap has been systematically investigated [14].
The selected ions are subsequently transferred to the second, precision Penning trap for the mass measurement. The time-of-flight ion-cyclotron resonance (TOF-ICR) technique [15] is employed to determine the cyclotron frequency of an ion stored in the Penning trap (see left inset of Fig. 1), from which the mass can be extracted in conjunction with a reference cyclotron-frequency measurement [16]. A new mass-measurement technique, the phase-imaging ion-cyclotron-resonance, has recently been proposed and tested at the SHIPTRAP mass spectrometer [17]. The technique uses position-sensitive instead of time-of-flight detection, to study the evolution of the ion's phase inside the Penning trap. From this its cyclotron frequency and subsequently its mass can be determined with increased precision compared to the TOF-ICR technique, even for lower measurement time (first tests [17] claim a factor five gain in precision for the same measurement time). The implementation of this technique at ISOLTRAP is currently in preparation.

1 Status report for IS463

- **Title: Decay studies and mass measurements on isobarically pure neutron-rich Hg and Tl isotopes**
- **Spokesperson: Magdalena Kowalska**
- **Accepted isotopes: $^{207-210}$Hg,$^{208-214}$Tl**

1.1 Performed studies

The IS463 experiment was accepted [18] for mass measurements and beta-gamma spectroscopy of mercury and thallium isotopes with $N > 126$. For the latter studies, a decay station was installed above the precision Penning trap of ISOLTRAP, as shown in Fig. 1 [19], to benefit from its high resolving power, on the order of $m/\Delta m = 10^5 - 10^6$, allowing in some cases even the separation of isomeric and ground states.
The proposal relied on the joint isobar selectivity of ISOLDE and ISOLTRAP: the quartz transfer line was expected to bring 10^3 supression of francium, with ISOLTRAP accounting for the remaining part. Unfortunately, there was no mercury beam visible with the quartz transfer line and for thallium, due to scheduling constraints, it was not possible to use the optimal target-ion source combination (quartz transfer line and RILIS). Nevertheless, we tried to observe the requested mercury and thallium isotopes, but we could not resolve anything from francium background: one reason could be insufficient francium suppression, another - lower than expected production cross-section. Consequently, only the uncertainty on the mass of ^{208}Fr could be reduced as a result of the experiment.
Therefore, in order to make use of the beam times, the neutron-deficient thallium isotopes were investigated instead (since they do not suffer from large contamination and are rather well produced). Situated in a region of isomerism and shape coexistence, these isotopes are intermediate between the spherical lead ($Z = 82$) isotopic chain and the mercury ($Z = 80$) chain, the latter with a sudden ground-state shape transition, followed by shape staggering, at $N = 105$ and below. In this context, the energy systematics of the 7^+ and $9/2^-$ isomeric states in the odd-odd and odd-even thallium isotopes, respectively, is an interesting study case, with the unknown excitation energy of the 7^+ isomer, as well as the ordering in energy between the 7^+ and the 2^- isomeric states.
By correlating mass measurements with beta-decay patterns recorded with the ISOLTRAP decay station, mass values could be associated with specific nuclear states. Both the 7^+ and the 2^- states were measured this way in ^{194}Tl, allowing a direct determination of the 7^+ isomer's excitation energy. In ^{190}Tl, the mass of the 7^+ state was determined directly. By also using the mass of the ground state in ^{198}At, measured as part of the IS518 experiment, we determined the mass of the 2^- state in ^{190}Tl, using in addition the alpha-decay Q values by which the two states are linked. As such, the ordering of the 7^+ and 2^- states in ^{190}Tl, as well as the excitation energy of the 7^+ state, were determined for the first time. These results are presented in [20].
Furthermore the masses of ^{184,186,193,195}Tl were determined and are already included in the AME2012 [21] and NUBASE2012 [22] evaluations. They are the object of an article in preparation [23].

1.2 Future plans with available shifts

Of the original 22 shifts, 4.5 shifts are still available for IS463. No further measurements of neutron-rich mercury and thallium isotopes seem feasible without target and ion source development (TISD) aimed at suppressing the significant francium contamination of the beam. This region of the nuclear chart is interesting not only for ISOLTRAP (IS584), therefore we would thus like to keep the proposal open, to encourage and use the shifts for future TISD in this direction.

2 Status report for IS473

- **Title: Search for New Candidates for the Neutrino-Oriented Mass Determination by Electron Capture**
- **Spokesperson: Sergey Eliseev**
- **Accepted isotopes: ^{194}Hg,^{194}Au,^{202}Pb,^{202}Tl**

2.1 Performed studies

The IS473 experiment was accepted in 2008 [24] (INTC-P-242) for the measurement of electron-capture (EC) Q values of possible EC candidates for the determination of the electron-neutrino mass. EC pairs whose Q value ensures a low kinetic energy of the emitted neutrino in the EC process are the best candidates.
The Q value of electron-capture in ^{194}Hg was determined with increased precision by measuring the masses of ^{194}Hg and ^{194}Au with ISOLTRAP. The resulting value of 29(4) keV, published in [25], is sufficiently precise and shows a significant deviation from the Q value based on the masses of the AME2003 evaluation of 69(14) keV [26]. The new value reveals a new possibility of lowering the upper limit on the electron neutrino mass from EC measurements on ^{194}Hg to 20 eV, a factor 10 improvement with respect to the current limit, but still one order of magnitude higher than the limit on the anti-neutrino mass.
In the case of the ^{202}Pb-^{202}Tl EC pair, the mass of ^{202}Pb has been determined with ISOLTRAP, achieving a precision of $\approx$ 3 keV. An attempt was made to determine the EC Q value of ^{202}Pb, by measuring in the same run the cyclotron frequency of ^{202}Pb and ^{202}Tl. Both nuclides were produced from the same target, the former being laser ionized and the latter surface ionized. The attempt however failed to achieve the desired accuracy, due to an insufficient ISOLDE yield of surface-ionized ^{202}Tl and the contamination of the ^{202}Pb ground state by the 9^- isomeric state, of $\approx$ 2 MeV excitation energy [22].
In parallel, a program of off-line measurements has been undertaken, using the laser ion source of ISOLTRAP, to determine Q values of candidates for the neutrinoless double-beta decay ($0\nu\beta\beta$-decay). The search for this process hopes to solve a long-standing question of whether the neutrinos are their own antiparticle. As this decay mode would be extremely rare, the timescale for its observation is usually greater than 10^{25} years. Of experimental interest are candidates whose Q value is high enough to energetically allow for the $0\nu\beta\beta$ decay and to reduce the expected half-life below the experimental limit [27]. The decay energy of ^{110}Pd has been determined 17 times more precisely than the literature. The new result enables the distinction of signal from background in future experiments.

2.2 Future plans with available shifts

The determination of the Q value of the electron-capture pair ^{202}Pb/Tl is still outstanding and has not yet been performed elsewhere. An addendum for the measurement of the mass of ^{202}Tl has been approved in 2011 (INTC-P-242-ADD-1) with a sufficient number of shifts [28]. To obtain the desired yield, laser ionization of thallium is requested. No beam time has yet been scheduled using the approved shifts of the addendum:

Isotope	Half-life [22]	Yield (μC^{-1})	Target/ion source	Shifts (8h)
^{202}Tl	12.31 d	10^5	UC_x/RILIS	5
				Total shifts: 5

3 Status report for IS490

- **Title: Masses of Noble Gases**
- **Spokesperson: David Lunney**
- **Accepted isotopes: $^{46-48}$Ar,$^{70-72,96-98}$Kr**

3.1 Performed studies

The IS490 experiment was accepted in 2009 [29] (INTC-P-263) for mass measurements of the isotopes of noble gases. The physics goals of the proposal range from astrophysics ($^{70-72}$Kr masses as input for the rapid-proton-capture process), to the evolution of shell structure (the $N = 28$ shell gap from the masses of $^{46-48}$Ar), to the understanding of mid-shell collectivity (the two-neutron separation energies of $^{96-98}$Kr).
The outcome of this proposal consists so far not only of mass measurements, but also of technical developments. Noteworthy is the use of the resonant buffer-gas cooling technique for cyclotron-frequency measurements [14], as well as the first on-line tests with the MR-TOF MS as an isobaric purifier [5].
Successful mass measurements of neutron-rich krypton isotopes (^{96,97}Kr) were performed and published in [30]. They show that the shape transition, which takes place in the neutron-rich $A \approx 100$ nuclei at $N = 60$, extends as low as $Z = 37$ (rubidium), while no such transition is observed in the krypton chain up to $N = 61$, as shown in Fig. 2.
Experiments on neutron-deficient krypton isotopes and neutron-rich argon isotopes were performed in 2010, but the beams exhibited strong contamination of isobaric molecules: in the case of $^{70-72}$Kr, molecules of the form $^{35}Cl_2$, $^{35}Cl_2H$, $^{35}Cl^{37}Cl$, respectively, while in the case of neutron-rich argon, $^{12}C^{34}S$, as well as $^{30}Si^{16}O$ were observed on mass $A = 46$, with similar contamination expected for the more exotic isotopes. The measurements reached ^{73}Kr and ^{45}Ar with ISOLTRAP, but could not reach the proposed isotopes. The yields of neutron-deficient krypton and neutron-rich argon did not reflect the expected ionization enhancement of the VADIS ion source [33], with respect to the standard plasma sources. The large beam contamination however hindered obtaining clear yield information with ISOLTRAP.

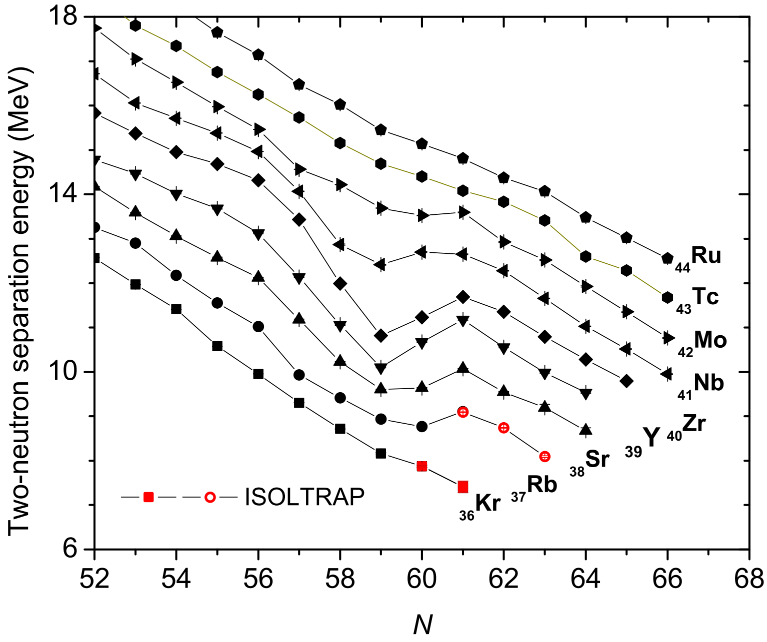

Figure 2: Experimental two-neutron separation energies of neutron-rich $A \approx 100$ nuclei. The black filled symbols represent the AME2012 data [21]. The red full squares show data originating from the measurements of ^{96,97}Kr performed withing IS490 [30] (included in AME2012). The red open circles represent data based on the rubidium measurements of the IS535 experiment (see corresponding section), replacing, where applicable, existing AME2012 data [31].

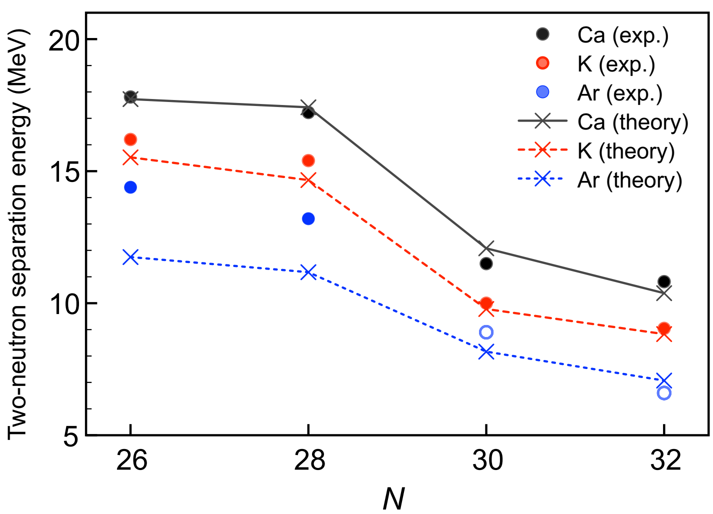

Figure 3: Ab-initio calculations using Gorkov-Green's Function theory [32] for the calcium, potassium, and argon isotopes. Experimental values are taken from [21] and are partly extrapolated from systematics (open symbols).

3.2 Future plans with available shifts

Of the original 28 shifts, 16 shifts are still available for IS490. The strength of the $N = 28$ shell closure continues to be a research subject of great interest [34] and, while information from spectroscopy has reached $Z = 14$ (^{42}Si) [35], the binding-energy information lags behind and argon ($Z = 18$) is still the first isotopic chain for which the $N = 28$ two-neutron shell gap is not determined.

In the framework of microscopic calculations with realistic interactions, the importance of the $N = 28$ closure as a benchmark has been recently recognized, in connection with the role of three-body forces [36]. With the ongoing effort of extending ab-initio calculations beyond the closed proton shells, as shown in Fig. 3 [32], the binding energies across the $N = 28$ magic number become relevant for the state-of-the art theoretical approaches. The measurements of $^{46-48}$Ar thus continue to be of high interest and have not yet been performed elsewhere.

The mass of ^{71}Kr has been recently determined [37] with a precision of $\approx$ 140 keV, a more than four-fold improvement with respect to the AME2003 value [26]. This makes the impact of a potential ISOLTRAP measurement of ^{71}Kr less significant. Based on the published yields of ^{70}Kr (see table below), its measurement is very challenging without significant improvement from TISD. Considering also the difficulties brought on by the observed contamination of the argon beams, all the above impose a redistribution of the available number of shifts between the krypton and argon programs.

The ^{46,48}Ar yields below are estimated using the literature ^{47}Ar [38] and ^{49}Ar [39] yields. All yields of krypton and argon are given for an MK7 plasma source. The possible enhancement brought on by the use of the VADIS ion source is not considered.

Isotope	Half-life (s) [22]	Yield (μC^{-1})	Target/ion source	Shifts (8h)
^{46}Ar	8.4(6)	10^5	UC$_x$/VADIS	2
^{47}Ar	1.23(3)	10^4 [38]	UC$_x$/VADIS	3
^{48}Ar	0.475(40)	$10^2 - 10^3$	UC$_x$/VADIS	5
^{72}Kr	17.16(18)	2×10^3 [40]	Nb foil or Y oxide/VADIS	1
^{71}Kr	0.100(3)	2 [40]	Nb foil or Y oxide/VADIS	2
^{70}Kr	0.052(17)	$< 10^{-1}$ [41]	Nb foil or Y oxide/VADIS	3
				Total shifts: 16

4 Status report for IS498

- **Title: High-Precision Mass Measurements in the Rare-Earth Region to Investigate the Proton-Neutron Interaction**
- **Spokesperson: Rabia Burcu Cakirli**
- **Accepted isotopes:^{168,170}Dy,^{174}Er,^{178,180}Yb**

4.1 Performed studies

The IS498 experiment was accepted in 2009 [42] (INTC-P-273) for mass measurements of rare-earth nuclides related to the study of mid-shell nuclear collectivity. The chosen even-even cases allow an extension of the knowledge of the two-neutron separation energy S_{2N}, of the two-neutron gap $S_{2N} - S_{2N-2}$ and of the empirical proton-neutron interaction δV_{pn}.

So far, no physics results could be achieved due to the poor production of the requested isotopes and large isobaric contamination. Only the yield of ytterbium was close to the requirements of the present experiment, making ^{178}Yb the only measured isotope, of the proposed ones. The mass of ^{137}Eu was measured for the first time as a by-product of this experiment for commissioning the use of the MR-TOF device as a mass separator and was published in [6]. The precision on the masses of ^{207,208}Fr was also improved as part of the IS498 beam time [23].

The cocktails of rare-earth beams and contaminants proved excellent test cases for the techniques recently developed at ISOLTRAP. Some of the first on-line tests with the MR-TOF MS as an isobaric purifier were performed with IS498 beams in 2010. A new experimental scheme (stacking), using fast MR-TOF MS purification and multiple accumulations in the preparation Penning trap was also successfully applied on ^{178}Yb and ^{179}Lu in 2011 and published in [10]. Tests revealed that ^{179}Yb is also feasible with the stacking technique, but not enough beam time was still available to exploit it.

4.2 Future plans with available shifts

Of the original 8 shifts, a number of 4.5 shifts is still available for IS498. These shifts alone are still enough to pursue part of the physics program, of which ^{180}Yb is the most feasible at the current time. This proposal would benefit from the ongoing TISD efforts of improving the production of neutron-rich rare-earth beams. If the outcome of these developments is promising, an addendum to IS498 may be submitted at a later time.

5 Status report for IS513

- **Title: Study of the odd-A, high-spin isomers in neutron-deficient trans-lead nuclei with ISOLTRAP**
- **Spokesperson: Thomas Elias Cocolios**
- **Accepted isotopes: ^{193,195,197,199}Po**

5.1 Performed studies

The IS513 experiment was accepted in 2011 [43] (INTC-P-293) to study the $13/2^+$ isomers in the odd-A polonium isotopes, with possible implications for the understanding of the phenomenon of shape coexistence in the region. As in the case of IS463, the proposed experimental program comprises correlated mass measurements and decay-spectroscopy studies, this time also including a decay station capable of charged-particle (alpha) spectroscopy. No beam time has yet been scheduled for the IS513 experiment. A UHV-compatible decay-spectroscopy station has been built by the CRIS collaboration and its use has been demonstrated [44]. A new decay-station setup, compatible with the requirements of the IS513 experiment, is currently being designed at ISOLTRAP.

5.2 Future plans with available shifts

As planned originally, the study will start with a proof of principle using ^{199}Po identified with the existing decay station for the identification of the decay patterns. That approach has been demonstrated at ISOLTRAP with the study of the thallium isotopes [20]. We shall then proceed further with the use of the alpha-decay spectroscopy station.
There is no new information relating to the mass or isomer excitation energy of the even-Z, odd-A isotopes in this region.

Isotope	Yield (μC^{-1})	Target/ion source	Shifts (8h)
^{197,199}Po	$> 10^6$	UC$_x$/RILIS	9
^{193,195}Po	$10^2 - 10^4$	UC$_x$/RILIS	12
			Total shifts: 21

6 Status report for IS518

- **Title: Extending and Refining the Mass Surface around ^{208}Pb by High-Precision Penning-Trap Mass Spectrometry with ISOLTRAP**
- **Spokesperson: Susanne Kreim**
- **Accepted isotopes: ^{202,204,205}Au, $^{220-223}$At, $^{226-234}$Fr**

6.1 Performed studies

The IS518 experiment was accepted in 2011 [43] (INTC-P-299) for studies related to r-process, nuclear deformation and the strength of the $N = 126$ shell closure.
The masses of the francium isotopes were successfully measured up to ^{233}Fr. The half-life of ^{233}Fr was also determined with the ISOLDE decay station. In addition, the masses of ^{233,234}Ra were determined. These results are the object of an article in preparation [45].
The francium contamination was however a major obstacle for the measurement of the astatine isotopes. After two attempts, ^{219}At was measured, benefiting from the suppression of ^{219}Fr due to its 20 ms half-life. The observed yield of ^{219}At (estimated at $10^4 - 10^5 \mu C^{-1}$ by the observed count rate on the ISOLTRAP detectors) makes the more exotic isotopes feasible to measure from the yield point of view, but the sudden increase in francium contamination at $A = 220$ (with the increase in half-life) could not yet be overcome.
A similar situation is true for the proposed gold isotopes, where the surface-ionized thallium contamination is orders of magnitude more abundant than the laser-ionized gold. The attempts to measure the neutron-rich gold isotopes were unsuccessful, also partially

due to exceptional technical problems occurring at ISOLTRAP during the scheduled beam time.
The IS518 beam times gave the opportunity to develop a new experimental application of the MR-TOF MS. As discussed in the experiment's description, a TOF detector placed behind the MR-TOF MS produces a TOF spectrum, in which the different isobaric species of the ISOLDE beam appear as separated TOF peaks. By changing the different parameters of the ISOLDE ion production, one can observe how each isobaric species responds to them individually. One such parameter is the frequency of each RILIS excitation step. By scanning the frequency of the laser excitation and monitoring the change of ionization efficiency on the TOF peak of the ion of interest, one can perform in-source resonance-ionization spectroscopy with direct ion detection and MR-TOF separation [2, 6, 9].
The method was applied in 2012 to study the hyperfine structure of gold and astatine isotopes, in a joint study with the Windmill collaboration (IS534) (see also Status Report of Windmill collaboration [46]). The neutron-deficient gold isotopes $^{179-182,185,191}$Au were studied as a proof-of-principle case with the MR-TOF MS, using the broad-band mode of RILIS operation, while the ^{205,207,209,211}At isotopes were studied with RILIS in narrow-band mode. The data analysis is ongoing. In the process, the masses of some neutron-deficient gold (^{178,180,185,188,190,191}Au) and astatine (^{197,197m,198}At) isotopes were measured with ISOLTRAP. A new isomeric state, of very different hyperfine splitting than the ground state, was discovered with the Windmill setup in ^{178}Au. By tuning the frequency of the first RILIS excitation step to resonantly ionize either the isomer or the ground state, the mass of the isomer and its excitation energy was determined with ISOLTRAP.

6.2 Future plans with available shifts

Experiment IS518 has 3.5 remaining shifts of the approved 34. To continue the studies of isomerism through hyperfine-structure scans and mass measurements in the gold isotopic chain, within the addendum to the IS534 experiment INTC-P-319-ADD-1 these shifts were transferred to IS534 for measurements of gold isotopes. As part II of the addendum, concerning the gold isotopes, has been approved [47], we ask to use these shifts within IS534 and subsequently close the IS518 experiment.

7 Status report for IS532

- **Title: Seeking the Purported Magic Number $N = 32$ with High-Precision Mass Spectrometry**
- **Spokesperson: Susanne Kreim**
- **Accepted isotopes: $^{52-54}$Ca,$^{52-55}$Sc**

7.1 Performed studies

The IS532 experiment was accepted in 2011 [28] (INTC-P-317) for mass measurements of calcium and scandium isotopes to study the evolution of the $N = 32$ subshell far from

stability. At neutron number $N = 32$, the high energy of the first 2^+ excited state in the calcium isotopic chain suggested a prominent subshell closure, however the knowledge from ground-state properties was missing.
An important outcome of the IS532 experiment was the development of a new mass-measurement technique with ISOLTRAP. As discussed in the experiment's description, by placing a TOF detector behind the MR-TOF MS one obtains a TOF spectrum, which can be calibrated with ions of known masses to yield a mass spectrum. As a function of the masses of these reference ions, the mass of any ion of interest can be determined using the MR-TOF MS. If one or more of the reference ions are isobars of the ion of interest, pertaining to the same TOF spectrum, the relative mass precision of the device was shown to lie below 10^{-6} for a few thousand detected ions. Part of the requested beam time of the IS532 experiment was scheduled for tests of this method with radioactive isobar triplets. Because the MR-TOF MS only requires a few ms or tens of ms to perform the mass measurement and only time-of-flight separation of the ion of interest and contaminants (not complete purification), the new MR-TOF MS technique is a promising approach for pushing mass measurements farther from stability than previously possible. The IS532 measurements of the calcium isotopes are an example of this improvement. While the mass of ^{52}Ca could be determined in the traditional mode of ISOLTRAP operation (in the precision Penning trap, by the TOF-ICR technique), the decrease in yield and half-life going to ^{53,54}Ca made the Penning-trap measurement impossible. Consequently, the masses of ^{53,54}Ca were measured using the MR-TOF MS. The two-neutron separation energies calculated with the determined masses firmly established the strong shell effect at $N = 32$, providing a crucial test of modern nuclear theories. The results were published in [8] and are shown in Fig. 4.

7.2 Future plans with available shifts

After the successful run on $^{52-54}$Ca, from the initial 21 shifts only 3 are left, insufficient to pursue the approved measurement program in the scandium isotopic chain. An addendum is submitted as a separate document, requesting the original number of shifts from the INTC-P-317 proposal, dedicated to measurements of scandium isotopes.

8 Status report for IS535

- **Title: Penning-trap mass spectrometry of neutron-rich copper isotopes for probing the $Z = 28$ and $N = 50$ shell closures**
- **Spokesperson: Vladimir Manea**
- **Accepted isotopes: $^{76-79}$Cu**

8.1 Performed studies

The IS535 experiment was accepted in 2012 [48] (INTC-P-321) for studying the evolution of the $Z = 28$ and $N = 50$ shell closures, through the measurement of copper isotopes,

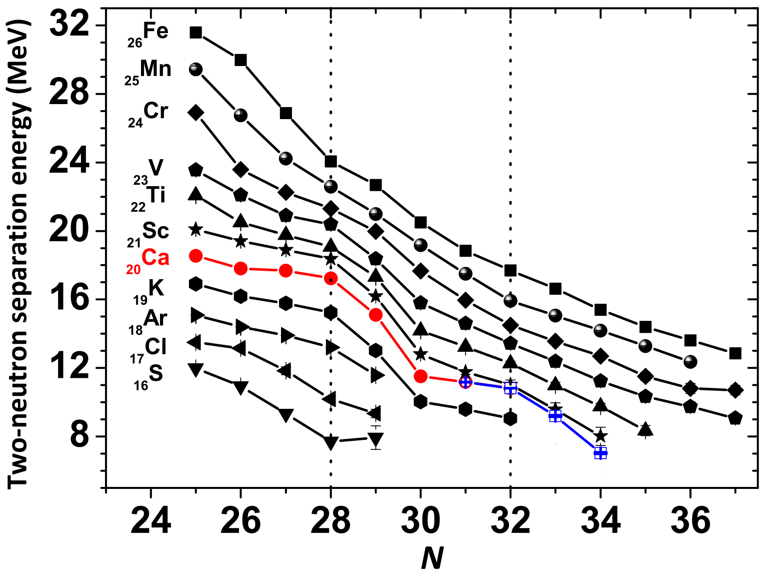

Figure 4: Experimental two-neutron separation energies of nuclei crossing the $N = 28$ and $N = 32$ lines from AME2012 [21] and the IS532 measurements. The new data points from IS532 are represented in blue open symbols. The characteristic drop of S_{2N} at the crossing of a magic neutron number is observed both at $N = 28$ and $N = 32$ for the calcium isotopes.

while approaching the doubly-magic ^{78}Ni.
To reduce the neutron-deficient contamination of the beam, a neutron-converter target unit was requested in the proposal. The only experiment scheduled so far used a target unit with a new geometry of the neutron converter, designed to reduce the amount of protons scattered onto the target material and thus suppress even more the amount of neutron-deficient reaction products. At the beginning of the experiment, however, the neutron converter was damaged, which required shooting the protons directly on the target for the rest of available beam time. Since under these conditions none of the proposed copper isotopes could be measured, the beam time was dedicated to surface-ionized rubidium and cesium isotopes, still produced abundantly enough. As part of this experimental run, the masses of $^{98-100}$Rb and $^{132,144-148}$Cs were determined with ISOLTRAP, the mass of ^{100}Rb being determined for the first time. The rubidium masses, published in [31], refine and extend the information on the shape transition in the neutron-rich $A \approx 100$ region of the nuclear chart, showing the different evolution of the nuclear shape in the rubidium isotopic chain, with respect to the neighbouring krypton isotopic chain (for which masses measured with ISOLTRAP in the IS490 experiment show a different picture). The new results are part of Fig. 2.

8.2 Future plans with available shifts

As discussed in the proposal INTC-P-321, we intend to measure the masses of $^{77-79}$Cu and to remeasure ^{76}Cu, seeking the so-far unconfirmed isomeric state [22]. In the case of ^{76}Cu, the hyperfine structure can also be investigated for possible evidence of two nuclear

states, using the MR-TOF MS as beam analyzer and the narrow-band mode of RILIS. To suppress the neutron-deficient contamination in the copper beam, a target unit with a neutron converter is requested. The ongoing developments of the neutron converter for enhancing its suppression of neutron-deficient contaminants and especially its efficiency, are of interest for the IS535 experiment.
With the successful mass measurements of ^{53,54}Ca using the MR-TOF MS, it was shown that a relative precision $\delta m/m < 10^{-6}$ can be achieved, using this new technique, for isotopes with production rates of ≈ 10 ions/s and half-lives in the ≈ 100 ms range. This makes the MR-TOF mass-measurement technique a promising approach for the neutron-rich copper isotopes, especially for the very rare ^{79}Cu, which have not been addressed yet by precision measurements at any radioactive-ion-beam facility.
Of the approved 14 shifts, 4 were counted following the only scheduled run, because some new physics results were obtained, as discussed above, although not in the copper isotopic chain. Because ^{79}Cu is a very challenging case, the full number of 14 shifts is still required. The yields specified below are the original ones from the INTC-P-321 proposal, given for shooting protons directly on the UC_x target. The yields resulting from the use of a neutron converter can be expected to be an order of magnitude lower, depending on the converter's efficiency [49].

Isotope	Half-life (s) [22]	Yield (μC^{-1})	Target/ion source	Shifts (8h)
^{76m}Cu	1.27(30)	2×10^4	UC_x/RILIS+n-converter	1
^{77}Cu	0.468(2)	2×10^3	UC_x/RILIS+n-converter	2
^{78}Cu	0.335(11)	2×10^2	UC_x/RILIS+n-converter	3
^{79}Cu	0.220(19)	2×10^1	UC_x/RILIS+n-converter	4
				Total shifts: 10

9 New experiments

9.1 IS542: Remeasurement of ^{32}Ar to test the IMME

IS542 (INTC-P-332) was proposed in 2012 and 9 shifts have been approved [48]. The measurements have not yet been performed elsewhere. This proposal is waiting to be scheduled.

9.2 IS565: Q-values of Mirror Transitions for Fundamental Interaction Studies

IS565 (INTC-P-369) was proposed in 2013 and 8 shifts for the mass measurements of ^{23}Mg/^{23}Na and ^{21}Na/^{21}Ne have been approved [47]. The measurements have not yet been performed elsewhere. This proposal is waiting to be scheduled.

9.3 IS567: Energy of the 2p1h intruder state in ^{34}Al: an extension of the "island of inversion"?

IS567 (INTC-P-372) was proposed in 2013 and 17 shifts have been approved [47]. The measurements have not yet been performed elsewhere. This proposal is waiting to be scheduled.

9.4 IS574: Precision Mass Measurements with ISOLTRAP to Study the Evolution of the $N = 82$ Shell Gap far from Stability

IS574 (INTC-P-382) was proposed in 2013 and 19 shifts have been approved [50]. The measurements have not yet been performed elsewhere. This proposal is waiting to be scheduled.

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Appendix

The table below lists the publications and theses resulting from the presented IS experiments.

IS exp.	Type	Bibliographic information
IS463	Article	J. Stanja *et al.*, "Mass spectrometry and decay spectroscopy of isomers across the $Z = 82$ shell closure," Phys. Rev. C **88**, 054304 (2013).
		M. Kowalska, S. Naimi *et al.*, "Trap-assisted decay spectroscopy with ISOLTRAP," Nucl. Instr. Meth. Phys. Res. A **689**, 102-107 (2012).
	Thesis	J. Stanja,"Synergy of decay spectroscopy and mass spectrometry for the study of exotic nuclides," PhD thesis, Technical University of Dresden, Germany (2013) [CERN-THESIS-2013-251].
		Ch. Borgmann, "Mass Measurements of Exotic Ions in the Heavy Mass Region for Nuclear Structure Studies at ISOLTRAP," PhD thesis, University of Heidelberg, Germany (2012) CERN-THESIS-2012-270.
IS473	Article	S. Eliseev *et al.*, "Direct mass measurements of ^{194}Hg and ^{194}Au: A new route to the neutrino mass determination?" Phys. Lett. B **693**, 426-429 (2010).
		D. Fink *et al.*, "Q Value and Half-Lives for the Double-β-Decay Nuclide ^{110}Pd," Phys. Rev. Lett. **108**, 062502 (2012).
		"^{110}Pd: a new possibility for $\beta\beta0\nu$ decay," CERN Courier, April, 2012.
	Thesis	D. Fink, "The ISOLTRAP Laser-Ablation Ion Source and Q-Value," Diploma, University of Heidelberg, Germany (2010) CERN-THESIS-2010-286.
IS490	Article	S. Naimi *et al.*, "Critical-point Boundary for the Nuclear Quantum Phase Transition Near $A = 100$ from Mass Measurements of ^{96,97}Kr," Phys. Rev. Lett. **105**, 032502 (2010).
		A. Herlert *et al.*, "Effects of space charge on the mass purification in Penning traps," Hyp. Int. **199**, 211-220 (2011).
		S. Naimi *et al.*,"Mass measurements of short-lived nuclides using the ISOLTRAP preparation Penning trap," Hyp. Int. **199**, 231-240 (2011).
	Thesis	S. Naimi, "Onsets of nuclear deformation from measurements with the ISOLTRAP mass spectrometer," PhD thesis, University of Paris VII, France (2010) CERN-THESIS-2010-285.
IS498	Article	F. Wolf, F. Wienholtz *et al.*, "ISOLTRAPs multi-reflection time-of-flight mass separator/spectrometer," Int. J. Mass Spectrom. **349-350**, 123-133 (2013).
		M. Rosenbusch *et al.*,"Ion-Bunch Stacking in a Penning Trap after Purification in an Electrostatic Mirror Trap," Appl. Phys. B, in press (2013) doi:10.1007/s00340-013-5702-0.
IS518	Article	S. Kreim *et al.*,"Recent exploits of the ISOLTRAP mass spectrometer," Nucl. Instr. Meth. Phys. Res. B**317**, 492-500 (2013).
IS532	Article	F. Wienholtz *et al.*, "Masses of exotic calcium isotopes pin down nuclear forces," Nature **498**, 346 (2013).
	Thesis	R. Wolf,"First on-line applications of a multi-reflection time-of-flight mass separator at ISOLTRAP and the mass measurement of ^{82}Zn," PhD thesis, University of Greifswald, Germany (2013).
IS535	Article	V. Manea *et al.*, "Collective degrees of freedom of the $A \approx 100$ nuclei and the first mass measurement of the short-lived nuclide ^{100}Rb," Phys. Rev. C **88**, 054322 (2013).