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HIGH-PRECISION MASS MEASUREMENTS OF EXOTIC NUCLEI WITH THE TRIPLE-TRAP MASS SPECTROMETER ISOLTRAP

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Abstract

The masses of close to 200 short-lived nuclides have already been measured with the mass spectrometer ISOLTRAP with a relative precision between $1\cdot10^{-7}$ and $1\cdot10^{-8}$. The installation of a radio-frequency quadrupole trap increased the overall efficiency by two orders of magnitude which is at present about 1%. In a recent upgrade, we installed a carbon cluster laser ion source, which will allow us to use carbon clusters as mass references for absolute mass measurements. Due to these improvements and the high reliability of ISOLTRAP we are now able to perform accurate high-precision mass measurements all over the nuclear chart. We propose therefore mass measurements on light, medium and heavy nuclides on both sides of the valley of stability in the coming four years. ISOLTRAP is presently the only instrument capable of the high precision required for many of the proposed studies.

1. Introduction

The mass measurement program of ISOLTRAP (IS302, IS377, IS388, IS394) has been very successful in the past years. A number of scientific highlights have been achieved which demonstrate the leading role of ISOLTRAP in the precise determination of nuclear binding energies far from stability. A high performance of the apparatus has been achieved. ISOLTRAP is able to study nuclides with half-lives well below 100 ms and produced with yields as low as a few 100 ions/s. A mass resolving power of 10^7 and a precision of close to 10^{-8} can be obtained if required.

For the coming years we propose an extensive mass measurement program in the regions of light, medium heavy, and heavy nuclei.

- A new region should be explored in the light mass range. It is foreseen to perform in particular mass measurements on possible proton and neutron halo nuclei like ^{6,8}He, ^{11}Li, ^{11,12}Be, ^{17}Ne and $^{20-22}$N. In addition ^{9}Li and $^{18-19,23-25}$Ne will be addressed because of their importance for recent laser and β-NMR spectroscopy experiments.

- Tests of the conserved vector current (CVC) hypothesis and the isobaric multiplet mass equation (IMME) require very high precision mass data: Measurements on ^{14}O, ^{17}N, ^{17}Ne, ^{22}Mg, ^{26m}Al, ^{38m}K, and ^{62}Ga are proposed.

- Mass measurements on neutron-rich Ni, Cu, Zn, Ga, and Mn isotopes allow to explore largely unknown terrain.

- The improvement of masses of neutron-rich Sn, Cd, and Ag isotopes in the vicinity of ^{132}Sn are of astrophysical importance as well as for understanding the shell structure in this region.

- Measurement of masses east and north east of ^{208}Pb (Tl, Pb, and Bi), very close to stability are proposed. In this region masses are largely unmeasured and are of interest both for the understanding of nuclear structure and for the astrophysical r-process leading to the synthesis of very heavy elements.

For this program in total 104 shifts of radioactive beam are requested for a period of four years, starting from the year 2003.

The main reason why such an extensive experimental program is covered by a single proposal is the following: Due to the significant shortening of the running time of ISOLDE a very effective beam time scheduling and coordination is essential. By proposing an experimental program covering several years we hope to contribute to an efficient use of target/ion source systems requested also by other experiments. In addition, ISOLTRAP is either operational or in a stand-by-mode all year long and is therefore able to take beam in case of a breakdown of scheduled experiments on short notice.

2. Present status of the ISOLTRAP experiment

The Penning trap mass spectrometer ISOLTRAP, permanently installed at ISOLDE, plays a leading role in mass spectrometry of short-lived nuclides [Bol01]. In total the masses of about 200 short-lived nuclides have been measured with a relative precision of $\delta m/m \approx 1\cdot10^{-7}$ (corresponding to δm < 10 keV for A < 100) [Bec97, Ame99, Bec00, Her01a, Sch01, Rai02] and close to 10^{-8} in some special cases [Her02]. The technique ISOLTRAP uses is the determination of the cyclotron frequencies of ions stored in a homogeneous and stable field of a super-conducting magnet. In order to obtain a mass from the measured cyclotron frequency, the magnetic field has to be known. This is achieved by a measurement of the cyclotron frequency of a reference ion with well-known mass.

In the last three years ISOLTRAP showed highly reliable operation with 2 to 6 successful on-line runs of up to 23 shifts per year. In total 39 masses were measured as can be seen from Table 1. In 2002 we are scheduled for four beam times.

Table 1: ISOLTRAPs beam-times in 1999-2002.

Year	Nr. of beam-times	Shifts of radioactive beam	Shifts of stable beam	Masses measured
1999	3	14	6	^{33,34,42,43}Ar, $^{114...123}$Xe, ^{183,184}Hg
2000	6	23	12	^{34}Ar, ^{76,77}Sr, $^{129..132}$Sn, $^{178..182}$Hg, $^{73..78}$Kr, ^{74}Rb
2001	2 (+ technical improvements)	12	4	^{32,44,45,46}Ar, ^{72}Kr
2002	*4*	*22*	*10*	*$^{68-71}$Se, $^{79-85}$Y, $^{206-210}$Tl, $^{209-212}$Pb, $^{210-214}$Bi, + test beam for light masses*
SUM	14	71	32	39 (+ *25*) masses

2.1 Experimental setup and principle of mass measurements

ISOLTRAP (Fig. 1) consists of three functional parts: a radio-frequency quadrupole (RFQ) ion trap for beam preparation and two Penning traps [Bol96, Her01b]. A very recent addition is a carbon cluster ion source [Bla02a, Kel02a].

The linear gas-filled RFQ ion trap stops the 60 keV continuous ISOLDE beam and prepares it for efficient transfer into the cooling Penning trap. To this end the ISOLDE ions are electro-statically retarded before they enter the RFQ, where they are cooled by energy loss due to helium buffer gas cooling. After a certain accumulation time (typically 10-20 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 1s) and contaminant ions are removed. For this, a mass-selective buffer gas cooling technique is used [Sav91]. The ions are then transferred to the second, precision Penning trap where the actual mass measurement is carried out.

The frequency of an exciting azimuthal quadrupolar RF field is scanned for determination of the ions cyclotron frequency. The resonance is detected with a time-of-flight technique [Grä80]. A characteristic cyclotron resonance curve [Kön95] is shown in the inset of Fig. 1. The mass m of an ion with charge q is obtained by the comparison of its cyclotron frequency

$$\nu_c = 1/2\pi \cdot q/m \cdot B \qquad (1)$$

with the cyclotron frequency of a known reference ion mass. In more detail, the exact value of the magnetic field B is measured by a determination of the cyclotron frequency of an ion with well-known mass both before and after the measurement of the cyclotron frequency of the ion of interest.

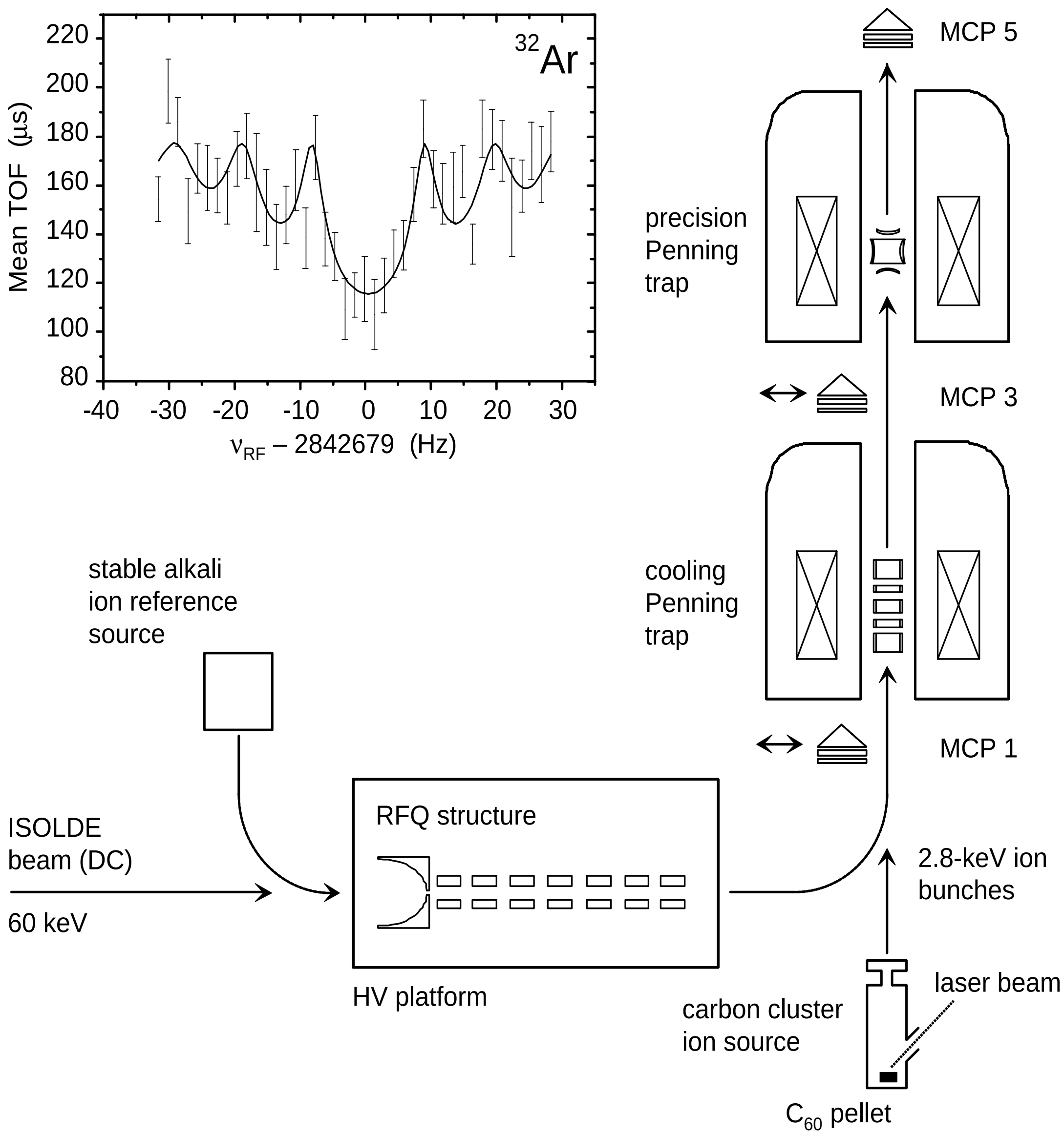

Figure 1: Schematic drawing of the mass spectrometer ISOLTRAP including the RFQ trap, the cooling Penning trap, the precision Penning trap, as well as the new carbon cluster ion source. Micro-channel-plate (MCP) detectors are used to monitor the ion transfer as well as to record the time-of-flight resonance (MCP5) for the determination of the cyclotron frequency. The inset spectrum shows the cyclotron resonance curve of $^{32}Ar^{+}$ *after three hours measurement time with a fit of the theoretically expected line shape to the data points.*

2.2 Technical improvements

During the last two years, the performance of the Penning trap mass spectrometer ISOLTRAP has been considerably enhanced. Within the European RTD network EXOTRAPS, a linear segmented and gas-filled radio-frequency quadrupole (RFQ) trap was developed and has increased the overall efficiency by two orders of magnitude. Such devices are now also in operation at SHIPTRAP/GSI, JYFLTRAP/Jyväskylä and planned as general device for beam emittance improvement at ISOLDE and for MISTRAL/Orsay. In the framework of the TMR network EUROTRAPS and the RTD network NIPNET it was shown that the precision of ISOLTRAP reaches $\delta m/m = 1.1\cdot 10^{-8}$ and that, for the first time, absolute mass measurements in terms of the microscopic mass standard, the unified atomic mass unit $u = 1/12\ m(^{12}C)$, are now possible for short-lived nuclides. These breakthroughs in mass spectrometry of radionuclides are briefly described in the following.

2.2.1 Absolute mass measurements

Since the unified atomic mass unit is defined as 1/12 of the mass of ^{12}C, carbon clusters provide an ideal mass reference for absolute mass measurements: They eliminate by definition the uncertainty of the mass of the reference ion. The molecular binding energies of the carbon clusters, being of the order of $V_b/(mc^2) \approx 10^{-9}$ [Egg94, Man01], can be neglected at the level of precision aimed for in this proposal. For these reasons, a carbon cluster reference ion source for ISOLTRAP was developed [Bla02a]. In ISOLTRAP the carbon cluster ions are produced in a compact ion source by use of laser-induced desorption, fragmentation and photoionization of C_{60} fullerenes, the soccer-ball-shaped molecules of carbon [Kro85, Lif00]. For this purpose a frequency-doubled Nd:YAG laser beam is focused on a C_{60} pellet as shown in Fig. 1.

2.2.2 Accuracy

Up to now the combined uncertainty was estimated conservatively to be $\delta m/m \approx 1\cdot 10^{-7}$ [Bol96], which includes such uncertainties as caused by inhomogeneities of the magnetic and electric fields, by magnetic field drifts or fluctuations, and the mass-dependent systematic error stemming from the difference in mass Δm between investigated ion and reference ion.

During the last year we performed about 300 off-line carbon cluster cross-reference mass measurements over a wide mass range of 240 u, i.e. covering the complete nuclear chart. The observation of cyclotron frequencies of different cluster sizes up to n = 20 allowed us to study the various contributions of various systematic effects to the combined uncertainty of a mass determination. This investigation yielded a mass-dependent systematic uncertainty as low as $\delta m/m = 2.0(7)\cdot 10^{-10}\cdot \Delta m/\mathrm{u}$ which can be corrected for. Once all known effects are taken into account, the remaining uncertainty is found to be $8\cdot 10^{-9}$. This also represents the current limit of precision of our set-up [Kel02b]. The result of this correction is shown in Fig. 2. In this figure, the weighted means of all individual cross-reference measurements are shown as a function of the mass of the simulated ion of interest. The error bars represent the experimental mean uncertainties of the weighted means. As can be seen right away, these results agree rather well with the true value, represented by the horizontal line.

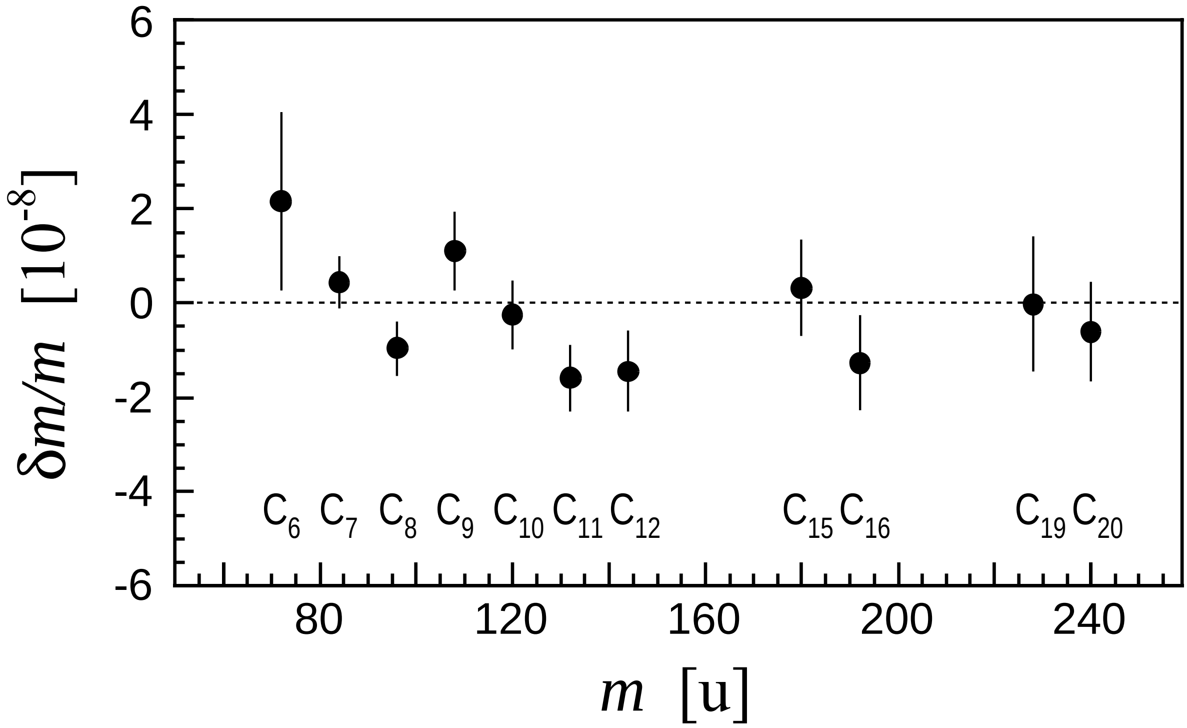

Figure 2: Weighted means of the cyclotron frequency ratios for all carbon cluster cross-reference measurements after taking all known systematic effects into account.

2.2.3 Resolving power

Accurate high-precision mass measurements with Penning traps require clean beams to avoid systematic errors in the mass determination arising from a Coulomb interaction of different ion species in the trap. To this end, in the first "cooling" Penning trap of ISOLTRAP, a mass-selective cooling technique is employed which was developed for ISOLTRAP mass measurements [Sav91]. A mass resolving power of about $R = 10^5$ can be achieved which is sufficient to resolve and separate isobars even close to stability [Rai97].

An important issue in direct mass measurements is to resolve isomeric and ground states since nearly one third of the nuclides in the nuclear chart have long-lived isomeric states with - in many cases - unknown excitation energies. To achieve this, a very high resolving power is required. An empirical formula for the resolving power is given by [Bol01]

$$R = m / \Delta m = \nu_c / \Delta\nu_c(\mathrm{FWHM}) \approx 1.25 \cdot \nu_c \cdot T_{RF} \,. \qquad (2)$$

A resolving power of $R \approx 10^6$ is reached in the precision Penning trap for $A = 100$ ions with an excitation time of $T_{RF} \approx 1$ s as typically used in on-line experiments. The same resolution would be achieved for $A = 10$ ions in only 100 ms. Even higher resolving powers can be achieved by further increasing the RF excitation time. In the case of short-lived nuclides, the resolving power will be limited by the half-life. In cases of particular interest, the precision can be recovered by accumulating more statistics. Thus, the only limit to ISOLTRAP possibilities is for very short-lived nuclides to have isomers with low excitation energies.

2.2.4 Half-life

Very recently, it has become possible to push the applicability of Penning trap mass measurements to radionuclides with half-lives well below one second. Therefore, an alternative measurement cycle with a total cycle time of only about 200 ms was developed. The nuclide with the shortest half-life measured until now is ^{74}Rb with an half-life $T_{1/2}$ of only 65 ms [Her02].

2.2.5 Efficiency

The installation of the RFQ trap as well as a complete realignment of the setup resulted in an increase of the overall efficiency of the ISOLTRAP spectrometer by several orders of magnitude. It reaches now about 1% for stable or long-lived nuclides as determined in November 2001 from the ratio of the number of ^{36}Ar ions observed by the micro-channel-plate detector MCP5 (Fig.1) to the number of ions measured at the focal plane of the ISOLDE separator. For very short-lived nuclides such as ^{32}Ar with $T_{1/2}$ = 98 ms, an overall efficiency of about 0.1% was achieved, mainly due to additional decay losses.

3. Recent highlights

Based on the improved performance of ISOLTRAP as discussed above, quite a number of important mass measurements have been performed during recent years. A few examples will be presented in the following.

The mass of ^{33}Ar was determined by ISOLTRAP with an accuracy of $1 \cdot 10^{-7}$ [Her01a]. The result was not consistent with the mass calculated by use of the isobaric multiplet mass equation (IMME). This discrepancy could have had severe consequences for the presently best exclusion test of scalar contributions to weak interaction as performed by Adelberger et al. [Ade99] at ISOLDE by use of ^{32}Ar. Therefore, our measurements prompted further investigations which now resolved the problem in the case of ^{33}Ar [Pyl02].
In the meantime, also the mass of ^{32}Ar was measured by ISOLTRAP. Here, a precision of $\delta m/m < 1 \cdot 10^{-7}$ (inset of Fig. 1) was reached despite a production rate of only about 100 ions/proton pulse [Bla02b]. The result differs from the IMME prediction used by Adelberger et al. by nearly 3σ and as a consequence a re-evaluation of the Adelberger experiment is under way.

The mass of ^{34}Ar ($T_{1/2}$ = 844 ms) was determined with a relative uncertainty of only $1.1 \cdot 10^{-8}$ [Her02]. This is the highest precision ever obtained in direct mass measurements of short-lived nuclides. With this result the Q_{EC} value for the β decay of ^{34}Ar was determined with an uncertainty well below 1 keV, sufficient to be used in a decisive test of Coulomb correction calculations for *ft*-values. In the very same context, also the *Q* value of ^{74}Rb is important. Here ISOLTRAP was able to measure the mass of ^{74}Kr with a precision of $3.2 \cdot 10^{-8}$, but due to limited statistics, the mass of ^{74}Rb could only be obtained with an uncertainty of $2.6 \cdot 10^{-7}$ or δm = 18 keV. Note, however, that ^{74}Rb, with a half-life of only $T_{1/2}$ = 65 ms, is the shortest-lived nuclide ever investigated in an ion trap [Her02].

Resolution of nuclides in their ground and isomeric state has been demonstrated several times. For example, the low-lying levels of the I = 13/2 neutron-deficient Hg isomers in the mid-neutron shell was resolved by ISOLTRAP mass spectrometry [Sch01]. This measurement confirmed the coexistence of nuclear shapes at nearly degenerate energies (≈100 keV) as previously deduced from laser and nuclear spectroscopy. Furthermore, the excitation energies of the isomeric states in the nuclei $^{187,191}Hg$ were determined by ISOLTRAP mass measurements for the first time [Sch01].

ISOLTRAP mass measurements in long isotopic and isotonic chains allowed the study of the fine structure of the mass surface and clarified discontinuities in order to extract nuclear structure information from binding energies [Sch01, Bol01]. As an example for such a systematic survey Fig. 3 shows two-neutron separation energies in the vicinity of $Z = 82$ excluding (top) and including (bottom) ISOLTRAP data in the atomic mass evaluation.

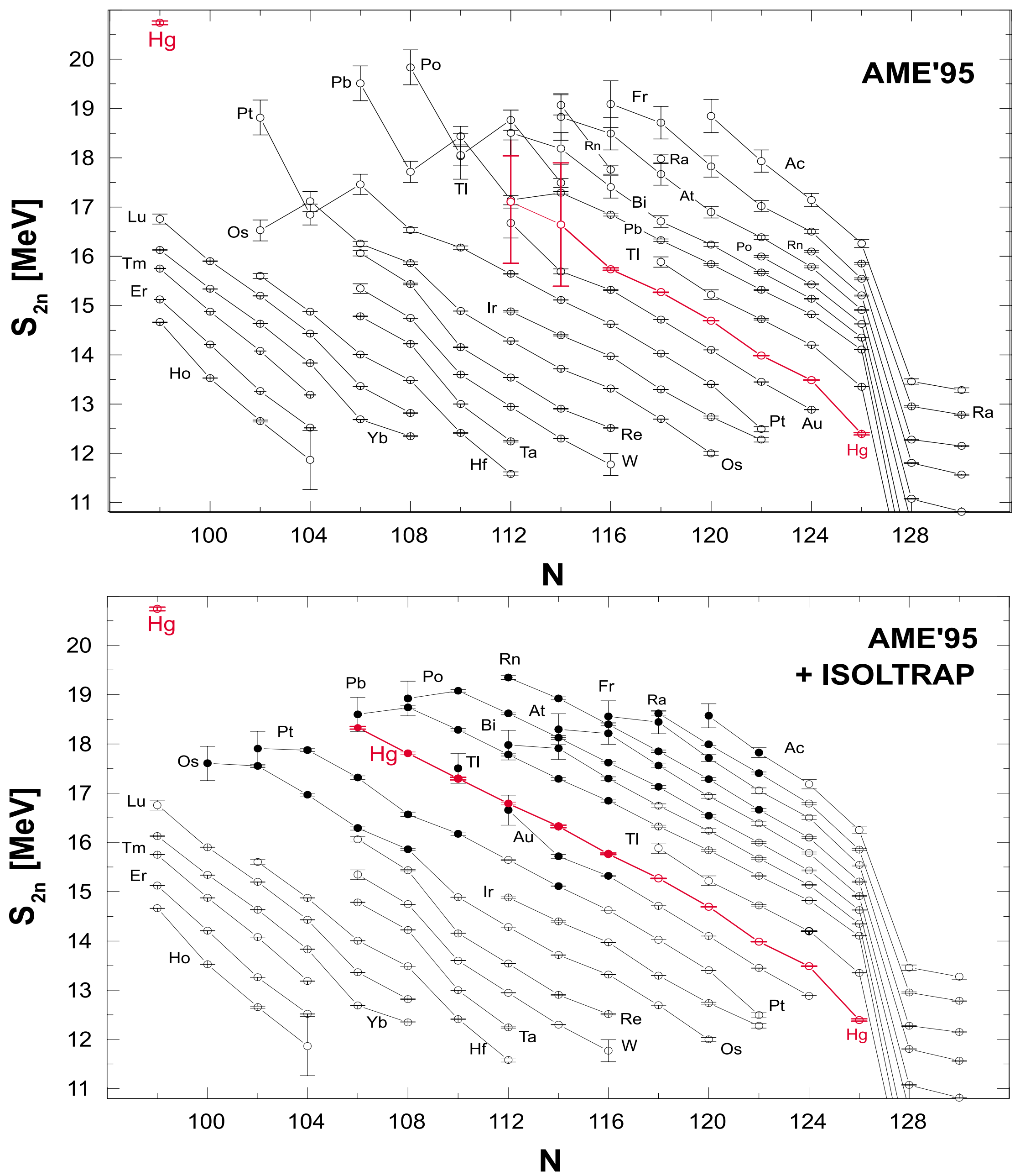

Figure 3: Two-neutron separation energies in the vicinity of Z = 82 as a function of neutron number. Shown are S_{2n} values excluding (top) and including (bottom) ISOLTRAP data in the atomic mass evaluation.

4. Proposed mass measurements

Based on the improved performance of ISOLTRAP as achieved recently (see Section 2) and on the yields available at ISOLDE we propose the following mass measurements with ISOLTRAP. A compilation of the requested beam time is given in Section 5 "Beam time request". If target/ion source development is required it will be explicitly mentioned.

4.1 Masses of light nuclides near the drip line

Nuclear binding energies provide key information on the isospin dependence of nuclear matter. They tell us when a nuclear system becomes unbound, and in this way define the position of the drip lines. Bound/unbound transitions are critical phenomena, which require high-quality input data as, for example, nuclear masses or, more precisely, nucleon separation energies. Concepts developed near stability such as the stabilization at magic nucleon numbers are sensitively tested in nuclei with extreme proton-to-neutron ratios. Surprises might be expected as experienced in the case of the discovery of halo nuclei or the shell quenching at $N = 20$ and $N = 28$.

A halo state can be formed when bound states close to the continuum exist. The neutron-separation energy, which can be obtained from atomic masses, is a key parameter in the study of neutron halo nuclei. A small neutron separation energy leads to a large spatial extension [Han87]. Also other properties, which determine structure and quantum numbers of a halo nucleus, depend sensitively on the neutron separation energy and a precise knowledge is thus required.

Most of the theoretical and experimental investigations have addressed neutron-rich nuclei, but also proton halos do exist. They have less pronounced spatial extension because of the Coulomb barrier. The first nuclei for which a proton halo was observed was ^{8}B [Sch95], which has a proton separation energy of only 140 keV. Another proton-halo candidate is ^{17}Ne, which shows a much larger total-interaction cross-section than the isobar ^{17}N [Tan99] and is thus expected to have a sizable proton halo.

Accurate mass measurements of exotic nuclides close to the dripline are not only required for the understanding of nuclear halos, but also yield new insight into and the evolution of nuclear structure at extreme isospin values. For instance, the pioneering work of the Orsay group that led to the discovery of the disappearance of the magic number $N = 20$ has been carried out at CERN many years ago employing direct mass measurements [Thi75]. However, only quite recently, the appearance of a new shell closure at $N = 16$ near the neutron dripline has been reported [Oza00]. These latest findings are based on a survey of neutron separation energies, $B(E2;\, 0_1^+ \rightarrow 2_1^+)$ values and total-interaction cross sections. The results clearly demand for a precise mass survey of this region.

Direct mass measurement of these very light and mostly very short-lived nuclides at ISOLTRAP is an experimental challenge. We propose ISOLTRAP mass measurements on some specific nuclides, which are of particular interest and where the measurements can be performed with reasonable effort.

^{6,8}He

^{6}He and ^{8}He have been well studied in recent years. They are best described to consist of a ^{4}He core and 2 or 4 additional neutrons: ^{6}He is a three-body system (α + 2n), whereas ^{8}He is a five-body system (α + 4n). Matter radii have been derived from proton elastic scattering in inverse kinematics [Alk97], but charge radii have not yet been investigated. The question is whether the halo neutrons would change the charge radius of the α–core due to the strong interaction among the nucleons. The effect is sensitive to the isospin dependence of the three-body nucleon force and is predicted to be small. Therefore a very accurate determination of the charge radii via a measurement of the optical isotope shift has been proposed by employing laser spectroscopy in a magneto-optical trap [Lu01]. The isotope shift receives contributions from two effects: The mass shift due to the change of nuclear mass, and the field shift due to the change of nuclear charge radii. In order to extract the difference of charge radii, one has to know the atomic structure and the nuclear masses. It is expected that the isotope shift between ^{6}He and ^{8}He can be measured to a precision of less than 10% or < 100 kHz. The contributions from the mass uncertainties ($\delta m_{6\text{-He}} \approx 1$ keV, $\delta m_{8\text{-He}} \approx 7$ keV) are about 11 kHz and 85 kHz, respectively. In order not to limit the obtainable precision in the charge radius determination it will be required to reduce the mass uncertainty for ^{8}He significantly. ISOLTRAP will be able to measure the masses of both ^{6}He and ^{8}He with an accuracy of 1 keV or better. For doing so, cooling in the RFQ trap and the cooling Penning trap by H_2 gas (instead of He) has to be demonstrated.

^{9,11}Li

The observation of anomalous large total-interaction cross sections of ^{11}Li led to the discovery of the halo phenomenon. Thus ^{11}Li is the most prominent and best-studied halo nucleus. Nevertheless, its two-neutron separation energy S_{2n} is only relatively poorly known at present. Since the mass of ^{9}Li is determined with an accuracy of 2 keV, the main contribution to this uncertainty comes from the experimental results for the ^{11}Li mass. Four experimental values exist [Thi75, Wou88, Kob91, You93], which have been obtained employing different experimental techniques yielding partially conflicting results. From these values an adjusted value for the two-neutron separation energy of $S_{2n} = (300 \pm 27)$ keV has been derived in the Atomic Mass Evaluation [Aud95]. This unsatisfactory situation can be resolved with an ISOLTRAP measurement at a level of a few keV. Because of the importance of the halo nucleus ^{11}Li, this measurement should be performed in parallel to the accepted MISTRAL experiment (IS402) [Lun01]. Furthermore, extreme mass accuracy is required for ^{9}Li and ^{11}Li by the accepted proposal IS385 [Dax00] which aims at a measurement of the charge radii of those isotopes. As in the case of neutron-rich He isotopes, the much larger mass shift as compared to the volume shift calls for better mass data. The short half-life of ^{11}Li of only $T_{1/2}$ = 8.5 ms is a new challenge to explore the limits of ISOLTRAP.

^{11,12}Be

^{11}Be is a well-established one-neutron halo and ^{14}Be is a two-neutron halo. Concerning the masses we find the following situation: $\delta m_{10\text{-Be}} = 0.4$ keV ($T_{1/2}$ = 1.5My), $\delta m_{11\text{-Be}} = 6$ keV ($T_{1/2}$ = 14s), $\delta m_{12\text{-Be}} = 15$ keV ($T_{1/2}$ = 21ms), $\delta m_{14\text{-Be}} = 110$ keV ($T_{1/2}$ = 4.4ms). ISOLTRAP is able to improve the mass uncertainties of ^{11,12}Be. These isotopes are produced with sufficient intensity at PSB-ISOLDE. However, due to the low yield of 10 ions per second, the most interesting case of ^{14}Be is not feasible at present. It is expected that the ongoing work to increase the overall-efficiency and sensitivity of ISOLTRAP still further in combination with progress in the target/ion source technology may make such a measurement possible within the coming years.

$^{17-22}$N

There are a number of nuclides which are expected to exhibit a halo structure, but so far - if any - only scarce experimental information is available. A list of candidates can be found in a recent review [Oza01]. There is strong evidence for a one-neutron halo in ^{22}N [Oza01] and ^{20}N is known to have a neutron skin [Boc98]. The masses of nitrogen isotopes from ^{17}N through ^{22}N have errors ranging from 20 keV to 200 keV according to [Aud95]. All nitrogen isotopes from ^{17}N through ^{22}N are in reach for ISOLTRAP, and the mass uncertainties can be reduced to the few-keV level.

$^{17-19,\ 23-26}$Ne

^{17}Ne is a proton-halo candidate, which has recently been studied at ISOLDE with collinear laser spectroscopy [Neu00, Neu02]. From the result of these isotope shift measurements a significant increase of the charge radius from ^{18}Ne to ^{17}Ne is observed, which could be attributed to the formation of a proton halo. For the neutron-rich ^{23,24,25}Ne isotopes no significant increase of their total interaction cross sections is observed [Suz02]. However, there are recent Relativistic Mean-Field (RMF) calculations [Lal96], which suggest a multi-halo formation for neon isotopes close to the neutron dripline. In order to put theoretical predictions on a solid basis we propose measurements on these isotopes.

4.2 CVC test and CKM unitarity

ISOLTRAP has already significantly contributed to the test of fundamental relations like the Constant Vector Current (CVC) hypothesis and the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix [Cas98, Abe00, Har01, Har02]. These investigations require an accuracy in the mass determination presently only achievable by Penning trap mass spectrometry.

The nuclear beta decay is a unique laboratory for investigations of the weak interaction. Of special interest are the superallowed $0^+ \rightarrow 0^+$ nuclear β decays where the axial-vector decay strength is zero. The transition rate Ft for these decays should be nucleus independent if the vector current is a conserved quantity (CVC hypothesis). In this case the vector coupling constant G_V can be extracted and be used together with value for G_V extracted from muon decay to determine the V_{ud} element of the CKM matrix which is a key for testing the unitarity of the CKM matrix and hence for the Standard Model itself.

Small nucleus-dependent corrections that are related to the presence of charge-dependent forces in the nucleus have to be applied when Ft is extracted from nuclear β decay. These corrections, the radiative correction δ_R and the Coulomb correction δ_C, have to be calculated.

Until now the parameters of 9 superallowed β decays have been measured with high accuracy [Har02]. For many of the other potential candidates the knowledge of the Q_{EC}-value is limited. That prohibits an accurate determination of the *Ft* value. To reach an uncertainty level of 0.1% or better for the *Ft* value an uncertainty of 0.1% or better is required for half-life and branching ratio. But since the statistical rate function *F* is proportional to Q_{EC}^5 the Q_{EC} value has to be determined with an uncertainty of better than 0.01%. This requires mass measurements of mother and daughter nuclei with relative uncertainties $\delta m/m \leq 3\cdot10^{-8}$. This is only possible with ISOLTRAP.

For the 9 well-known cases the *Ft* values appear to be constant [Har02], supporting CVC. However, the extracted V_{ud} together with the much smaller V_{us} and V_{ub} result in a CKM matrix that is not unitary by 2.2 standard deviations [Har99]. One important point to be clarified here is the correctness of the calculated Coulomb correction δ_C. The well-known cases have quite low calculated Coulomb corrections in the order of 0.5%. The best candidates for testing these calculations are thus nuclei with Coulomb corrections predicted to be large, as for instance ^{34}Ar already studied by ISOLTRAP or ^{14}O, ^{22}Mg and ^{30}S. Furthermore, to test new theoretical approaches as well as to probe CVC for higher *Z* it is necessary to extend the study of superallowed decays beyond $A = 54$ (Co). Decay studies of this kind are already under way in the cases of ^{62}Ga [Ced02] and ^{74}Rb [Äys00]. Complementing mass measurements are required.

The following candidates are proposed to be studied with ISOLTRAP with a precision of about $1\cdot10^{-8}$:

^{74}Rb:

The 1% error on the *Ft* value of the superallowed $A = 74$ β decay is dominated by the error on the mass measurement of ^{74}Rb which is at the level of $2.6\cdot10^{-7}$. The accuracy of this ISOLTRAP measurement was limited by statistics caused by accidentally low ion production during the run.

About 200,000 ions have to be detected in order to reach the accuracy needed to test the standard model. At a typical production rate of 1000 ions/s this can be achieved in 5 shifts of radioactive beam (+ time for calibration), as discussed in Section 5 (“Beam time request”).

^{62}Ga, ^{62}Zn:

In the case of the $A = 62$, masses of both ^{62}Ga and ^{62}Zn need to be determined with greater precision. The mass of the parent nuclide, ^{62}Ga, is known to $4.4\cdot10^{-7}$ and that of the ^{62}Zn daughter to $1.6\cdot10^{-7}$. The production of the latter ($\sim10^7$-10^8 ions/s) is sufficient to make a relatively rapid measurement whereas the ^{62}Ga production, at about a few hundred ions per second, will require the same number of shifts as for ^{74}Rb.

^{62}Ga [Ced02] and ^{74}Rb [Äys00] are both already under investigation at ISOLDE concerning branching ratio and half-life.

^{14}O, ^{22}Mg, ^{26m}Al:

Even for some of the well-known nuclei, namely ^{14}O, ^{22}Mg, ^{26m}Al and ^{46}V, the Q_{EC} value uncertainty is the dominant source of *Ft*-value uncertainty requiring additional high accuracy mass measurements [Har01]. ^{14}O, ^{22}Mg, and ^{26m}Al are available at ISOLDE and can be accessed with ISOLTRAP.

4.3 Test of the isobaric multiplet mass equation (IMME) with mass measurements on ^{17}Ne, ^{17}N, and ^{38m}K

In light nuclei isobaric analog states (IAS) have nearly identical wave functions. The charge dependent energy difference of these states can be calculated in first-order perturbation theory assuming only two-body Coulomb forces. This leads to the simple equation, noted first by Wigner [Wig57], $M(T_Z) = a + bT_Z + cT_Z^2$ that gives the mass M of a member of an isospin multiplet as a function of its isospin projection $T_Z = (N - Z)/2$. This quadratic relation is called the isobaric multiplet mass equation (IMME). Looking at the quartets [Ben79] it was found that IMME worked very well for 21 out of 22 cases. Due to its success and lack of newer experimental data, IMME is widely used to predict masses as well as level energies.

As already mentioned in Section 3, the ISOLTRAP mass value for ^{33}Ar resulted in a breakdown of the quadratic IMME for the $A = 33$, $T = 3/2$ quartet [Her01a]. These surprising results triggered new reaction spectroscopy experiments. The outcome was that one of the levels in ^{33}Cl was inaccurate [Pyl02].

This shows the importance of refined measurements. Of course, direct mass measurement can only determine the mass of ground state multiplet members. But these nuclei are often also the most exotic members of an isospin multiplet with a rather large mass uncertainty [Bri98].

An investigation of the presently known multiplets shows ISOLTRAP will be able to provide 2 more stringent IMME tests by determining the masses of ^{17}Ne, ^{17}N, and ^{38m}K.

4.4 Improved masses and exploration of new territory in the medium mass range

Mass measurements are proposed on neutron-rich nuclei in the vicinity of the $Z = 28$ and $Z = 50$ proton shell closure. In these regions the knowledge of nuclides and their properties is still very limited and many masses far away from stability are still unknown. Measuring masses along isotopic chains in these regions will allow to investigate the strength of the closed Z shell as a function of neutron excess. Furthermore, they will allow to probe the predicted shell quenching along the closed $N = 50$ and $N = 82$ shell, respectively [Dob96].

4.4.1 ^{78}Ni and vicinity

In Figure 4 the S_{2n} values for nuclides Z = 24−34 over the range of N = 35−50 are shown. In the upper (large S_{2n}) area of the curve, the data are very precise and the regular, linearly descending S_{2n} trend can clearly be seen. As we go towards the neutron drip line, the data deteriorate in quality and irregular deviations appear. Usually, we can glean information about nuclear structure from deviations - on the condition that there is some reliability and precision.

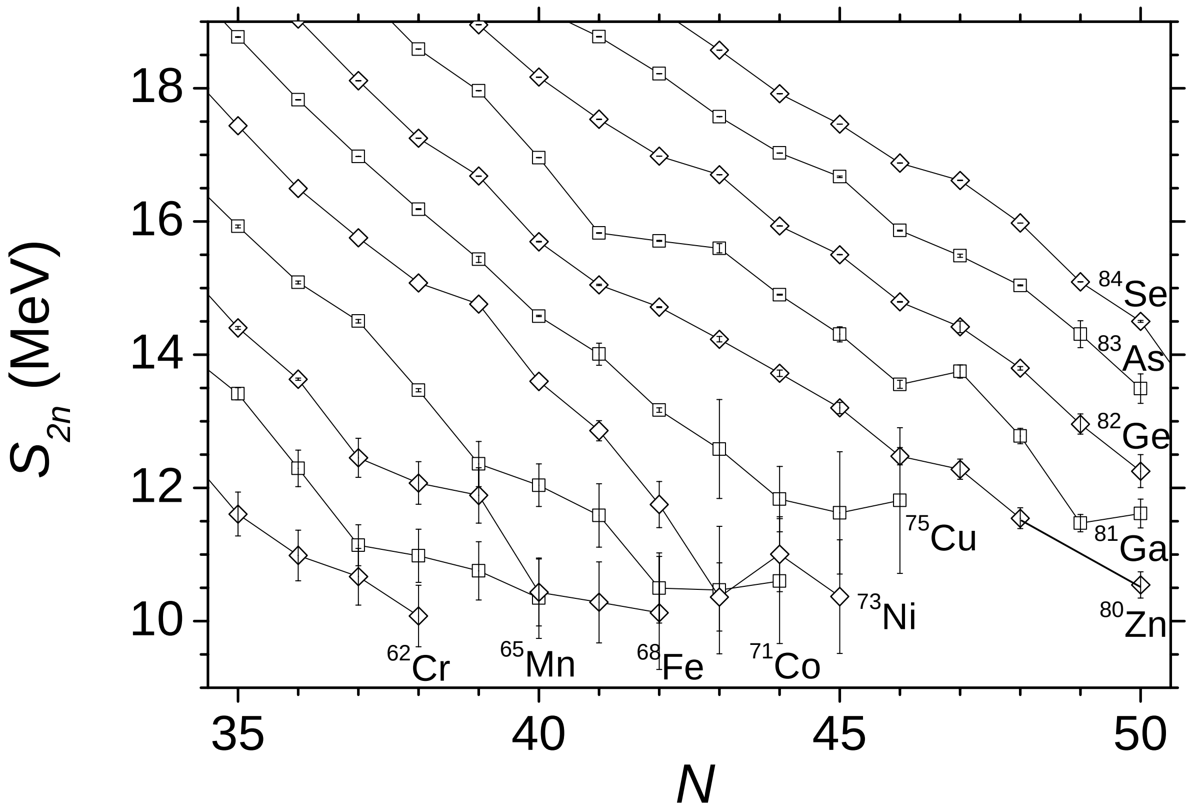

Figure 4: Two-neutron separation energies in the vicinity of Z = 28 as a function of neutron number. Shown are S_{2n} values over the range of N = 35 – 50.

An important question in nuclear structure is related to the behavior of shell closures far from stability. Detailed studies have been made of shell quenching (e.g. mass measurements around N = 28 [Sar00]), however it is also possible that new shell closures appear, e.g. at N = 16 [Oza00] and N = 40 [Sor02]. Coulomb excitation experiments show evidence that N = 40 becomes magic for Ni isotopes. If we look at the S_{2n} values for Ni, we see no corroborating effect whatsoever. It is possible, however, that the masses of ^{69}Ni and ^{70}Ni are wrong. Two aspects support this suspicion: First, the S_{2n} value of ^{67}Ni shows a sharp and isolated deviation from the linear trend, possibly due to the existence of a purported isomeric state [Aud97] that was not resolved in earlier experiments with the TOFI spectrometer [Sei94]. A similar isomeric state is suspected for ^{69}Ni. Secondly, the measurements of $^{71-73}$Ni by TOFI also show abrupt and uncorrelated variations with extremely large error bars (0.5 MeV). At N = 43, the S_{2n} value for ^{71}Ni drops below that of the lighter ^{70}Co, a situation that occurs nowhere else on the nuclear chart (except for ^{6}He) and therefore casting doubt on the integrity of the data.

Ni: A remeasurement of masses along the chain of nickel isotopes starting from ^{67}Ni up to possibly ^{74}Ni with ISOLTRAP will clarify these questions. An accuracy of $1\cdot10^{-7}$ will be important, not only to check the values but also to reveal fine structure in the change of the binding energies. In the case of ^{67,69}Ni the high resolution mode of ISOLTRAP can be used in order to resolve isomer and ground states and to verify isomeric energies, presently only available from systematics.

Cu: A similar situation exists for the neighboring copper isotopes. The mass values up to ^{75}Cu were derived from the same data set as the suspicious Ni isotopes. The present S_{2n} data may indicate the onset of deformation beyond $N = 44$ but the error bars are too large for a reliable conclusion. The high Cu yields available with the UC target and RILIS provide an excellent opportunity to extend the knowledge of masses by three more isotopes up to ^{78}Cu.

Furthermore, the known isomers of ^{68,70}Cu are produced at ISOLDE and will be resolved from their ground state with ISOLTRAP. A long-lived isomer is predicted [Aud97] in ^{76}Cu and may be seen for the first time with ISOLTRAP. In the case of ^{70}Cu, where two long-lived states exist [Kös02] which can be resolved with the resonance ionization laser ion source, ISOLTRAP will be able to make yet unknown assignments to ground and isomeric states.

Zn: The chain of zinc isotopes show a smooth trend in the S_{2n} values, but the errors are still very large. In addition, the value for ^{79}Zn is still missing. A remeasurement of the chain starting from ^{74}Zn would increase the accuracy for these isotopes by an order of magnitude and more. The Zn yields (Nb foil RILIS) are sufficient to allow measurements up to ^{76}Zn and even further, when the ongoing target development is taken into account, even further.

Ga: The gallium chain shows a couple of suspicious irregularities with only vague, if any, correlation to the trends in the neighboring chains. The S_{2n} values for ^{78,80}Ga show a clear departure from the linear trend, which is most likely caused by one or more wrong mass values. In any case, the present uncertainties are larger than $1\cdot10^{-6}$ for ^{74}Ga, ^{76}Ga and isotopes beyond. Extrapolation of the ZrO_2-RILIS yields or taking UC target yields indicate that measurements as far as to ^{82}Ga are feasible.

Mn: Finally, the same arguments can be evoked for manganese, the exotic heavy isotopes of which may indeed exhibit the behavior of shell effects near $N = 40$. At this neutron number the doubtful phenomenon of a sudden drop of S_{2n} values appear again. The isotopes from ^{58}Mn upwards are not known to the $1\cdot10^{-7}$ level and the UC-RILIS yields would allow ISOLTRAP to extend the chain to ^{66}Mn (~200 ions/s). Again, the presence of an isomer, in ^{60}Mn, renders the trap indispensable.

4.4.2 Masses in the vicinity of the doubly magic ^{132}Sn

The mass data in the vicinity of double closed shells for nucleons give highly valuable structure information. This has a particular significance for the far-from-stability regions where new phenomena as for instance shell quenching may arise due to low binding energies. As pointed out earlier, precise binding energies, derived from the atomic masses, are also of critical importance for the modeling of the astrophysical r-process. In addition to general trend studies in these mass region there exists a number of nuclides that are of special interest. A first attempt was made recently by use of ISOLTRAP (IS302) and yielded new mass values for the nuclides ^{129,130,132}Sn. Important deviations from accepted table values [Sik02] were found which show the need for more and more accurate values in this region.

Sn: To continue the trend studies, the masses of ^{133}Sn, ^{134}Sn and further should be addressed. High-resolution measurements are required in the case of ^{131}Sn to resolve the discrepancies between theoretical predictions and experimental data for the ground and first isomeric state [Fog99]. Recent shell model calculations [Bro02] showed, that the first isomeric state should be at about 50 keV, which is much less than the present accepted value of about 250 keV [Aud97] and still lower than earlier predictions of less than 140 keV [Gen99]. To resolve these two states a resolving power of 10^7 is required.

Cd: Of special interest is the neutron binding energy of the $N = 83$ nuclide ^{131}Cd, which determines the waiting-point behavior of ^{130}Cd. However, the entire isotopic chain starting at $A = 118$ is only known with relative uncertainties above 10^{-7}. For $A \geq 129$ no experimental data is available at all. This makes reliable theoretical models extremely difficult to setup. Mass measurements as accurate as possible and as far away from the valley of stability are required. The ultimate goal is to measure the neutron binding energy of ^{131}Cd directly.

Ag: The situation for the neutron-rich silver isotopes is very similar to the cadmium chain. For about $A \geq 114$ the relative uncertainty is above the 10^{-7} level and experimental mass data is missing for silver isotopes with $A > 121$. To uncover even smaller differences in the behavior of the binding energy trends and to improve the predictions for the waiting point nucleus ^{129}Ag mass measurements with relative uncertainties at and below $1 \cdot 10^{-7}$ are needed.

4.5 Neutron-rich masses of Tl, Pb and Bi isotopes

Considerable interest exists in the determination of the properties of these nuclei and the understanding of the nuclear structure as one proceeds away from the doubly magic ^{208}Pb. Despite their vicinity to the line of stable nuclides information on single particle levels, decay properties, and ground state properties is extremely scarce for nuclides east of ^{208}Pb. Knowledge of binding energies in this region is not only important for the understanding of nuclear structure in this region. An extension of experimentally known masses away from the valley of stability in this region is decisive to put constraints on nuclear models for predicting masses in the region where the r-process path may proceed towards the synthesis of the heaviest elements known in our solar system. First measurements in the close vicinity of ^{208}Pb ($^{206\text{-}210}Tl$, $^{209\text{-}212}Pb$ and $^{210\text{-}214}Bi$) are already planned and accepted in the proposal IS302 and are thus not included in this proposal.

Experimental effort to explore this terra incognita not far away from stability has started at ISOLDE a few years ago by use of a pulsed release technique which gave new information about the decay of the $A = 213\text{-}217$ isobars. ^{217}Bi has been identified for the first time; the unambiguous identification of ^{215}Pb is still open. New efforts at ISOLDE are the proposed beta decay studies (IS387, P128; ongoing of the IS354 experiment), which make use of the higher yields available with the use of the laser ion source.

ISOLTRAP will be able to complement these decay studies in a very beneficial way. The yields, which have been estimated in detail for P128, indicate that ISOLTRAP can provide masses as far out as ^{216}Tl, ^{217}Pb, and ^{218}Bi. The predicted half-lives of larger than one second for most of the nuclides are long enough to allow high-resolution measurements. Therefore, the mass measurements combined with decay studies will allow identifying ground and possibly isomeric states. It is also very well possible that ISOLTRAP will be able to discover some of these nuclides for the first time or at least help to identify them.

It should be mentioned that the pulsed release, that is decisive for background reduction in the decay experiments, is not required for ISOLTRAP and can be omitted in order to obtain higher yields.

4.6 Relevance of the proposed measurements for nuclear astrophysics

The measurements proposed on medium heavy and heavy neutron-rich nuclides are of relevance for modeling and understanding the rapid neutron capture process which is thought to be the source of over half of the heavy elements found in the solar system. The astrophysical models require as input data nuclear ground state masses, half-lives, and cross-section values for essentially the entire range of neutron-rich nuclides above ^{56}Fe. The r-process path involves mostly nuclides that are not experimentally accessible at today's RIB facilities. Therefore nuclear astrophysics is forced to rely on nuclear models. The choice of models needs to be constraint and their prediction to be improved. For this, experimental data have to be obtained as far away from stability as possible, which will allow a decisive test of the predictive power of the models and which provide an extended and reliable basis for the adjustment of their parameters.

The most important regions to provide new data are those where the r-process comes closest to stability. This is the case in the vicinity of magic neutron numbers, where the r-process slows down and proceeds towards more stable nuclei. It is obvious that nuclear structure effects like the quenching of shell strength or the formation of new shell closures will have an important impact on the r-process path. Both effects are directly observable in mass measurements.

Consequently, the proposed ISOLTRAP measurements in the vicinity of doubly magic ^{78}Ni, ^{132}Sn, and ^{208}Pb will provide important data where they are most crucial for a better understanding of the r-process.

5. Beam time request

The experience gained from many runs with ISOLTRAP in the last few years is the following: For mass measurements on unstable nuclei in new regions close to stability with production yields $>10^6$ ions/s there are normally two nuclides investigated within one shift with a mass accuracy below $1\cdot10^{-7}$. Going further out from stability near the edges of the nuclear chart and in the case of high accurate measurements in the range $\delta m/m \approx 1\cdot10^{-8}$ up to three shifts or in special cases even more might be required per nuclide. This can be seen from the following consideration.

The statistical uncertainty $(\delta m/m)_{stat}$ with which the cyclotron frequency can be determined is inverse proportional to both the resolving power R and the square root of the number N_{ion} of detected ions [Bol01]:

$$(\delta m/m)_{stat} = c \cdot \nu_c^{-1} \cdot T_{RF}^{-1} \cdot N_{ion}^{-1/2} \quad . \qquad (3)$$

An investigation of a large number of data obtained with ISOLTRAP has shown that the fore factor c is 0.898(8). By use of this relation the capability of Penning-trap mass measurements can be evaluated. Figure 5 shows the statistical uncertainty as a function of the time of observation T_{RF} and N_{ion} in a two-dimensional contour plot for an ion with $A = 100$ in a magnetic field of 6 T (which corresponds to the field strength used in our precision Penning trap).

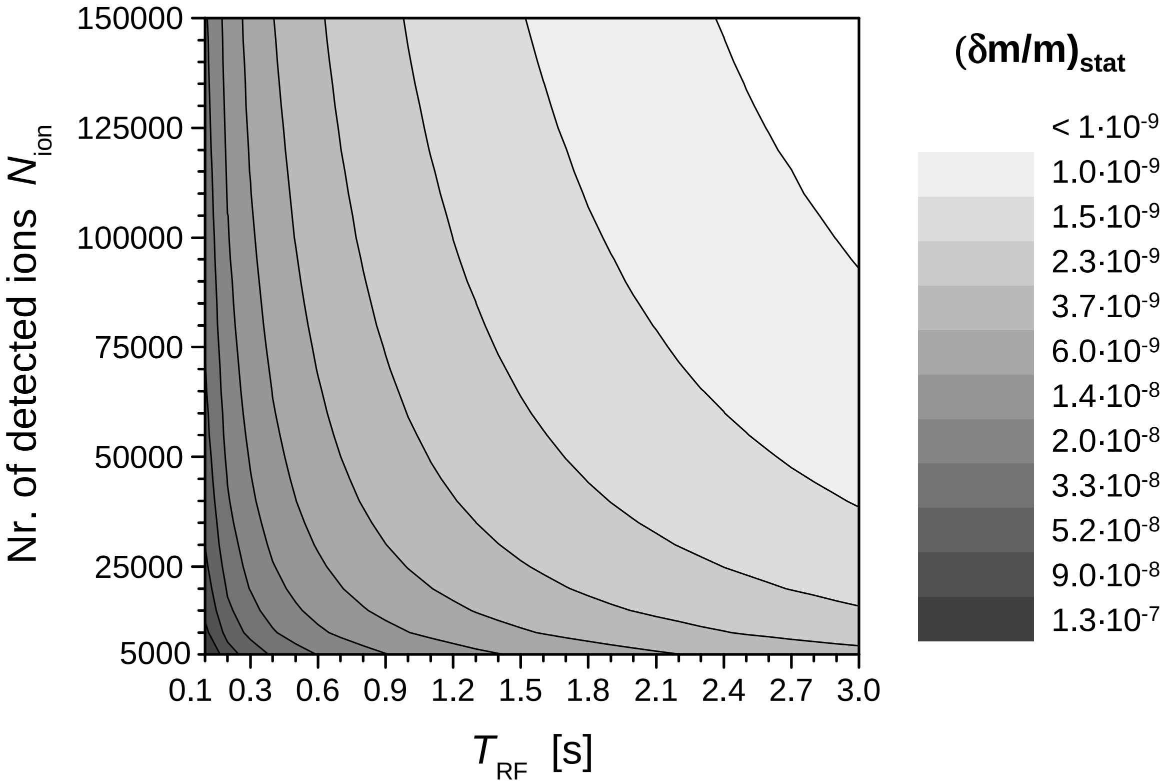

Figure 5: The statistical uncertainty $(\delta m/m)_{stat}$ as a function of the observation time T_{RF} and the number of detected ions N_{ion} for an ion with mass number $A = 100$ in a magnetic field of $B = 6$ T.

Under the assumption that the maximum storage time will be twice the half-life of the investigated nuclide one can now easily calculate from the ISOLDE yield and the ISOLTRAP efficiency the number of required shifts for a certain statistical uncertainty. For example in a high-accuracy mass measurement on a short-lived nuclide like ^{74}Rb ($T_{1/2}$ = 65 ms), about 200,000 ions will have to be detected in order to achieve a statistical accuracy of about $1\cdot10^{-8}$ as required for a meaningful CVC test. With an ISOLDE yield of about 1000 ions/s and an ISOLTRAP efficiency of ~$1\text{-}2\cdot10^{-3}$ a total of 5 shifts of radioactive beam plus one shift for calibration is needed for the mass measurement of ^{74}Rb. The number of shifts requested for the other measurements have been determined in the same way.

Due to the high reliability of ISOLTRAP and the advantage that we can run either with the HRS or the GPS we ask for 26 radioactive beam shifts per year for the next four years. The beam time can and should be distributed by the ISOLDE coordinator over three to five shorter beam time periods per year of typically 4-8 shifts per beam time. Before each radioactive beam 1 to 2 shifts of stable beam will be required for beam line and spectrometer tuning. Note, that ISOLTRAP will also be able to make use of beam time on short notice. The beam time request for the next four years covers the following mass measurements:

Nuclides	Required $\delta m/m$	No. of shifts	Target	Ion source
Masses of light nuclides near the drip line				
^{6,8}He	$5\cdot10^{-8}$ - $1\cdot10^{-7}$	4	Th carbide	plasma cooled transfer line
^{9,11}Li	$5\cdot10^{-8}$ - $1\cdot10^{-7}$	4	thin Ta foil	WSI
^{11,12}Be	$5\cdot10^{-8}$ - $1\cdot10^{-7}$	3	UC or Ta foil	RILIS
$^{17-22}$N	$5\cdot10^{-8}$ - $1\cdot10^{-7}$	6	Ca oxyde	plasma cooled transfer line
$^{17-19,\ 23-26}$Ne	$5\cdot10^{-8}$ - $1\cdot10^{-7}$	7	Mg oxyde	plasma cooled transfer line
CVC test, CKM unitarity and IMME				
^{74}Rb	$1\cdot10^{-8}$	6	Nb Metal pow.	Ta surface
^{62}Ga	$1\cdot10^{-8}$	6	ZrO_2	WSI
^{62}Zn	$1\cdot10^{-8}$	2	Nb foil	RILIS
^{14}O	$1\cdot10^{-8}$	3	U Carbide	hot plasma
^{22}Mg	$1\cdot10^{-8}$	4	RILIS	hot plasma
^{26m}Al	$1\cdot10^{-8}$	3	U Carbide	hot plasma
^{38m}K	$1\cdot10^{-8}$	4	Ti Metal foil	W surface
Medium mass range (^{78}Ni, ^{132}Sn and vicinity)				
$^{67-74}$Ni	$\leq 1\cdot10^{-7}$	5	UC/graphite	RILIS
$^{67-78}$Cu	$\leq 1\cdot10^{-7}$	8	UC/graphite	RILIS
$^{74-79}$Zn	$\leq 1\cdot10^{-7}$	4	Nb foil	RILIS
$^{74-82}$Ga	$\leq 1\cdot10^{-7}$	5	ZrO_2 or UC	RILIS/WSI
$^{58-66}$Mn	$\leq 1\cdot10^{-7}$	5	UC/graphite	RILIS
$^{131-134}$Sn	$\sim 1\cdot10^{-7}$	3	U Carbide	Hot plasma at 1950°C
$^{125-131}$Cd	$\sim 1\cdot10^{-7}$	5	U Carbide	DC heated FEBIAD RILIS
$^{115-123}$Ag	$\sim 1\cdot10^{-7}$	7	U Carbide	RILIS
Heavy mass range				
$^{211-216}$Tl	$\sim1\cdot10^{-7}$	4	Th / U Carbide	RILIS
$^{213-217}$Pb	$\sim1\cdot10^{-7}$	3	Th / U Carbide	RILIS
$^{215-218}$Bi	$\sim1\cdot10^{-7}$	3	Th / U Carbide	RILIS
Totally: 104 radioactive beam shifts over a period of 4 years				

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