Mass measurements and nuclear physics - recent results from ISOLTRAP

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Abstract. The Penning trap mass spectrometer ISOLTRAP is a facility for high-precision mass measurements of short-lived radioactive nuclei installed at ISOLDE/CERN in Geneva. More than 200 masses have been measured with relative uncertainties of $1 \cdot 10^{-7}$ or even close to $1 \cdot 10^{-8}$ in special cases. This pubication gives an overview of the measurements performed with ISOLTRAP and discusses some results.

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1. Introduction

The motivations for precise nuclear mass measurements are manifold. They cover atomic physics, nuclear structure physics, nuclear astrophysics and even fundamental interaction tests. However, the required precision $\delta m/m$ varies between 10^{-5} and 10^{-9}. Penning traps can provide this and ISOLTRAP has contributed to all these fields.

To reveal nuclear structure effects as for instance shell closures or shape coexistence it is needed to survey large areas. Then the interesting differential quantities like one- and two-neutron or proton separation energies can be extracted. Especially the two-neutron separation energy visualizes basic nuclear-structure information since both the staggering of the binding energy due to pairing and the general mass parabola around the valley of β stability are removed. The uncertainty that is needed for this type of investigation is in general about 10^{-6}. However, to uncover fine-structure effects like the ones caused by shape coexistence a relative uncertainty close to or below 10^{-7} is required.

The number of nuclear models is large and it is impossible to choose the one that best describes reality. There are two ways to solve this: first, it is needed to go further and further away from the valley of stability in mass measurements to reduce the need of extrapolation; second, only a large base of well-established mass values assure the development and improvement of nuclear models towards more reliable predictions. The quality of global nuclear mass models is often described by their mean deviation from experimental data, which is typically a few hundred keV [1, 2]. This illustrates the relative uncertainty of the measured mass values that is needed to check the quality of global nuclear models, about 10^{-6}.

Masses and half-lives are important input parameters from nuclear physics into nucleosynthesis network calculations . They determine the path of the nucleosynthesis and the time scale on which these processes appear. Unfortunately the experimental mass data base for the two more exotic paths, the r- and rp-process, is very weak due to the exotic nature of the participating nuclei. Most of the data needed for these calculations is therefore extracted from nuclear models [3, 4]. However, in some regions it is possible to access the key nuclei directly. In general, a relative uncertainty of about 10^{-6} is sufficient for input into the nucleosynthesis network calculations.

A β-decaying nucleus is a unique, relatively easy-to-access laboratory for investigations of the weak interaction. Of special interest are the superallowed $0^+ \rightarrow 0^+$ transitions where the axial-vector decay strength is zero allowing almost direct access to the vector coupling constant. For different types of investigations like the determination of the beta-neutrino angular correlation [5] or the systematical determination of the β-decay rate [6] the Q-value of the decay is an important quantity. Since the Q-value is essentially the mass difference between the initial and the final state, its measurement must be accomplished by measuring the mass of these states directly to obtain sufficiently high precision. To satisfy the needs of these investigations that serve for testing the electroweak sector of the Standard Model relative uncertainties in the lower 10^{-8} region are absolutely necessary.

While there are many methods [7] that can access the regions of radio nuclides with unknown or not precisely known masses also far off the valley of stability, only Penning traps provide the highest needed precision. This is mainly due to the possible long storage and hence observation times that are possible for charged particles in very well defined fields. With the technical developments performed mainly at ISOLTRAP it became possible to couple Penning traps to on-line production facilities [8] for radioactive nuclides and endeavour also regions very far away from the valley of β stability.

ISOLTRAP, a Penning trap mass spectrometer installed at ISOLDE/CERN [9] in Geneva, was designed for accurate high-precision mass measurements of short-lived radioactive nuclides. The mass determination is based on cyclotron frequency measurements. More than 200 nuclides have already been measured with relative uncertainties between 10^{-7} and 10^{-8} [10, 11]. Many of the measured masses have been measured for the first time or their uncertainties have been improved considerably. Examples for recent mass measurements are those that deal with the possible waiting point on the rp-process path ^{72}Kr. Additionally, mass values for ^{74}Rb, ^{34}Ar, and ^{74}Kr have been measured recently [12]. They are very important for the test of the CVC hypothesis and the unitarity of the CKM matrix using superallowed β decay. Further measurements that were performed in 2002 deal with very light as well as very heavy masses. Some Ne isotopes have been measured to pave the way for a mass measurement of the possible proton halo nucleus ^{17}Ne. On the heavy and neutron-rich side of the nuclear chart for instance ^{215}Bi and ^{216}Bi have been investigated.

2. The ISOLTRAP experiment

ISOLTRAP is a triple trap mass spectrometer connected to the on-line mass separator ISOLDE [9]. There, the radioactive nuclides are produced by bombarding a thick target with 1 or 1.4 GeV proton pulses with an average intensity of 2μA. The produced nuclides are transported by diffusion to an ion source and ionized either by a plasma discharge, surface ionization or resonant laser ionization. The ions are accelerated to 60 keV and mass-separated using a magnetic field with a resolving power $R = m/\Delta m$ of up to 8000.

The ion beam produced in this way is transported to the ISOLTRAP setup where it has to be efficiently stopped and cleaned from remaining isobaric and isomeric contaminants before the mass of a radioactive nuclide can be measured. To this end the ISOLTRAP spectrometer consists of three main parts as shown in figure 1: a gas-filled linear radio-frequency quadrupole (RFQ) trap, a gas-filled cylindrical Penning and a high-vacuum hyperboloidal Penning trap.

The radioactive beam delivered from ISOLDE is accumulated, cooled and bunched in the linear RFQ trap. The main task of this device is to transform the 60-keV continuous ISOLDE beam into ion bunches at low energy (2–3 keV) and low emittance ($\leq 10\,\pi$ mm mrad) [13]. These bunches can be efficiently transported to and captured in the first Penning trap. Here, a mass-selective buffer gas cooling technique is employed that allows this trap to be operated as an isobar separator with a resolving power of up to $m/\Delta m = 10^5$ for ions with mass number $A \approx 140$ [14]. The ions are then transported to the second Penning trap. This is the high-precision trap used for the mass measurements of the ions and that can also be used as an isomer separator with a resolving power of up to $m/\Delta m = 10^7$. The actual mass measurement is carried out via a determination of the cyclotron frequency $\nu_c = 1/(2\pi) \cdot q/m \cdot B$ of an ion with mass m and charge q in a magnetic field of strength B using an azimuthal excitation voltage whose duration T_{RF} determines the mass resolving power $R = m/\delta m = \nu/\delta\nu$, $\delta\nu = 1/T_{RF}$. The energy gained from the excitation is detected by the corresponding decrease in time of flight when the ions are pulsed out of the trap to a detector. B is determined measuring ν_c using a reference ion with a well-known mass [8].

Relative mass uncertainties in the range of 10^{-7} to 10^{-8} were reached with the ISOLTRAP spectrometer. Two contributions can be identified. The systematic uncertanties were recently thoroughly investigated and it was shown that they limit the relative mass uncertainty only to $8 \cdot 10^{-9}$ [11]. The statistical uncertainty is a function of the number of ions detected and the chosen resolving power. This implies a certain difficulty to reach very low uncertainties for nuclei that are either very short-lived or only produced in minute quantities, or both.

The overall sensitivity of the ISOLTRAP spectrometer is a few permille, i.e. in favourable cases already about 100 ions produced at ISOLDE per proton pulse are sufficient to perform a mass measurement in a few radioactive beam shifts of 8 hours each. However, for nuclides with half-lives less than one second radioactive decay loss plays an important role. Thus, for very short-lived nuclides especially short preparation times are required [15]. The present limit in half-life is about 50 ms for the ISOLTRAP spectrometer [16].

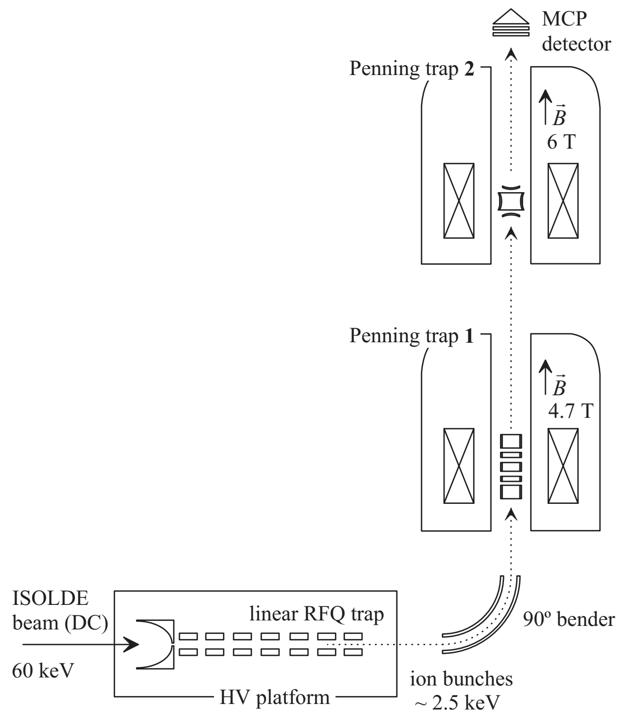

Figure 1. Experimental setup of the ISOLTRAP Penning trap mass spectrometer. The three main parts are: (1), a gas-filled linear radio-frequency quadrupole (RFQ) trap for retardation of ions, accumulation, cooling and bunched ejection at low energy, (2), a gas-filled cylindrical Penning trap for further cooling and isobaric separation, and (3), an ultra-high-vacuum hyperboloidal Penning trap for the actual mass measurement. For this, the cyclotron frequency is determined by a measurement of the time of flight of the ions ejected out of the Penning trap to a micro-channel plate (MCP) detector.

3. ISOLTRAP mass measurements and recent results

Figure 2 shows the nuclear chart with the relative mass uncertainties as known in autumn 2001 [17]. This emphasizes two things: First, that in the region were ISOLTRAP measurements have already been included in the atomic mass evaluation also many neighbouring masses are very well known. This is due in part to the very low uncertainty of ISOLTRAP mass values of $1 \cdot 10^{-7}$ or better, which provides the anchor points for other types of measurements as for instance storage ring mass spectrometry that allows to survey large areas [29] or decay spectroscopy that provides mass differences [7]. Second, it is obvious that ISOLTRAP can provide experimental mass values for numerous known nuclei whose mass has not been measured before or at least improve the relative uncertainty by up to 1000 times.

More than 200 radioactive nuclides and a few stable have been measured with the ISOLTRAP Penning trap mass spectrometer. These measurements concern mainly ground states but also a few low-lying isomeric states. The nuclei that have been measured at ISOLTRAP are highlighted in figure 2. The mass number ranges from $A = 18$ up to $A = 230$. Thirty different elements have been accessed so far. A more

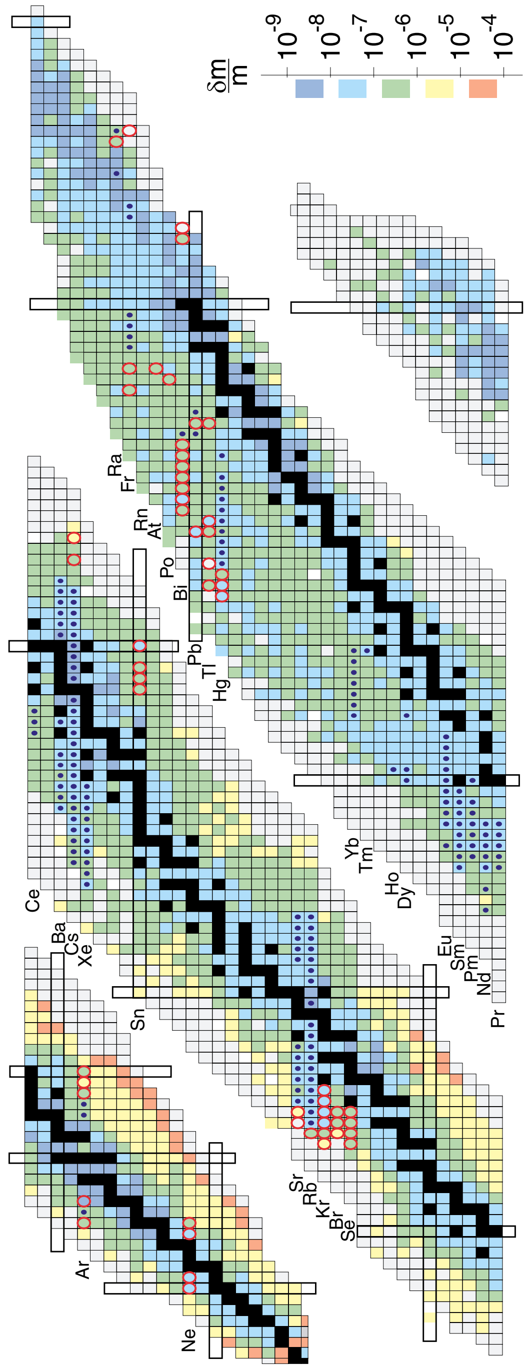

Figure 2. Overview of ISOLTRAP mass measurements on a chart of nuclides showing the relative mass uncertainty $\delta m/m$ of each nuclide [17] colour coded. The mass of nuclei marked with light grey were estimated using systematic trends [18]. Stable nuclides are drawn in black. Recently (between 2000 and 2002) performed ISOLTRAP mass measurements are indicated by red circles. The blue dots stand for earlier measurements (1999 and before).

Table 1. List of radioactive nuclei the mass of which was measured with the ISOLTRAP Penning trap mass spectrometer since its first operation at ISOLDE in 1989. In total the mass of more than 200 radioactive nuclei was determined.

Element	Mass number	reference
Ne	18, 19, 23, 24	‡
Ar	33, 34, 42, 43	[19]
	34	[12]
	32, 44, 45, 46	†
Se	70, 71, 72, 73	‡
Br	72, 73, 74	‡
Kr	74 . . . 78	[12]
	72, 73	†
Rb	75 . . . 84, 86, 88 . . . 94	[20, 21]
	74	[12]
Sr	78 . . . 83, 87, 91 . . . 95	[20, 21]
	76, 77	[22]
Sn	128 . . . 132	[22]
Xe	114 . . . 123	[23]
Cs	117 . . . 132, 134 . . . 142	[24]
	145, 147	‡
Ba	123 . . . 128, 131, 139 . . . 144	[24]
Ce	132, 133, 134	[25]
Pr	133 . . . 137	[26]
Nd	130, 132, 134 . . . 138	[26]
Pm	136 . . . 141, 143	[26]
Sm	136 . . . 143	[26]
Eu	139, 141 . . . 149, 151, 153	[26, 25]
Dy	148, 149, 154	[26, 25]
Ho	150	[26]
Tm	165	[25]
Yb	158 . . . 164	[25]
Hg	179 . . . 195, 197	[27]
Tl	181, 183, 186, 187	‡
Pb	196, 198	[27]
Bi	197	[27]
	191 . . . 196, 215, 216	‡
Po	198	[27]
At	203	[27]
Fr	209 . . . 212, 221, 222	[28]
	203, 205, 229	‡
Ra	226, 230	[28, 24]
	229	‡

†measured in 2001, to be published
‡measured in 2002, to be published

detailed summary of all measured masses can be found in table 1 along with references to articles that contain the relevant mass values and discussions.

The first mass measurements that were performed with ISOLTRAP had a restriction to surface-ionizable elements since the ISOLDE beam was stopped in a foil of tungsten or rhenium. To release the atoms again, the foil was heated and was acting as reionizator. However, it was the first time that the principle of on-line mass measurements with Penning traps was demonstrated. Additionally, the mass-selective cooling mechanism in a buffer-gas- filled Penning trap along with the transfer technique

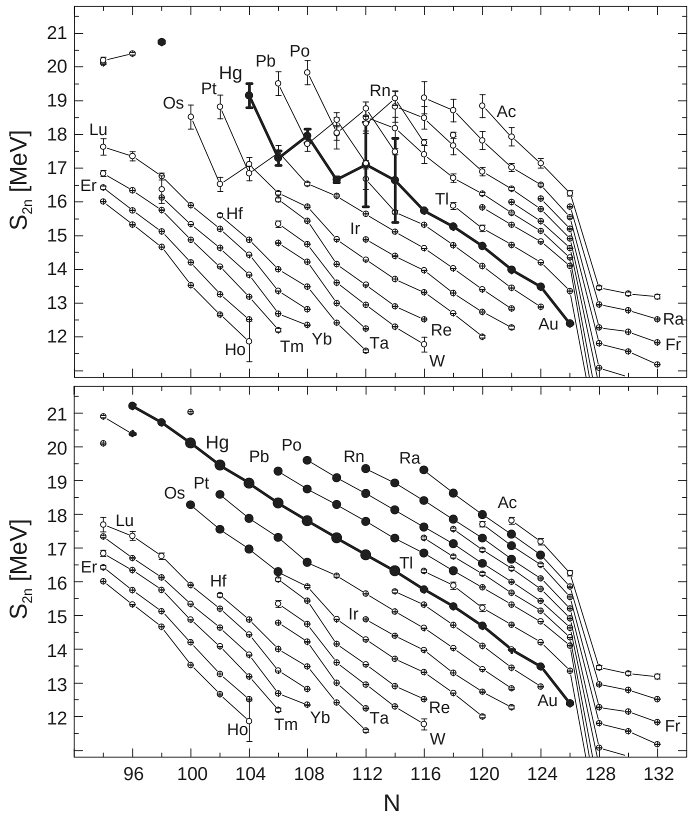

Figure 3. Two-neutron separation energies in the vicinity of $Z = 82$ as a function of neutron number. Shown are S_{2n} values excluding (top) and including (bottom) ISOLTRAP data in the atomic mass evaluation [27].

between two Penning traps has been developed and for the first time implemented [30]. This allowed already large area surveys for instance in the rare earth region as can be seen in figure 2 [26].

Later the first radio-frequency quadrupole trap, a very large conventional Paul trap, has made the ISOLTRAP spectrometer applicable to basically all elements, only restricted by the production principles of ISOL-type machines [9]. The power of this important step was proven by a comprehensive number of mass measurements on neutron-deficient mercury isotopes [27]. These nuclei are very interesting because of the shape coexistence that manifests itself also in the binding energy. Additionally, mass measurements with a relative uncertainty of only $1 \cdot 10^{-7}$ influence the mass surface in the entire region. Figure 3 shows the two-neutron separation energies for this region of the nuclear chart before and after the ISOLTRAP measurements were included into the atomic mass evaluation according to [18]. Clearly depicted are the linear trend in the mid-shell regions and the sharp drop at the shell closure. This linear trend was not at all evident before the ISOLTRAP data were available.

The installation of the buffer-gas-filled linear RFQ trap [13] boosted the efficiency

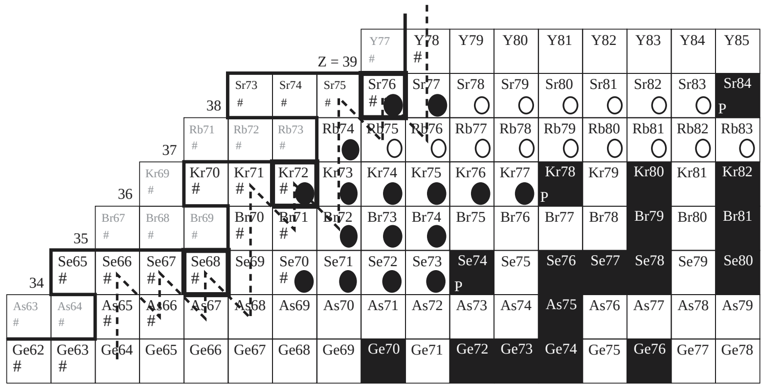

Figure 4. The astrophysical rp-process path above $Z = 35$. Nuclei stable to β decay are depicted with filled squares. The nuclides named in light grey are beyond the proton dripline, that is represented by a thick solid line. Nuclei marked with '#' did not have experimental mass values assigned in the atomic mass evaluation from 1995 [18]. The dashed line gives a possible main process path according to [3]. The path passes through so called waiting point nuclei that are marked with bold outline. ISOLTRAP measurements performed before the year 2000 or between 2000 and 2002 are indicated by open and filled circles, respectively.

of the ISOLTRAP setup. It permits now measurements on very weakly produced nuclei and, hence, to extend the experimental mass measurements further towards the particle driplines. This is illustrated in figure 4 showing an important region for nucleosynthesis calculations on the rp-process path above $Z = 32$. The most important nuclei are so-called waiting point nuclei since they determine considerably the path and time of the nucleosynthesis process. Two of these key nuclei, ^{72}Kr and ^{76}Sr, have been measured directly at ISOLTRAP recently, in addition to a large-scale survey of the entire region. The delivered relative mass uncertainty that is about 10^{-7} allows improved calculations and assures consistency in the mass values that are extracted from models [4].

Other recent measurements concern the nuclides ^{18,19,23,24}Ne. These nuclei present the lightest nuclei ever measured with ISOLTRAP and are the first step on the way to precise mass measurements of neutron and possible proton halo nuclei.

On the upper part of the nuclear chart a long chain of Bi isotopes has been measured. Especially on the neutron-rich side of the valley of β stability the power of direct mass measurements has been proven. The mass of ^{215}Bi was measured unambiguously for the first time.

4. Conclusion

ISOLTRAP mass measurements extend over the complete nuclear chart. The achieved sensitivity allows for mass measurements on nuclides that are only produced at less than 100 ions per second. The half-life of the nucleus to be measured can be as short as about 50 ms. The relative uncertainty of ISOLTRAP mass values can be as low as $8 \cdot 10^{-9}$. All together, this opens up a large variety of mass measurements that were not possible or not feasible. Some of these measurements have already been performed and provided valuable input for different fields of nuclear physics and beyond.

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