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ISOLTRAP mass measurements of exotic nuclides at $\delta m/m = 10^{-8}$

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The ISOLTRAP experiment at the ISOLDE facility at CERN is a Penning trap mass spectrometer for on-line mass measurements on short-lived radionuclides. It allows the determination of atomic masses of exotic nuclides with a relative uncertainty of only 10^{-8} . The results provide important information for, *e.g.*, weak interaction studies and nuclear models. Recent ISOLTRAP investigations and applications of high-precision mass measurements are discussed.

1. INTRODUCTION

The mass is a fundamental property of a nuclide. Thus, precise mass values are important for a variety of applications, ranging from nuclear-structure studies like the investigation of shell closures and the onset of deformation, test of nuclear mass models and formulas, to fundamental studies including tests of the Standard Model and the weak interaction. The relative accuracy required in mass measurements on radionuclides ranges thus from 10^{-5} to below 10^{-8} [1].

The studies reported here make use of recent improvements to the Penning trap mass spectrometer ISOLTRAP [2] at the ISOLDE [3] facility at CERN. Radionuclides far from stability can be investigated, even nuclides that are produced at rates of only 100 ions/s and with half-lives well below 100 ms. The mass resolving power has reached 10^7 and the relative uncertainty of the resulting mass values has been pushed down to $8 \cdot 10^{-9}$ [4].

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Figure 1. (color) Nuclear chart with the relative mass uncertainties $\delta m/m$ of all known nuclides shown in a color code (see scale bottom right, stable nuclides are marked in black). Masses of grey-shaded nuclides are estimated from systematic trends [5]. Masses measured with ISOLTRAP since 2002 are marked with red circles, earlier measurements with blue dots. The isobaric lines of the carbon clusters C_1 to C_{22} demonstrate the advantage of using a “carbon cluster mass grid” for calibration purposes.

ISOLTRAP has so far been used to measure the masses of close to 300 radionuclides across the chart of nuclides, which are included in the recent Atomic-Mass Evaluation (AME2003) [5], with the exception of the measurements performed in 2004. A summary is given in Figure 1.

2. EXPERIMENTAL SETUP

The ISOLTRAP apparatus, which is fed by the 60-keV ion beam from ISOLDE [3], consists of three traps. A sketch of the setup with the main components is shown in Figure 2. A detailed description is given in [4]. A gas-filled radiofrequency quadrupole ion trap accumulates and bunches the beam [6]. The first Penning trap then cools and purifies the ion bunch by mass-selective buffer gas cooling [7]. The second Penning trap located in a superconducting magnet with magnetic-field strength B finally provides the precision mass measurements via the cyclotron frequency $\nu_c = eB/(2\pi m)$ of singly charged ions with mass m . This is done by use of a time-of-flight (TOF) ion cyclotron-resonance-detection technique [8]. As an example, typical TOF cyclotron resonances of the stable nuclide ^{85}Rb and of the short-lived radionuclide ^{74}Rb ($T_{1/2} = 65$ ms) are shown in Figure 2. The mass of the ion of interest is obtained from the comparison of its cyclotron frequency with that of a well-known “reference mass”, *e.g.* ^{85}Rb . In this context, carbon clusters C_n (with $1 \leq n \leq 22$) provide the reference mass of choice [9]. The advantages of a “carbon cluster mass grid” (see isobaric lines in Figure 1) are obvious: A multitude of nearby reference masses are available all over the nuclear chart, minimizing systematic errors and allowing for absolute mass measurements, since the mass of ^{12}C defines the atomic mass unit.

Figure 2. Sketch of the ISOLTRAP setup. Insets: Typical time-of-flight cyclotron resonances for the stable nuclide ^{85}Rb and the short-lived nuclide ^{74}Rb . The solid lines are fits of the theoretically expected line shape to the data [10]. For details see text.

3. ISOLTRAP MASS MEASUREMENTS

Since the detailed carbon cluster studies were performed in 2001 [4], about 130 masses of radionuclides have been measured at ISOLTRAP and almost all of them with relative mass uncertainties in the order of 10^{-8} . These masses are marked with red circles in Figure 1. All other masses measured so far at ISOLTRAP are marked with blue dots. In the following, major achievements of high-precision mass measurements with ISOLTRAP in different fields of application are summarized.

Nuclear structure: The unique combination of resonant laser ionization, nuclear spectroscopy, and mass measurements has allowed to determine the low-energy nuclear structure of ^{70}Cu . By use of mass spectrometry the ground state ($T_{1/2} = 44.5\text{ s}$) and the two low-lying excited states ($T_{1/2} = 33\text{ s}$, $E_{exc} = 101.1\text{ keV}$ and $T_{1/2} = 6.6\text{ s}$, $E_{exc} = 242.4\text{ keV}$) were clearly distinguished and for the first time unambiguously identified as three beta-decaying isomers [11]. As ^{70}Cu has 41 neutrons, the results provide an important step in understanding the complex structure of nuclides with one neutron less, *i.e.* $N = 40$, which corresponds to a closed sub-shell. Furthermore, the high resolving power of ISOLTRAP of up to 10^7 allowed to prepare an isomerically pure sample of ^{68}Cu [12].

Mass formula: Mass measurements on ^{32}Ar ($T_{1/2} = 98\text{ ms}$) and ^{33}Ar ($T_{1/2} = 173\text{ ms}$) with relative uncertainties of $6.0 \cdot 10^{-8}$ and $1.4 \cdot 10^{-8}$, respectively [13], provide the most stringent test of the isobaric-multiplet mass equation (IMME). IMME relates the masses of the members of an isospin multiplet; ^{33}Ar is a member of a $T = 3/2$ quartet while ^{32}Ar is a member of a $T = 2$ quintet. Since the mass formula IMME is used to predict

unmeasured nuclear masses and level energies, that are necessary for, *e.g.*, calculations of astrophysical processes, such tests are of great practical importance to check the local reliability of IMME. The mass of ^{32}Ar also provides a better value for the beta-neutrino angular correlation coefficient, which is used to set constraints on scalar contributions to the weak interaction.

Astrophysics: Masses are the most critical nuclear parameters for reliable nucleosynthesis calculations. The extension of experimentally known masses away from the valley of stability is decisive to put constraints on nuclear models for predicting masses in the region where, *e.g.*, the *r*- and *rp*-process path may proceed. Recently the masses of many nuclides in the vicinity of the *rp* path have been measured with high precision at ISOLTRAP (see Figure 1). Direct measurements have also been performed on two important waiting point nuclei, ^{72}Kr [14] and ^{76}Sr [15]. Defining clear observables for explosive astrophysical phenomena like nova bursts, is another field where ISOLTRAP has recently contributed [16]. Mass measurements on the reaction partners $^{21}\text{Na}(p, \gamma)^{22}\text{Mg}$ yielded an independent determination of the resonance energy and should allow more detailed calculations of the resonance strength of the $^{21}\text{Na}(p, \gamma)^{22}\text{Mg}$ capture reaction as an input for nova models.

Standard Model: Direct high-precision mass measurements on superallowed β -emitters and their daughters contribute to tests of two fundamental postulates of the Standard Model: The conserved-vector-current hypothesis of the the weak interaction and the unitarity of the Cabibbo-Kobayashi-Maskawa matrix [17]. The required relative mass uncertainty of about $1 \cdot 10^{-8}$ is available today at ISOLTRAP. Recent measurements in this context are the determination of the decay energies of $^{74}\text{Rb}(\beta^+)^{74}\text{Kr}$ [18] and $^{22}\text{Mg}(\beta^+)^{22}\text{Na}$ [16].

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