

Masses of nuclei close to the dripline

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Abstract

Mass measurements of radioactive nuclides are one of the cornerstones of our understanding of the nucleus. The Penning trap spectrometer ISOLTRAP performs direct mass measurements far away from the valley of stability, as well as high-precision measurements of key nuclei to anchor long decay chains. Both schemes provide valuable information on the dripline itself and on nuclei in its close vicinity.

1 Introduction

The mass is one of the gross properties of a nucleus. The mass, explored over large areas, helps the understanding of the nucleus considerably by revealing weaknesses in nuclear models, by uncovering nuclear fine structure effects as well as shell closures. At the drip-line, known or predicted mass differences help to find especially interesting decay modes as for instance the two proton decay.

There are many different methods to measure the mass of radioactive nuclei as for instance summarized in [1]. Two principle ways can be distinguished, so-called direct and indirect measurements. In the latter case the mass of a nuclear state, that can of course be its ground state, is deduced from the energy difference of two nuclear states measured basically by observing particles or radiation that were emitted during the transitions from the initial to the final state. Here, the energy of one of the two states has to be known to determine the other one. Possible transitions mechanisms are nuclear reactions, α and β decay. This method of mass measurement is hence limited not only by the uncertainty of the transition energy determination but also by the uncertainty in the mass of the second state. The advantage is, however, that especially in the case of monoenergetic particles emitted like in α decay very short half-lives

and very low production rates of the nucleus of interest can be accepted. This allows to access nuclei at or even beyond the driplines.

In the direct method the nuclear state of interest, mostly the ground state, is observed directly for instance in magnetic spectrometers or while measuring its flight time. However, the used devices have to be calibrated in order to reach the desired accuracy. This is usually done by measuring a well known, often stable, nucleus. Consequently the mass of the radioactive ion of interest is then related to the mass of the nuclei used for the calibration. Ideally this would be ^{12}C the atomic mass unit is based on. In general, the uncertainty of the various direct methods is indirect proportional to the accessible half-lives. The shorter the accessible half-live the bigger is the reachable mass uncertainty.

The most precise direct technique is the Penning trap mass spectrometry. Since its implementation at on-line facilities it can also deliver very precise mass values of rather short-lived radioactive nuclei. The reachable accuracy makes the measured nuclei ideally suited to serve for calibration of the less precise techniques but also to anchor long decay chains that do not end in the valley of β stability. The intensive development of the Penning trap technique itself and its coupling to different on-line production facilities permits to extend the region that can be accessed in terms of half-live but also in terms of required production rate. ISOLTRAP has developed and implemented many innovations and is at the forefront of the recent developments.

2 The ISOLTRAP spectrometer

The triple trap mass spectrometer ISOLTRAP (Fig. 1) is installed at ISOLDE at CERN in Geneva. There, a 1 or 1.4 GeV proton pulse containing in average about $3 \cdot 10^{13}$ protons hits a target with a thickness of a few g/cm^2 . This way, radioactive nuclei are produced via spallation, fission and fragmentation reactions. They are ionized, accelerated to 60 keV and mass separated in a magnetic sector field before they are distributed to the different experiments.

At the time the ISOLDE ion beam arrives at the first trap of the ISOLTRAP setup, the buffer-gas filled linear radio-frequency quadrupole (RFQ) trap [2] the ions are electrostatically decelerated and injected into the RFQ trap to be cooled and accumulated. The formed ion cloud is ejected and energy adapted to form a short (a few μs) bunch with low transversal emittance ($10 \pi \text{ mm mrad}$ at 2.5 keV) that is ideally suited for transport to and injection into the first Penning trap. This is a buffer-gas filled cylindrical trap where the ions are mass selectively centered. This allows to run this trap as an isobar separator with a resolving power $m/\Delta m$ of up to 10^5 at mass number $A \approx 140$ [3].

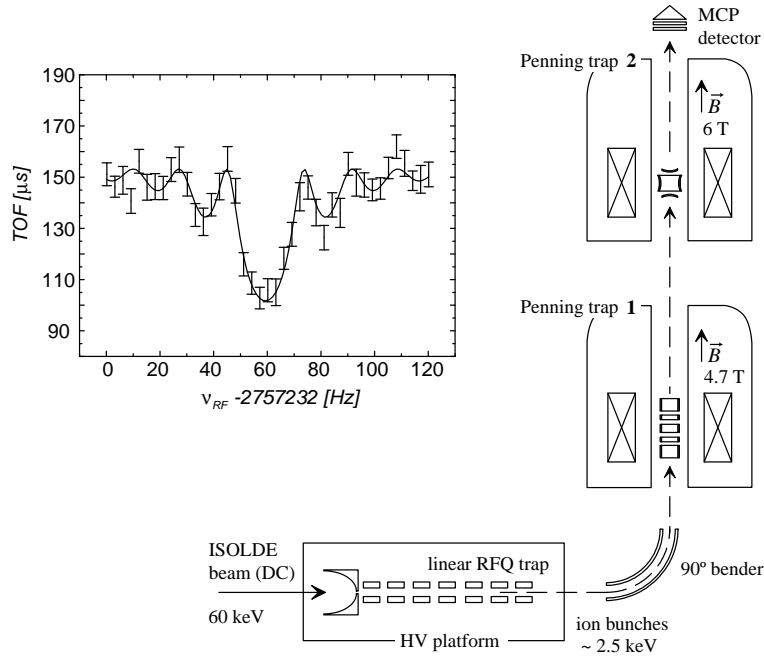


Figure 1: Experimental setup of the ISOLTRAP Penning trap mass spectrometer. The three main parts are: (1), a gas-filled linear radio-frequency quadrupole trap for retardation of ions, accumulation, cooling and bunched ejection at low energy, (2), a gas-filled cylindrical Penning trap for further cooling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

The purified and cooled ions are subsequently transferred to a hyperboloidal Penning trap at high vacuum (10^{-8} mbar) where the actual mass measurement takes place. In the measurement trap a resolving power $m/\Delta m$ of up to 10^7 can be reached, which enables the separation of isomeric states.

The mass measurement is based on the 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 . To this end, the ion motion is excited using an azimuthal radio-frequency quadrupole field before the ions are ejected from the trap. While their passage through the inhomogeneous fringe field of the magnet the radial energy gained through the excitation is converted into axial energy. Since the energy gain is maximal for an excitation at the cyclotron

frequency the time of flight will be minimal in that case. The inset in Fig. 1 shows an example plot of the time-of-flight versus the excitation frequency with a fit of the theoretically expected function that is used to determine the cyclotron frequency [4].

3 Mass measurements

At ISOLTRAP more than 200 nuclides have already been measured with relative uncertainties between 10^{-7} and 10^{-8} [5]. The technical developments during the last years focussed on two issues, the mass uncertainty and the overall efficiency. Both have been improved considerably. The overall efficiency is now in the range of a few per mille to a few percent. This allows to measure nuclides very close to the dripline since they are very short-lived and only produced in minute quantities. The limits are production rates of only a few hundred ions per proton pulse and half lifes of about 50 ms [6]. The mass uncertainty has been thoroughly investigated and found to be limited at $8 \cdot 10^{-9}$ [7].

Two examples shall demonstrate how ISOLTRAP can contribute to the investigation of the drip line and its vicinity. The first is a measurement in the rare earth region not right at the dripline but in a region of many endpoints of long α -decay chains that start close to or even beyond the dripline. The α -decay energies have been measured very well, however, without at least one member of which the mass is well known relative to the atomic mass standard it is impossible to fix the drip-line.

As shown in Fig. 2 there was a strong discrepancy apparent between theory and experiment regarding the prediction of the dripline for the iridium isotopes. The ISOLTRAP measurement could resolve this measuring the mass of ^{150}Ho directly [10].

The second example concerns the direct access to nuclei at the dripline. ^{74}Rb is the last rubidium isotope stable against proton decay. Even though this nucleus has a half-live of only 65 ms it has been possible to measure its mass with the ISOLTRAP mass spectrometer. Two beam times have been dedicated to measure this nucleus. The mass uncertainty is now lower than 5 keV. ^{74}Rb is especially interesting because of its superallowed β decay branch. The decay rate of all superallowed beta emitters should be nucleus independent if the weak interaction is not modified in the presence of the strong force (conserved vector current - CVC - hypothesis). The decay of ^{74}Rb is the heaviest system that is beeing investigated.

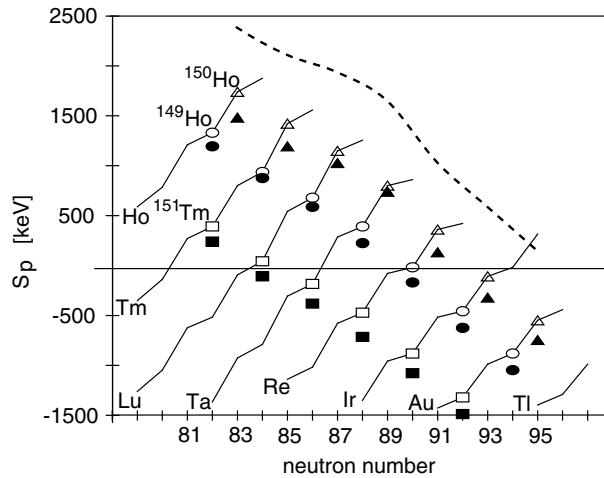


Figure 2: The proton separation energy is plotted versus the number of neutrons for different elements. The drip line is the line with $S_p = 0$. Three different α -decay chains are indicated by squares, circles and triangles. The open symbols and the isotopic lines are calculations by Liran and Zeldes [8], the filled symbols are the values after the ISOLTRAP measurements have been added to the atomic mass evaluation from 1995 [9]. The dashed line connects the values that belong to the α -decay chain ending in ^{150}Ho if the old mass value for ^{150}Ho is used.

Acknowledgments

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