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Overview of the JYFLTRAP mass measurements and high-precision Q-values for weak interaction studies

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Abstract. The JYFLTRAP Penning trap set-up at the University of Jyväskylä, Finland, is a Penning trap facility that has provided high-precision atomic mass values for short-lived nuclides since 2003. Until now, masses of more than 250 short-lived nuclides have been measured. Since JYFLTRAP is coupled to the chemically insensitive IGISOL mass separator, any element can be accessed. So far, a huge mass surface extending from magnesium ($Z = 12$) to lead ($Z = 82$) has been covered.

Keywords. Atomic mass; Penning trap; high precision.

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1. Introduction

Presently, the most precise atomic mass values are measured with Penning traps [1]. The JYFLTRAP spectrometer at the University of Jyväskylä [2] is used to measure masses of short-lived ions, mostly concentrating on refractory elements that are produced in fission (see for example [3]). Since the IGISOL system [4] provides access to any chemical element, a special emphasis has been given to superallowed β emitters. Having simultaneous access to both the β decay parent and daughter nuclei, the mass difference can be determined with much higher precision than would normally be possible since for the mass doublets the systematic uncertainties become negligible. Recently, precision of better than 100 eV has been demonstrated [5]. The doublet technique has also been utilized in Q value measurements of double beta decays [6,7].

2. Experimental method

2.1 *Production of ions*

The ions of interest are produced with the IGISOL method [4,8] using ion guides of different geometry for different production methods. The basic principle is simple: reaction products are thermalized in gas and transported out with gas flow and

electric fields. To access neutron-rich nuclides such as ^{111}Mo or ^{122}Pd, a fission ion guide is used. Fission is induced by bombarding a fissile target with light ion beams, usually protons or deuterons of 15–30 MeV energy.

Isotopes close to the valley of β stability can be produced with light-ion-induced fusion reactions. For instance, ^{62}Ga is available in ^{64}Zn(p,3n)^{62}Ga reaction with 48 MeV protons [9]. The light-ion guide has been successfully used to produce all superallowed β emitters having isospin $T_z = 0$ ranging from ^{26m}Al to ^{62}Ga. In addition, $T_z = -1$ nuclei ranging up to ^{42}Ti are available as ion beams (see [10–12]).

Nuclides further away from the valley of β stability in the neutron-deficient side of the nuclide chart are available in the heavy-ion ion guide [13].

After production, extraction and acceleration to 30q keV, the ions are mass separated with a dipole magnet having a mass resolving power of about 500. This is sufficient for separating ions with different mass numbers A. The selected isobaric chain is injected into an RFQ structure for ion cooling and bunching [14] before injecting to the purification Penning trap of JYFLTRAP. Figure 1 shows the lay-out of the IGISOL and JYFLTRAP set-ups.

2.2 *JYFLTRAP*

The JYFLTRAP set-up consists of two cylindrical Penning traps housed inside the same superconducting 7 T solenoid. The first in line is the purification trap which is filled with low-pressure helium gas to allow cooling of ions. By employing sideband cooling technique, a mass resolving power of 10^5 is reached [15,16]. Usually this resolving power is sufficient to provide ions of only one species. An example of a purification frequency scan is shown in figure 2.

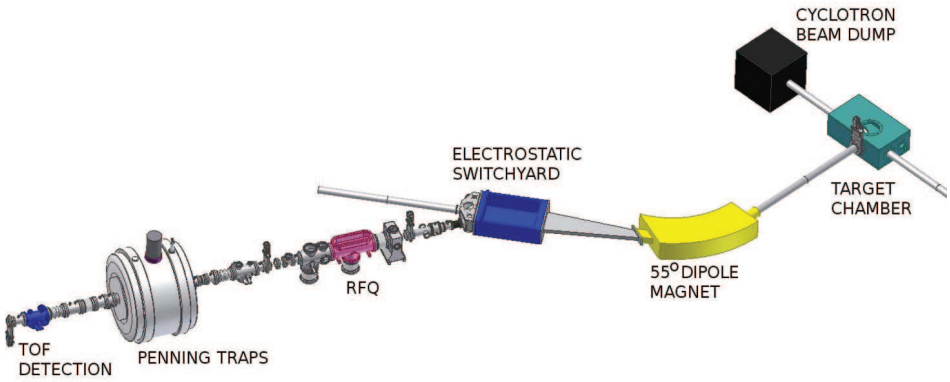

Figure 1. Lay-out of the IGISOL and JYFLTRAP installations. The ion guide is housed inside the target chamber (far right). The produced ions are extracted, mass separated with a dipole magnet and steered to the RFQ structure. The cooled and bunched beam from the RFQ is injected to the Penning traps for isobaric/isomeric cleaning and for cyclotron frequency measurement. From the trap, the ions are extracted either to determine their time-of-flight or to perform decay spectroscopy experiments.

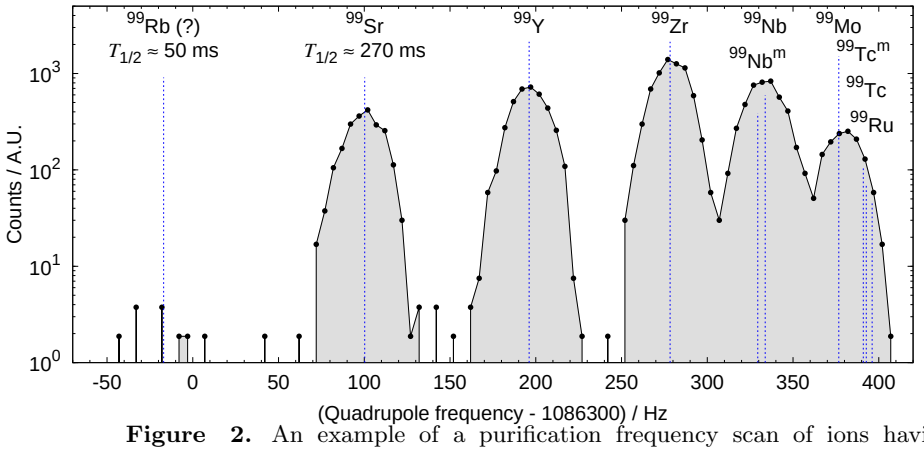

Figure 2. An example of a purification frequency scan of ions having $A/q = 99$ produced in proton induced fission of uranium. Mass resolving power of about 3×10^4 is obtained.

The vacuum-operated precision measurement trap is separated from the purification trap using a channel of 5 cm length and 2 mm diameter. The precision trap is used for high-resolution cleaning (reaching a mass resolving power of about 10^6) [17] and for high-precision mass measurements using time-of-flight ion-cyclotron (TOF-ICR) technique [18,19].

2.3 *Principle of mass measurement*

After preparing a clean sample of ions, the actual mass measurement procedure is started in the precision trap. First, the ions' magnetron orbit is expanded with a phase-locked dipolar RF electric field [20]. Next, the induced magnetron motion is mass-selectively converted to cyclotron motion with a quadrupolar RF electric field. The frequency of the field is scanned over the sideband frequency $\nu_{c'} = \nu_{+'} + \nu_{-'}$. When the frequency of the field matches the sideband frequency, the motion conversion is complete. This resonance frequency can be observed by measuring the time-of-flight of the ions upon extraction from the trap to the microchannel plate (MCP) detector. More cyclotron motion the ions have, the faster they fly to the detector.

Before a mass value can be determined, the frequency of some accurately known reference ion must be measured too. The final experimental result is thus the frequency – or mass – ratio of the ion of interest and the reference ion. At JYFLTRAP, the sideband frequency ratio $\nu_{c',\mathrm{ref}}/\nu_{c',\mathrm{ion}}$ actually corresponds to the real cyclotron frequency $\nu_c = qB/(2\pi m)$ ratio in the level of 10^{-8} (see refs [21,22] for more details).

One way to enhance precision of the frequency determination is to use time-separated oscillatory fields (the Ramsey method) [23,24]. The Ramsey method has been routinely used at JYFLTRAP. An example of such a resonance is shown in figure 3.

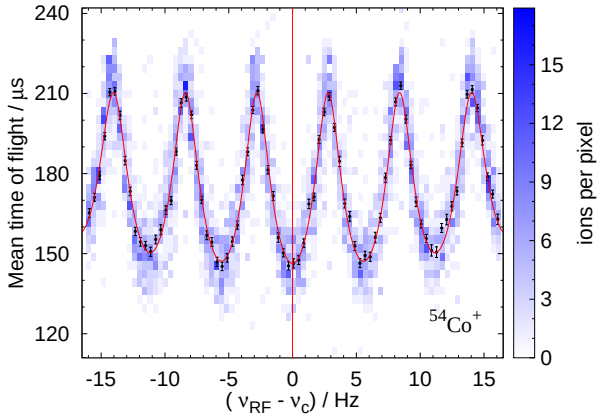

Figure 3. An example of the time-of-flight ion-cyclotron resonance obtained for $^{54}Co^{+}$ ions. Excitation time pattern of 25-150-25 ms (on-off-on) was used. It should be noted that the half-life of this ^{54}Co ground state is only about 200 ms. The different shaded pixels represent the number of ions detected; the darker the pixel the more are the ions. The red solid line represents fit to the data points. The fitted cyclotron frequency is marked with a vertical line.

2.4 *Isomeric cleaning*

In cases where sideband cooling technique [15] is not sufficient, i.e. where mass resolving power of more than 10^5 (corresponding to cyclotron frequency difference of less than 10 Hz) is desired, RF electric dipole excitation in the precision trap can be used. The contaminants can be mass-selectively excited to large radial orbit while the ions of interest remain unaffected. Upon re-transfer to the purification trap, the contaminants hit the narrow electrode and are thus completely removed [17]. The best resolution so far has been demonstrated with the separation of ^{133m}Xe isomer from its ground state requiring mass resolving power $M/\Delta M = 5 \times 10^5$ as the mass difference is only 233 keV, corresponding to a cyclotron frequency difference of about 1.5 Hz.

3. Overview of JYFLTRAP atomic mass measurements

In figure 4, all nuclides whose masses have been measured at JYFLTRAP have been marked. As can be seen, extensive regions have been covered from both sides of the valley of β stability as also the masses of some stable isotopes have been determined. In the following section, some highlights are given.

3.1 Q_{EC} *values of the superallowed* β *emitters*

Currently, the most precise determination of the V_{ud} matrix element of the Cabibbo–Kobayashi–Maskawa (CKM) quark-mixing matrix is determined from

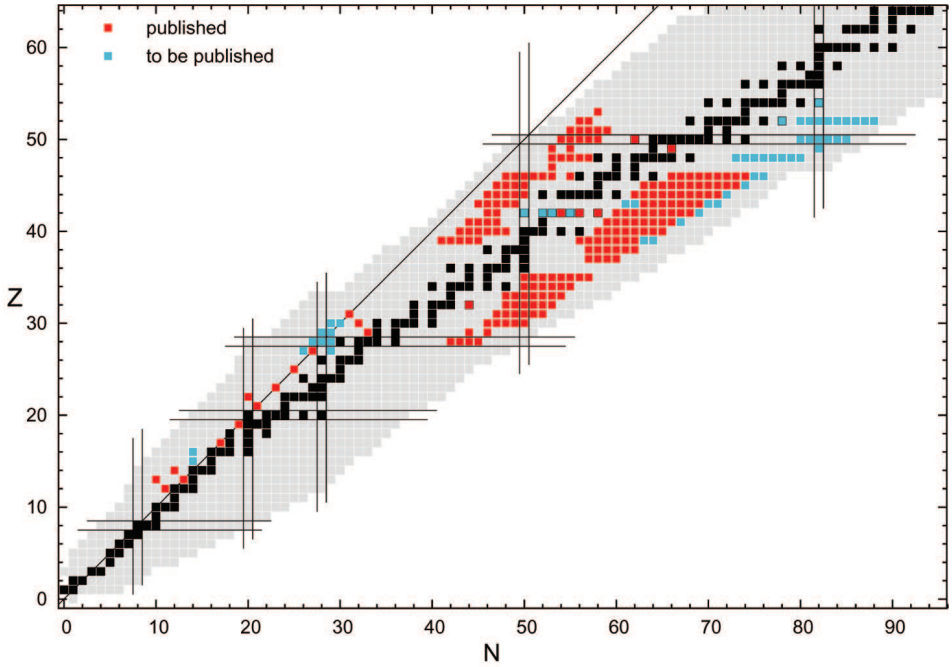

Figure 4. The chart of nuclides. The nuclei whose masses have been determined with JYFLTRAP are shown.

superallowed nuclear β-decays [25]. These are decays between nuclear states having spin J and parity π of $J^\pi = 0^+$ and isospin $T = 1$. Since there is neither spin nor parity change, the decay mode is strictly of Fermi-type, excluding Gamow–Teller branch to the ground state completely. According to the CVC hypothesis, the ft values should be the same for any superallowed transition and is given by

$$ft = \frac{K}{G_{\mathrm{V}}^2 |M_{\mathrm{F}}|^2} = \text{const.}, \tag{1}$$

where K is a constant, G_{V} is the vector coupling constant for semileptonic weak interactions and M_{F} is the Fermi matrix element (here $M_{\mathrm{F}} = \sqrt{2}$ since $T = 1$). However, additional theoretical corrections are needed since isospin is not an exact symmetry and thus needs to be corrected for. The correct ft value, denoted by $\mathcal{F}t$ is given as

$$\mathcal{F}t = ft\,(1 + \delta_{\mathrm{R}})\,(1 - \delta_{\mathrm{C}}) = \frac{K}{2G_{\mathrm{V}}^2\,(1 + \Delta_{\mathrm{R}}^{\mathrm{V}})} = \text{const.}, \tag{2}$$

where δ_{C} is the isospin symmetry-breaking correction, δ_{R} is the transition-dependent radiative correction and $\Delta_{\mathrm{V}}^{\mathrm{R}}$ is the transition-independent radiative correction.

To deduce the ft value, three experimental quantities are needed. t stands for partial half-life and depends on the half-life of the parent state and also on the

branching ratio to the final 0^+ state. The statistical rate function f depends strongly (in its fifth power) on the Q_{EC} value.

JYFLTRAP is ideally suited for Q_{EC} value measurements. Since the Q_{EC} value is just the mass difference of the parent and daughter states, it is sufficient to measure the cyclotron frequencies of these two states with a Penning trap if the mass of the daughter (or parent) state is known with moderate precision. The Q_{EC} value expressed with cyclotron frequencies is as follows:

$$Q_{\mathrm{EC}} = M_{\mathrm{m}} - M_{\mathrm{d}} = \left(\frac{\nu_{\mathrm{d}}}{\nu_{\mathrm{m}}} - 1\right)(M_{\mathrm{d}} - m_{\mathrm{e}}) - \Delta B_{\mathrm{m,d}}, \tag{3}$$

where M_{m} and M_{d} are the masses of the parent and daughter atoms, respectively; $\nu_{\mathrm{d}}/\nu_{\mathrm{m}}$ is their cyclotron frequency ratio with singly-charged ions, m_{e} is the electron mass and $\Delta B_{\mathrm{m,d}}$ is the electron binding-energy difference between the parent and daughter atoms. Since the term $(\frac{\nu_{\mathrm{d}}}{\nu_{\mathrm{m}}} - 1) < 10^{-3}$, the precision of the daughter atomic mass has very little contribution to the obtained Q_{EC} value. Additionally, since both are mass doublets having the same mass-over-charge ratio, mass-dependent systematic error cancels out. Overall, Q_{EC} value precision $\Delta Q/M$ of about 2×10^{-9} has been reached.

At JYFLTRAP, Q_{EC} values have always been measured so that eq. (3) can be applied. In other Penning trap facilities, Q_{EC} value is usually determined by measuring masses of the parent and the daughter separately (see for example ^{74}Rb measurement from ISOLTRAP in ref. [26]).

Until December 2009, the Q_{EC} values of $^{26}\mathrm{Al}^m$, ^{26}Si, ^{30}S, ^{34}Cl, $^{38}\mathrm{K}^m$, ^{42}Sc, ^{42}Ti, ^{46}V, ^{50}Mn, ^{54}Co and ^{62}Ga have been determined at JYFLTRAP (see also figure 4). Also, cyclotron beam time to measure ^{10}C and ^{14}O has been approved. For most of the cases the Q_{EC} values were already precisely determined (see compilation by Hardy and Towner [27]) prior to Penning trap measurements. The Q_{EC} value of ^{46}V was first found out to be clearly off from the previously adopted values by the Canadian Penning trap group [28]. This was later confirmed by JYFLTRAP too [29]. This raised questions whether other similar deviations could exist. Later, the Q_{EC} values of ^{50}Mn and ^{54}Co turned out to deviate by about the same amount from the previously adopted values [30]. In fact, the deviating values originated from a 30-year old publication [31] (see figure 5). Recently, Faestermann *et al* [32] measured the Q_{EC} value of ^{46}V using essentially the same experimental components as in [31], confirming the large discrepancy. The values originating from ref. [31] have now been discarded in the most recent compilation of superallowed β emitters [25].

The most recent results from JYFLTRAP are the Q_{EC} values of ^{34}Cl and $^{38}\mathrm{K}^m$ [5]. The new results confirm the previous measurements which were based on (p, n) and $(p, \gamma) + (n, \gamma)$ reactions as summarized in figure 6.

3.2 *Mass measurements for nuclear structure studies*

Atomic masses of neutron-rich nuclides between $Z = 28$ (nickel) and $Z = 52$ (tellurium) have been extensively studied, most exotic having half-lives of less than 100 ms [3,36–40]. The two-neutron separation energies in $N = 60$ indicate the

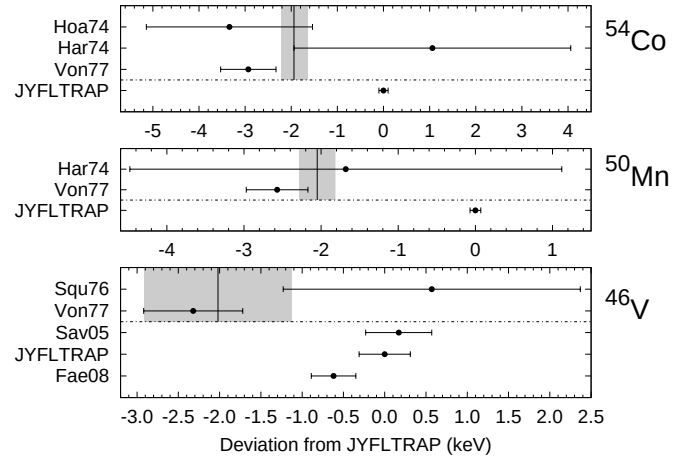

Figure 5. The different Q_{EC} value measurements of ^{46}V, ^{50}Mn and ^{54}Co. Difference of each measurement to the JYFLTRAP measurement is given. The values above the dashed horizontal lines are included in the compilation by Hardy and Towner [27] in 2005. The compilation value is marked with vertical bar with one standard deviation (shaded). Hoa74: Hoath *et al* [33], Har74: Hardy *et al* [34], Von77: Vonach *et al* [31], Squ74: Squier *et al* [35], Sav05: Savard *et al* [28] and Fae08: Faestermann *et al* [32].

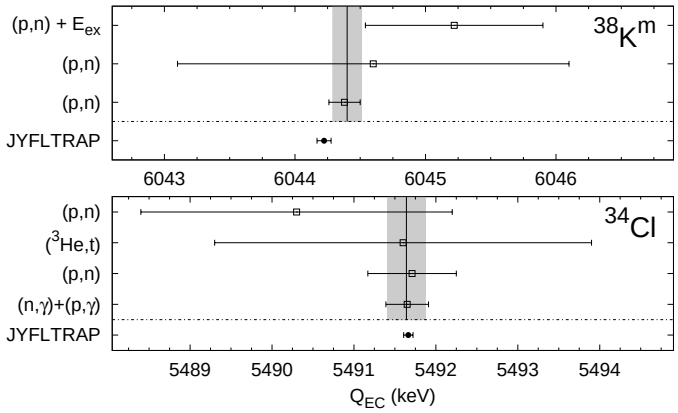

Figure 6. Comparison of the new JYFLTRAP values to the previously measured values (see ref. [25]). The compilation value given in Hardy and Towner [25] is marked with vertical bars with one standard deviation (shaded).

onset of deformation in nuclei near ^{100}Zr. This is apparent not only from atomic masses [3] but also from nuclear moments [41].

Another area extensively probed is the doubly magic $Z = 28, N = 50$ region. Masses of zinc isotopes ($Z = 30$) were measured up to ^{80}Zn, providing valuable information about $N = 50$ shell. The next milestone would be to measure ^{82}Zn.

3.3 *Mass measurements near the endpoint of the rp-process*

One motivation to measure masses near the proton or neutron drip lines is the astrophysical processes. The rapid proton capture process, the so-called rp-process, is a series of proton captures and β^+ decays. Precise atomic mass measurements provide input data for reaction network calculations that ultimately provide composition of isotopes that are produced in the reaction [42]. Recent mass measurements down to ^{104}Sn indicate quenching of the SnSbTe end cycle [43].

4. Summary and outlook

So far, atomic masses of more than 250 different isotopes have been measured with JYFLTRAP. These range from nuclides far away from the valley of β stability to the stable isotopes. JYFLTRAP is ideally suited for decay Q value measurements where both the parent and daughter have the same mass number and relative precision $\Delta Q/M$ of close to 1×10^{-9} have been obtained.

Future mass measurements will be performed in the extension of the Jyväskylä Accelerator Laboratory. There, IGISOL will have access to beams from both the old K130 and the new MCC30 cyclotrons. With the latter, more beam intensity is available and fission studies especially will benefit from this, enabling access to even more neutron-rich nuclei.

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