JYFLTRAP: MASS SPECTROMETRY AND ISOMERICALLY CLEAN BEAMS*

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A radiofrequency quadrupole (RFQ) cooler and buncher and two Penning traps form the JYFLTRAP setup, which is located at the Department of Physics, University of Jyväskylä, Finland. It is used as a high-resolution mass filter for decay-spectroscopy experiments as well as for high-precision mass measurements. Recent developments have enabled JYFLTRAP to prepare isomerically clean beams with a mass resolving power $R = \frac{M}{\Delta M} \geq 10^6$.

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1. Introduction

The JYFLTRAP setup is an integral part of the IGISOL facility [1]. More than half of the experiments with radioactive ions use JYFLTRAP either for mass measurements of short-lived nuclei or for providing isobarically clean ion beams for decay spectroscopy. More than 170 masses of exotic nuclei have been measured with a relative precision of better than 10^{-7} [2–7]. Using different production techniques a large variety of nuclei from both sides of the valley of stability can be produced.

On the neutron-deficient side, close to the $N = Z$ line, mass measurements on isotopes of yttrium up to indium were done to provide data for a better modeling of the rp-process path. On the neutron-rich side, near the $N = 50$ region, the studied nuclei reach the astrophysical r-process path.

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JYFLTRAP also contributes to weak interaction studies by supplying high-precision Q_{EC}-values of superallowed beta decays [8, 9]. One of the recent activities are Q-value measurements for double beta-decay studies.

Several successful decay spectroscopy experiments with isobarically clean beams have been performed. For example, the half-life measurement of the superallowed beta emitter ^{26}Si ($T_{1/2} \sim 2.2$ s) would have not been possible without an extremely high-purity ion samples provided by the trap [10]. Here, a new multiple-injection scheme was developed in order to increase the bunch size of the ^{26}Si. In addition, several neutron-rich nuclei produced in proton-induced fission have been studied without contamination from neighboring isobars [11, 12].

Recent technical improvements have enabled the cleaning of nuclear isomers with a mass resolving power $R = \frac{M}{\Delta M} \geq 10^6$ by using an excitation with time-separated oscillatory fields. This so-called Ramsey excitation scheme has been used in the time-of-flight ion cyclotron resonance determination as well which improves precision.

2. Experimental setup

Figure 1 shows a schematic drawing of the combined IGISOL and JYFLTRAP setups. Radioactive ions are produced by impinging a primary beam from the JYFL cyclotron on a thin target (A). Neutron-rich nuclei are produced with proton-induced fission and neutron-deficient nuclei with fusion-evaporation reactions. The nuclei close to stability can be produced with light-ion-induced fusion reactions with relatively high yields. Alternatively, for off-line studies, mixed beams of stable elements can be produced using a spark ion source.

The produced ions are stopped in the helium-filled gas cell, thermalized and extracted through a small nozzle. This method is chemically unselective and thus also beams of refractory elements such as niobium, tantalum and zirconium are available. The ions go through a differentially pumped sextupole ion guide (SPIG) [13], and are then accelerated typically with 30 kV, and later mass separated with a dipole magnet having R between 200 and 500 (B).

Later, the ions are electrostatically deflected to the trap beam line (C). The chamber also houses a carbon cluster reference ion source [14] which can be used as an alternative source for calibration. Afterwards, the beam is injected into the RFQ [15] (D) by decelerating the beam to 100 eV. The cooled beam is either extracted to the collinear laser spectroscopy beam line (E) or to the Penning traps for beam purification or mass measurements (F).

Two cylindrical Penning traps are situated inside the same 7 T superconducting solenoid, each being 10 cm away from the geometrical center of the magnet. The purification trap, the one closer to the RFQ, is filled with

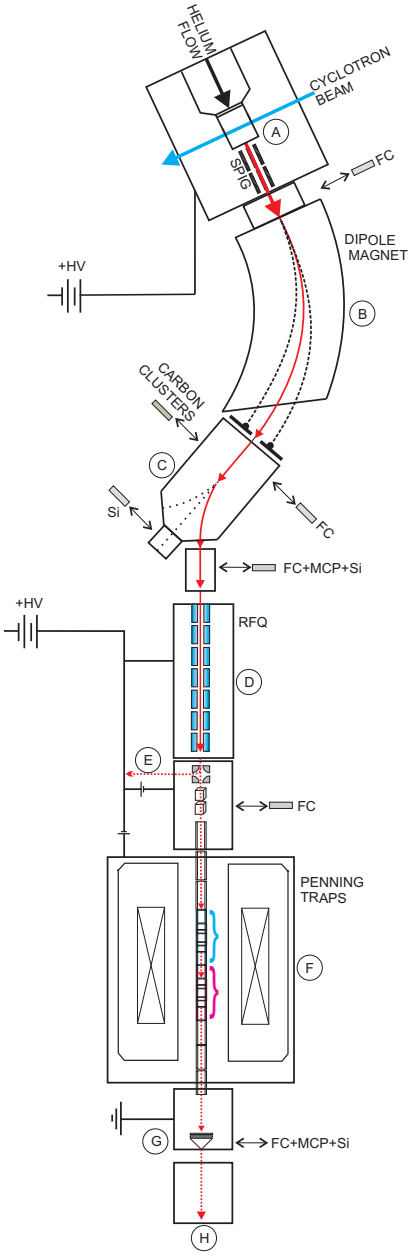

Fig. 1. The JYFLTRAP setup after the IGISOL mass separator. FC: Faraday cup, MCP: micro-channel plate detector, Si: silicon detector. For further explanation see text.

helium buffer gas in order to be able to perform isobaric cleaning with the sideband cooling technique [16]. A mass resolving power of up to 10^5 [17] can be reached which is usually sufficient for isobaric cleaning. The cleaned bunch of ions is then injected to the second trap (precision trap) for time-of-flight ion cyclotron resonance measurements.

Optionally, if $R \gtrsim 10^5$ is needed, the precision trap can be used for high-resolution cleaning, as described in Section 5.2. After ejecting the ions from the trap, they are re-accelerated with 30 kV. The detector station (G) is used for time-of-flight determination and the end of the beam line (H) is reserved for decay spectroscopy.

3. Mass measurements

3.1. Experimental procedure

A Penning trap mass measurement of an ion having mass m and charge q in a magnetic field B is based on the determination of its cyclotron frequency

$$\nu_{\mathrm{c}} = \frac{1}{2\pi}\frac{q}{m}B\,. \tag{1}$$

In order to do so, the ions are first subjected to a magnetron rf-excitation which increases the magnetron radius of all ions in the trap. Subsequently, the magnetron motion is converted to cyclotron motion by using a quadrupole rf-electric field for a given duration and amplitude. The frequency of the applied field is scanned over a frequency range which includes the resonance frequency (1). After the excitation, the ions are extracted and their time-of-flight to the detector is recorded. Depending on the excitation frequency, the conversion factor from the magnetron motion to the cyclotron motion is different. More the ions have cyclotron motion, the faster the ions arrive to the detector since the energy of the cyclotron motion is about 10^6 times the energy of the magnetron motion. The frequency where the ions have the shortest time-of-flight to the detector corresponds to the resonance frequency (Eq. (1)).

To determine the atomic mass m of an ion of interest, the frequency is calibrated against the resonance frequency $\nu_{\mathrm{c,ref}}$ of a well-known mass m_{ref}. Once the frequencies of the corresponding ions are measured, a frequency ratio

$$r = \frac{\nu_{\mathrm{c,ref}}}{\nu_{\mathrm{c}}} \tag{2}$$

is obtained. Combining Eqs. (1) and (2), the atomic mass of the ion of interest for singly charged ions is

$$m = r\,(m_{\mathrm{ref}} - m_e) + m_e\,, \tag{3}$$

where m_e is the electron mass. In addition to absolute mass values, differences between masses, especially Q-values can be addressed in relative measurements. For the electron capture Q-value, Q_{EC}, Eq. (3) gives

$$Q_{\mathrm{EC}} = m_{\mathrm{mother}} - m_{\mathrm{daughter}} = (r-1)(m_{\mathrm{ref}} - m_e)\,, \tag{4}$$

with the mass of daughter nuclide being the reference. Since the quantity $(r-1)$ is rather small for mass doublets ($< 10^{-3}$), the uncertainty in the reference mass is negligible compared to the uncertainty in r, and thus Q_{EC}-values can be obtained with a high precision even though the reference mass uncertainty is large.

3.2. Results

Since commissioning of the precision trap in 2003 more than 170 masses of radioactive nuclei have been determined at JYFLTRAP. Those include nuclei reaching the astrophysical rp-process path in the neutron-deficient side of the nuclide chart and the r-process path in the neutron-rich side. The latter also contribute to nuclear structure studies (see Ref. [19] in this issue). In addition, several Q_{EC}-values for superallowed $0^+ \rightarrow 0^+$ beta-decays have been measured with high precision.

The masses studied at JYFLTRAP are shown in Fig. 2. The shortest living nucleus studied is ^{62}Ga having a half-life of $\sim$120 ms. Typically, the measured masses have uncertainty better than 10 keV and the Q-values can be determined even with sub-keV precision.

The Q_{EC} measurements of superallowed beta-decays contribute to tests of the Standard Model of particle physics. In addition, precise half-life and branching ratio measurements are needed. For each superallowed beta-emitter an $\mathcal{F}t$-value is obtained after applying theoretical corrections. Once averaged over all emitters, the final $\mathcal{F}t$-value can be turned into V_{ud} of the Cabibbo–Kobayashi–Maskawa quark mixing matrix [22].

By the end of 2006, the beta-decay Q_{EC}-values of ^{26m}Al, ^{42}Sc, ^{46}V and ^{62}Ga have been measured [8,9]. The first three belong to the "12 best known" cases in the compilation by Hardy and Towner from 2005 [22]. The measurement of ^{62}Ga improved the precision of its Q_{EC}-value to a comparable level with the other well-known superallowed emitters. One of the striking results is the Q_{EC}-value of ^{46}V, measured at CPT [23] and confirmed by JYFLTRAP, did not agree to the previously adopted value in [22]. The Q_{EC}-values of ^{26m}Al and ^{42}Sc did agree to previous values, rendering the ^{46}V to be an anomalous case. Two more cases included in the "best known" set, namely ^{50}Mn and ^{54}Co, were measured in two beam times in 2006 and 2007 to check whether the Q_{EC}-value anomaly appears in those nuclei too.

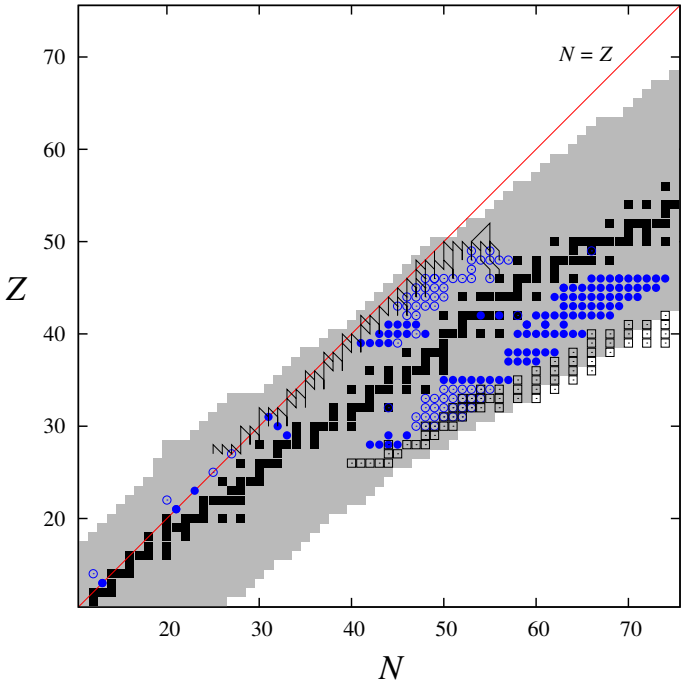

Fig. 2. A part of the nuclide chart. The stable nuclei are marked with squares. The nuclei studied at JYFLTRAP are marked with circles (filled = published, empty = in preparation). The empty squares denote the r-process waiting point nuclei [20]. The trail near the $N = Z$ line shows the rp-process path [21].

To otherwise complement the set of well-known cases, the Q_{EC}-values of ^{26}Si and ^{42}Ti have also been measured. Fig. 3 summarizes the $\mathcal{F}t$-values given in [22] and with the new Penning trap Q_{EC}-data. It should be noted that the Q_{EC}-values of the well-known beta-emitters ^{22}Mg, ^{34}Ar and ^{74}Rb have also been measured with high precision with Penning traps [24–26]. In those cases the precision in the $\mathcal{F}t$ value is limited by the accuracy of half-life and branching ratio measurements.

4. Decay spectroscopy with isobarically clean beams

JYFLTRAP has been successfully used as an isobaric mass filter for several decay-spectroscopy experiments (see *e.g.* [11, 12]). Especially nuclei far from the valley of stability produced in fission reactions have often overwhelming isobaric background. Once the trap is used to remove the contaminants, the background can only arise from the decay of ion of interest which can be several isobars away from stability.

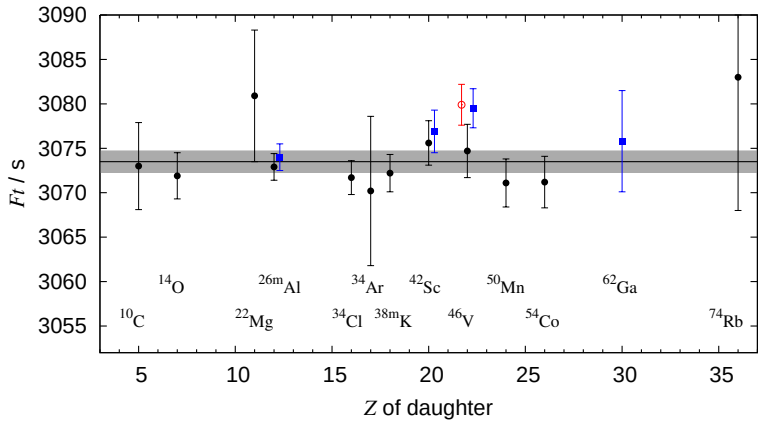

Fig. 3. $\mathcal{F}t$-values plotted as a function of the charge of the daughter nucleus. The filled circles are from [22] and the horizontal bar denotes the average $\mathcal{F}t$-value given in the same reference. The squares are derived from the JYFLTRAP measurements and the empty circle is derived from CPT data; these are not yet included in the average value.

In March 2007 the trap was used to prepare clean bunches of ^{26}Si to measure the half-life of this superallowed beta-emitter [10]. The aim was to measure it with a relative precision of 0.1 % avoiding any direct implantation of its beta-decaying daughter, ^{26m}Al.

A trapped cloud of ions serves as an excellent source for conversion electron spectroscopy [27]. Since the decaying ion is trapped in vacuum, emitted electron does not suffer from scattering in the source material which would deteriorate the lineshape. The high magnetic field efficiently transports the electrons to the detector. Unfortunately, preparing the setup for in-trap decay spectroscopy requires removal of part of the extraction beamline, rendering other trap activities impossible. Nevertheless, a successful feasibility test was performed in 2005 [28] and a permanent, easily accessible setup is being designed.

5. Recent developments

5.1. Excitation with time-separated oscillatory fields

Although the first time-of-flight ion cyclotron resonances in a Penning trap with time-separated oscillatory fields dates back to 1992 [29], the theoretical fitting function for the resonance lineshape has only recently become available for regular use [30,31]. In this method the excitation is interrupted for certain time periods while preserving phase coherence. The lineshape resulting from the excitation can be rather complicated. In its simplest form

the excitation can be split into two parts, as shown in Fig. 4. This enhances the sideband structure and improves the fit result considerably when compared with a conventional resonance.

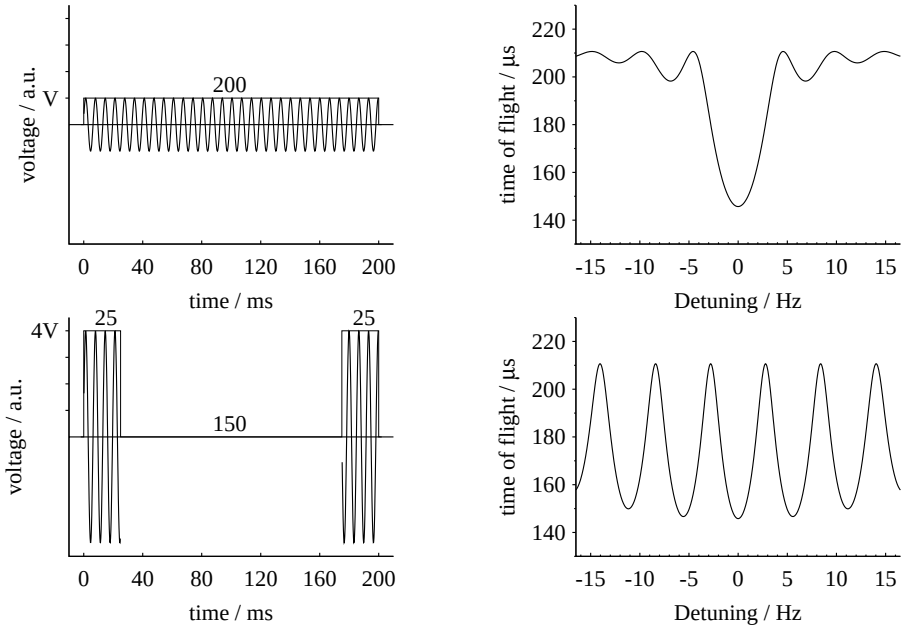

Fig. 4. Excitation time pattern (left) and expected time-of-flight cyclotron resonance spectrum (right). The excitation with time-separated oscillatory fields (bottom) enhances the sidebands and reduces the linewidth of the resonance. The expected resonance shape with a conventional 200 ms excitation (top right) [32] and with a (25–150–25) ms (On–Off–On) pattern (bottom right) [30] is shown.

At JYFLTRAP, this method was used to measure the Q_{EC}-values of ^{50}Mn and ^{54}Co. Since the half-lives of these nuclei are rather short (~ 300 ms and 200 ms, respectively), the applicable rf-excitation time is also limited. With the time-separated excitation, the precision could be significantly improved. A time-of-flight cyclotron resonance curve of ^{54}Co is shown in Fig. 5 where an excitation pattern of (25–150–25) ms (On–Off–On) was used. The excitation with time-separated oscillatory fields is now in routine use at JYFLTRAP.

5.2. Isomeric separation

An other application employing the excitation with time-separated oscillatory fields is the dipolar cleaning of contaminating ions in the precision trap. The motivation for developing such a scheme arose from the

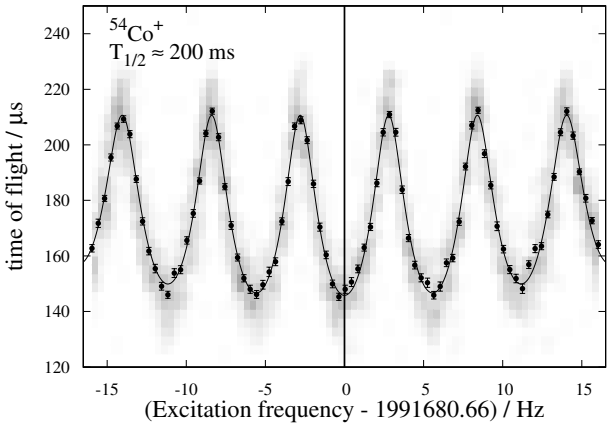

Fig. 5. Time-of-flight cyclotron resonance of the ground state of $^{54}Co^{+}$ with an excitation time pattern of (25–150–25) ms. The grey squares indicate the ion distribution to different time bins. The vertical bar denotes the cyclotron resonance frequency ν_c.

Q_{EC}-value measurements of ^{50}Mn and ^{54}Co where low-lying nuclear isomers ($T_{1/2} > 1$ min) at excitation energies of $\sim$ 200 keV are present. The cleaning had to be done rather fast due to the short half-lives of the ground states of these superallowed beta-emitters. The dipole-excitation time-pattern and frequencies were chosen such that impurities were excited to larger orbits, but the ions of interest were not. The dipolar excited bunch was re-transferred towards the purification trap through a 2-mm diaphragm which allowed only the ions of interest to pass through. In the cases of ^{50}Mn and ^{54}Co, about 200 ms were spent in this cleaning process.

With this method a resolving power $R > 10^6$ can be reached just by increasing the total duration of the excitation pattern. An example of a cleaning scan is shown in Fig. 6. Once fixing the frequency to either of the peaks, the other state is rejected. More detailed description of the cleaning procedure can be found in [33].

5.3. Multiple injection

About 10^5 ions can be loaded to the purification trap and the isobaric cleaning procedure is still applicable. In the ^{26}Si half-life measurement a bunch was allowed to enter the detection setup every 25 seconds.

Since the fraction of ^{26}Si was rather small, every bunch contained only a small amount of ^{26}Si. To overcome the number limit in the purification trap, a new scheme was developed. Instead of cleaning only one bunch, several bunches were cleaned prior to the final extraction to the detector setup.

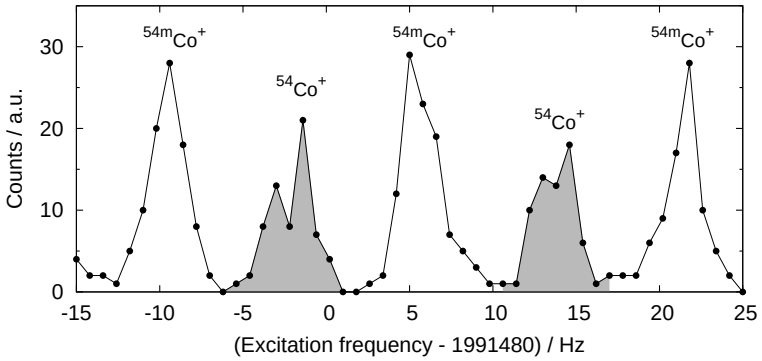

Fig. 6. Isomer purification scan of ^{54}Co and ^{54m}Co in the precision Penning trap. The peaks correspond to the transmission of ^{54}Co (shaded) and ^{54m}Co (unshaded). The employed excitation pattern was (10–55–10) ms (On–Off–On). A mass resolving power R of 2.5×10^5 is obtained.

Once a bunch was ready, it was extracted towards the 2-mm diaphragm on the extraction side. The contaminants hit the diaphragm electrode and the ions of interest were reflected back to the purification trap where the cleaned bunch was recaptured. With the next injection of an uncleaned bunch the cleaning process was repeated increasing the fraction of wanted ions. After sufficient amount of cleaning cycles, the accumulated bunch was extracted to the detector setup. Up to 500 ^{26}Si ions per bunch were accumulated within 9 cleaning cycles.

6. Outlook

JYFLTRAP has become an integral part of the IGISOL setup. More than half of the on-line experiments involve the use of the trap setup. Several decay spectroscopy experiments with purified beams and mass measurements have been scheduled in the near future. For instance, one week of beam time for mass measurements in neutron-rich Sn–Sb–Te region is scheduled to December 2007. Beam time has also been granted for Q_{EC}-value measurements of the superallowed beta-emitters ^{10}Si, ^{14}O, ^{34}Cl and ^{38m}K, and also for the half-life measurement of the superallowed beta-emitter ^{42}Ti.

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