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Precision experiments on exotic nuclei at IGISOL

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Abstract

Cooling and trapping techniques of low-energy radioactive ion beams of refractory elements employed at the IGISOL facility are presented with emphasis on high-precision measurements of the ground state properties of exotic nuclei. The impact of the new generation Paul and Penning traps on mass measurements of short-lived nuclei is discussed with examples on precision measurements of masses of super-allowed beta emitters and neutron-rich nuclei. As a new concept the trap-assisted spectroscopy of radioactive ions is presented with applications in collinear laser spectroscopy, decay spectroscopy of isobarically purified sources and in nuclear cross-section measurements by ion counting.

Keywords: Ion guide; Penning trap; Radio frequency ion cooler; Atomic masses; Collinear laser spectroscopy

1. Introduction

A wealth of novel physics phenomena associated with nuclei far from the valley of stability largely drives today's low-energy nuclear physics research. The physics with radioactive ion beams represents one of the frontiers of nuclear physics, which explains the build up of numerous facilities around the world. The energy range of radioactive ion beams, as requested by the research community, ranges from very low electron volt (eV) energies of relevance for surface studies to several mega-electron volt (MeV) needed in creating nuclear reactions with radioactive ions themselves. Other areas of importance are the purity of the ion beam as well as its intensity. Therefore, the production of these beams is a science in itself as exemplified by pioneering work done at the ion guide isotope separator on-line (IGISOL) facility located at the accelerator laboratory of the University of Jyväskylä. Among the currently operating facilities, IGISOL offers one of the widest diversity of exotic radioactive nuclei for precision experiments on rare, radioactive isotopes.

In this article we present experimental activities at IGISOL employing novel ion cooling and bunching techniques that are based on the use of Paul and Penning traps. Ion trap technology was introduced to atomic mass measurements of radioactive isotopes at ISOLDE, CERN by Hans-Jürgen Kluge et al. [1,2]. In the early days of these experiments, the fast and efficient injection into the trap was a serious limitation for using traps for exotic short-lived isotopes. This obstacle was overcome by the introduction of a fast injection scheme based on the gas-filled linear Paul trap concept (see Refs. [3,4] for further reading).

The IGISOL technique was initially developed to overcome the long release times of the conventional ISOL approach for refractory elements [5]. It is based on the stopping of the recoil ions in a buffer gas resulting in a fast reset to the 1^+ ionic charge state. With this technique ion beams can be made of short-lived ($T_{1/2} > 0.1$ ms) radionuclides of all elements, including the most refractory ones. Another variant of the method is based on selective laser ionization of short-lived radioactive species thermalized in gas as neutral atoms [6,7]. The use of the IGISOL technique has led to the discovery and detailed studies of decays of more than 40 new neutron-rich isotopes in nuclear fission. It has also been implemented successfully in connection with light-and heavy-ion induced fusion reactions. In addition to decay spectroscopy, the ion guide technique has a broad applicability in studies of other properties of exotic nuclei. However, the standard IGISOL technique has two drawbacks, a rather large energy spread of the ion beam and chemical non-selectivity. To overcome these problems we initiated a research

Abbreviations: IGIS, ion guide isotope separator on-line; RFQ, radio frequency quadrupole

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programme to implement ion cooling and trapping techniques to post-process the primary radioactive beams produced at IGISOL.

2. JYFLTRAP facility

2.1. Ion guide isotope separator on-line (IGISOL)

At IGISOL the projectile beam hits a thin target and product nuclei recoil out as highly charged ions into a fast-flowing buffer gas, usually helium. As the ions slow down and thermalize their charge state changes continuously via charge exchange processes with the gas atoms. A significant fraction retain a 1^+ charge state and are guided out of the ion source with the gas flow, whereby they are injected into the mass separator via stages of differential pumping. After acceleration to between 30 and 40 kV depending on the experimental requirements the beam is mass separated by a dipole magnet, allowing separation of nuclei with a typical mass resolving power of the order of 250–500 depending on the operational parameters of the ion guide and the front-end of the separator. The attractive features of this technique are the fast (sub-millisecond) release, and chemical non-selectivity making it possible to produce even the most refractory of elements. In connection with nuclear fission, the IGISOL method has led to the production of neutron-rich refractory isotopes such as Nb, Mo, Tc, Ru and Rh, with beam intensities approximately 10^5 ions/s. The typical transverse emittance of an extracted ion beam is 12π mm mrad and the energy spread is relatively large, up to 50–100 eV. In order to reduce these physical parameters an additional cooling is required as will be explained in the flowing section. Recently the IGISOL separator was upgraded resulting in an average yield approximately three times higher than the previous version [8].

2.2. RFQ cooler and buncher

For more than a decade nuclear spectroscopy experiments have been performed successfully at IGISOL, but progress in the field had made it necessary to upgrade the existing facility. The first phase was completed in the year 2001 with the commissioning of a buffer gas-filled radio frequency quadrupole (RFQ) [4]. In an RFQ ions are confined with a transverse time-dependent electric field and energy loss is obtained in ion and buffer gas atom interactions. A small electric potential of about 5 V over the length of the RFQ draws the ions through the cooler, resulting in a transit time of the order of 1 ms. By applying a positive voltage to the end plate, a potential well is created just inside the cooler where the ions may be accumulated for up to a second. Lowering the plate voltage releases the cooled ions in a bunch with a duration of a few microseconds and an energy spread of less than 1 eV. These values have been obtained with a typical transmission efficiency of 60–70% for ions with $A > 40$ providing strongly improved conditions for collinear laser spectroscopy [9,10] and an ideal injector to the purification trap of JYFLTRAP [11]. For more details on ion coolers and bunchers (see Ref. [12]).

2.3. Mass determination with a Penning trap

The mass determination using a Penning trap is based on the determination of the cyclotron frequency of an ion in a strong magnetic field. In the presence of an axially symmetric quadrupole field the ions perform a characteristic motion consisting of three independent components, which are an axial motion with a frequency f_z and two radial motions, a slow magnetron motion (f_-) and a fast-reduced cyclotron motion (f_+). The overall radial motion is a superposition of the two radial motions and is connected to the magnetic field via the relation $f_c = f_- + f_+ = (q/m)(B/2\pi)$, where f_c is the cyclotron frequency of an ion with a charge-to-mass ratio of q/m oscillating in the external magnetic field B. The resolving power of a Penning trap as a mass spectrometer depends on how accurately the magnetic field and the cyclotron frequency can be determined. In general, the mass resolving power $\mathrm{MRP} = m/\Delta m = f_c/\Delta f_c \approx f_c T_{obs}$, where T_{obs} is the time of observation. In typical conditions a mass resolving power of about 10^6 is obtained for ions with $A/q = 100$ stored over 1 s in a few Tesla magnetic field. This allows the measurement of unknown masses with a precision better than 10^{-7}, i.e., 10 keV for $A = 100$ ions.

2.4. JYFLTRAP — universal approach to precision measurements

JYFLTRAP consists of a screened superconducting solenoid with a 7 T magnetic field. The magnet has two 1 cm^3 homogenous regions along the beam axis, symmetrically 10 cm in both directions from the magnet center. In these regions the homogeneity $\Delta B/B$ of the magnetic field is below 10^{-6} and 10^{-7} and they are equipped with cylindrical Penning traps. These traps are called purification and precision traps and they are described in more detail below (Fig. 1).

Ion bunches from the RFQ cooler are sent at low energy into the purification trap where they are captured by a time-varying electric potential, thermalized and cooled in a buffer gas in the center of the potential. They are subsequently excited by applying successive dipole and quadrupole rf fields

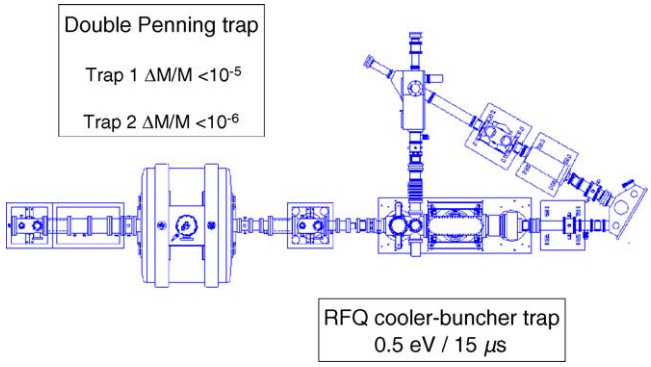

Fig. 1. A lay-out of the JYFLTRAP facility. The ion beam from the IGISOL separator enters the trap line from the right through the 30° deflector. It is first cooled and bunched in the RFQ, from where the bunches can be directed either to the double Penning trap or to a short connecting line serving conventional spectroscopy and collinear laser spectroscopy.

which lead to mass-selective cooling and centering according to $\omega_c = 2\pi f_c = qB/m$ (for more details see Refs. [13,14]). The ejection through a small diaphragm between the traps allows only those ions close to the trap axis to be extracted. For fission products with a mass around $A = 100$, a typical MRP value ranges from few times 10^4 up to 2×10^5, depending on the operational parameters applied [15]. For more technical details on the purification trap see Ref. [11].

The mass-purified ion ensemble is transported to the precision trap, where the cyclotron frequency of the ions is determined precisely by applying the TOF-technique [16]. By measuring sequentially cyclotron frequencies of an unknown and well-known reference ion, one can deduce the mass of the unknown isotope from the simple relation $m_{meas} = (m_{ref} - m_e)x + m_e$, which only depends on the mass of the known reference ion and the obtained frequency ratio $x = f/f_{ref}$.

Soon after the completion of the precision trap, a mass resolving power for nuclei with $A \approx 130$ of up to 800,000 could be achieved. Such a resolving power will enable a mass measurement with a relative accuracy of approximately 10^{-8}, which corresponds to 1.4 keV in this mass range. In addition it can be estimated that for relative measurements, such as that of Q-values, an accuracy of better than 1×10^{-9} can be achieved.

3. Trap-assisted spectroscopy

The availability of cooled ion beams with improved ion optical properties or a well-localized mass-purified ion sample floating freely in space can be of great advantage for spectroscopic studies. In the following sections we will describe a couple of applications for manipulated ion beams at the IGISOL facility.

3.1. Collinear laser spectroscopy

Fundamental, and model-independent, data on the structure of nuclear ground and isomeric states can be readily obtained from atomic physics techniques — more specifically, high-resolution optical measurements of the atomic structure [17]. Laser spectroscopic techniques provide both the sensitivity and accuracy required to measure the part-per-million effects on the atomic energy levels caused by a finite nuclear charge distribution, and nuclear electromagnetic moments. At the IGISOL facility optical spectroscopy is performed using a collinear fast beams geometry in which the ionic beam is overlapped with a counter-propagating laser beam. The acceleration of the ion beam to 40 keV results in a forward velocity compression, which given with a low-energy spread, the entire ionic ensemble can be brought into resonance with a single laser frequency.

With the availability of the RFQ cooler-buncher device, the efficient bunching of ionic ensembles enables collinear laser spectroscopy to be performed with extremely high sensitivity. By gating on the photons emitted in the laser–ion interaction region as the ion bunch passes the photomultiplier, suppression in scattered photon background equal to the ratio of the bunch-width to the cooler accumulation time is achieved. Release times of 15 μs from the cooler are typical for medium-mass elements and background suppressions of order 10^4 are achieved.

Access to cooled and bunched refractory isotopes has made it possible to study the nuclear properties of isotopes and isomers in the group IVb nuclei, namely Ti, Zr and Hf. Isotope shift and hyperfine structure measurements for seven Ti isotopes have been used to evaluate the mean square charge radii trend at $Z = 22$. The results suggest a more surface-peaked or diffuser proton structure for Ti as the $N = 20$ shell closure is approached [18]. A re-measurement of the charge radius of ^{175}Hf removed an anomalous value from an earlier work and suggests that the ^{175}Hf ground state shows a large inverted odd–even staggering and is in fact the most deformed ground state in the hafnium chain [9]. A chain of Zr isotopes from neutron-deficient ^{87}Zr to neutron-rich ^{102}Zr were also studied by collinear laser spectroscopy [19]. The results indicate a steadily increasing mean square charge radius as a function of neutron number until the known shape change at $N = 60$, almost identical to the behaviour of the Sr isotones. Very recently these studies were extended to both neutron-deficient and -rich Y isotopes (Billowes et al., personal communications).

3.2. Spectroscopic applications of isobarically purified radioisotopes

While designing the JYFLTRAP, a possibility of producing isobarically or even isomerically purified ion beams was considered an important application of the apparatus. The following two sections describe how the isobaric purification in the Penning trap has been applied at JYFL.

3.2.1. Decay study of deformed ^{100,102,104}Zr isotopes

Due to the unselectivity of the IGISOL technique, the reaction products are ionized with equal efficiency and thus the composition of the extracted ion beam from the separator reflects the production ratio in the reaction used. In the case of a fission reaction this may result in a serious isobaric background which prevents studying rare isotopes produced far from stability. In such cases, isobaric cleaning in the purification trap can be used to enhance both the sensitivity and selectivity of spectroscopy. As an example we describe here the beta-decay study of the neutron-rich ^{104}Zr isotope. This work is related to a study of GT-distribution and its dependence on deformation, which may provide means to obtain information about the sign of the deformation.

The production yield of ^{104}Zr was about 33 ions/s after the trap, while the isobaric yield in $A = 104$ is of the order of 10^5 ions/s. Fig. 2 illustrates the effect of the isobaric cleaning on the beta-gated gamma spectrum obtained at $A = 102$ with two different cyclotron frequency settings. In addition to a better sensitivity of the spectroscopy due to the absence of directly produced isobaric contamination, this method allows a precise determination of the total beta-decay intensity and thus an improved accuracy of the ground state branching. The initial results deals with the beta decay of ^{100,102,104}Zr (Rinta-Antila et al., unpublished).

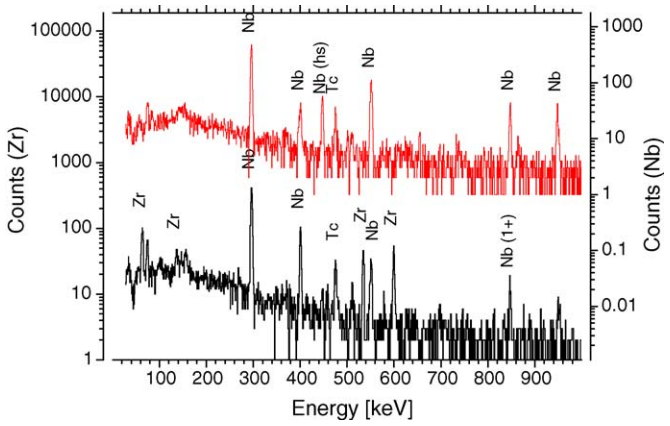

Fig. 2. Two gamma-spectra measured at mass $A = 102$. Isobaric purification has been applied for ^{102}Zr (lower spectrum) and ^{102}Nb (upper spectrum). Transitions appearing only in the beta decay of high spin isomer of ^{102}Nb are marked with Nb(hs).

3.2.2. *Isotopic distributions in fission*

The purpose of these experiments is to study the relative isotopic distributions of fission products in proton-induced fission of uranium. These experiments performed at JYFLTRAP provide experimental data for testing and improving the low-energy particle-induced fission models.

These measurements involved extraction of relative yields directly from the mass scans after the purification trap. The mass resolving power of the purification trap is adequate to give an unambiguous identification of ions in most cases. The method turned out to be far more reliable and sensitive than conventional means relying, for example, on decay spectroscopy. Within 20 h the most complete experimental data set for the relative, independent, isotopic fission yields for Zr and Mo isotopes could be measured in this proof-of-principle experiment. In 3 days of beam time similar yield distributions as shown in Fig. 3 were measured for 10 elements, including Ge, Nb, Tc, Cd and Sn.

3.3. *In-trap decay spectroscopy*

Trapping radioactive ions or atoms in vacuum in a magnetic or a magneto-optical trap provide totally new possibilities for spectroscopy, since trapped ions or atoms form a source without any energy loss or scattering in the source material itself. In this case, one expects to achieve an improved line shape and a better peak-to-background ratio, thus allowing for obtaining more precise spectroscopic information. Additionally, the radioactive decay removes the daughter activities reducing the background. Physics applications include the measurement of beta-neutrino angular correlations, a measurement of the shape of the beta spectra by detecting the recoil energy spectrum, electron and charged particle-spectroscopy for nuclear structure studies, and precision experiments on atomic states.

Here we would like to report our first on-line measurements, where conversion electrons were observed from the isomeric states populated directly in fission. The isomers were captured and stored in the purification trap in a similar manner as explained in Chapter 2. Instead of transporting centered ions

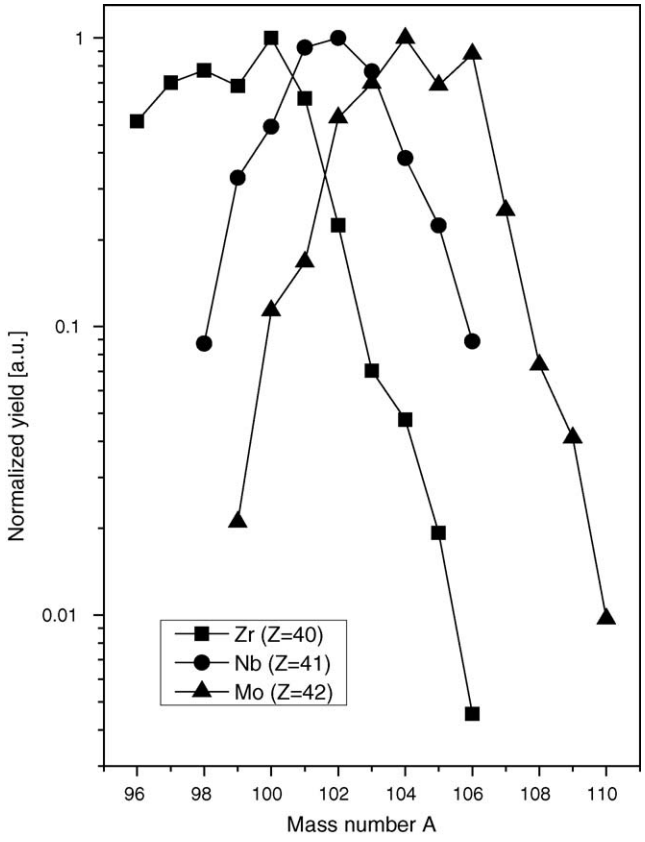

Fig. 3. Isotopic distribution for Zr, Nb and Mo isotopes determined from isobaric scans after the purification trap. Yields are normalized to one for the maximum of each yield curve.

from the purification trap to the precision trap, a cycle of repeated storing and re-centering was applied in the purification trap and at the same time, conversion electrons were observed in the Si-detector placed further down stream. The detector was placed in the region of decreasing magnetic field, but the field was still strong enough to confine conversion electrons up to 300 keV to the area of the detector (10 mm^2). Fig. 4 illustrates an example of a conversion electron spectrum in the decay of

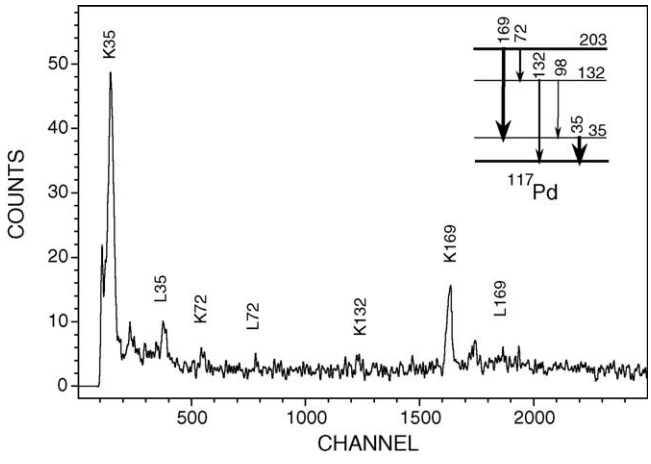

Fig. 4. Conversion electrons emitted from a mass-purified and stored sample of ^{117}Pd isomer. Decay scheme of the 203 keV isomeric stare is inserted.

a 203 keV isomeric state in ^{117}Pd. This state has a half-life of only 19.1 ms and it decays via two excited states with four converted transitions [20].

4. Precision mass measurements

An accurate measurement of the nuclear mass surface and its fine structure reveals knowledge on the underlying symmetries and microscopic features of nucleon systems. In nuclear astrophysics the masses of exotic, often short-lived, nuclei are crucially important in network calculations (for example see Ref. [21]). A specific class of nuclidic masses are those linked to each other by the charge symmetry of nuclear interaction. Accuracies required in such measurements are in the range of 1 keV or even sub-kiloelectron volt. In the following we show results of two types of mass measurements carried out at JYFLTRAP, namely high-precision Q_{EC}-value measurements for super-allowed beta decays and mass measurements of neutron-rich refractory fission products.

4.1. Super-allowed $0^+ \rightarrow 0^+$ decay of ^{62}Ga

The super-allowed $0^+ \rightarrow 0^+$ beta decay between the isobaric analog states can be used as a test for the conserved vector current hypothesis and for obtaining precise values for the up–down quark mixing matrix element of the Cabibbo–Kobayashi–Maskawa matrix. This involves the precise measurement of a number of quantities, the decay Q-value, half-life and branching ratio as well as a number of theoretical corrections for radiative and charge dependent effects. Beta-decay strengths have to be measured with an ultimate precision of close to 10^{-4}. This involves, for example, the determination of the beta-decay Q-value with an accuracy better than 1 keV. The current status of this field is described in a recent review article of Hardy et al. [22].

The next heaviest nucleus in the series of $T_z = 0$, $0^+(T = 1)$ super-allowed beta emitters beyond the currently well-known heaviest case, ^{54}Co, is ^{62}Ga. It is a particularly interesting $T_z = 0$ nucleus because its beta-decay half-life and branching ratio have been determined with high precision in several experiments [23–25]. However, the Q_{EC}-value of ^{62}Ga has been determined with a modest precision of 26 keV only via a beta-end-point measurement [26].

The mass and the Q_{EC}-value of ^{62}Ga were obtained by measuring its mass relative to the daughter nucleus ^{62}Zn in repeated successive measurements at the JYFL double Penning trap setup. Fig. 5 shows an example of a TOF resonance curve measured for ^{62}Ga. Similarly, the Q_{EC}-value was also obtained from the measurements of the ^{62}Ga–^{62}Ni and ^{62}Zn–^{62}Ni pairs. In the relative measurements the only contribution to the uncertainty arose from the measured frequency uncertainties, without a contribution from the reference mass uncertainty. The total error consists of a statistical fitting error of the resonance curve as well as of a systematic error.

The new experimental value for the decay energy, the half-life of 116.175 ± 0.038 ms and the branching ratio of 99.85

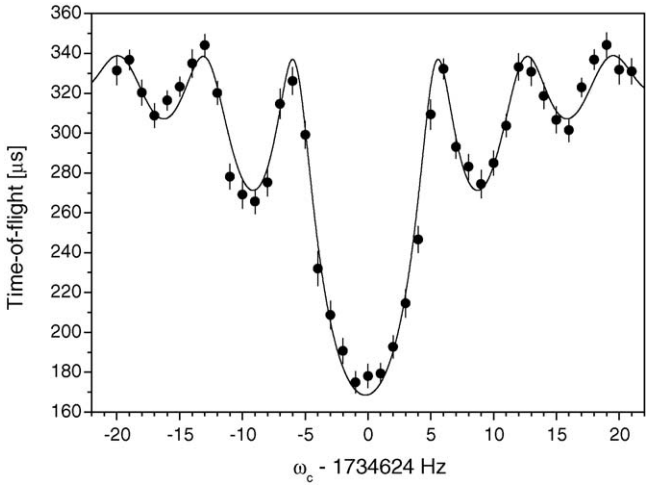

Fig. 5. A sample time-of-flight resonance curve of ^{62}Ga (see Ref. [27] for more details).

(+0.05–0.15)% yield the final Ft-value, which has to be corrected for radiative and isospin mixing effects according to Table IX of Ref. [22]. The obtained Ft-value is in good agreement with the "world average" of 3073.5 ± 1.2 as given in the review of Hardy et al. [22] (see also Fig. 6). The experimental contribution to the uncertainty is now dominated by the branching ratio measurement. The overall uncertainty, however, is strongly influenced by the uncertainties of theoretical corrections, and especially of $(1 - \delta_C)$ whose relative uncertainty is as large as 1.6×10^{-3}. For more quantitative details (see Ref. [27]).

A recent new measurement of the Q-value of the super-allowed decay of ^{46}V employing the CPT trap at Argonne National Laboratory is indicating a need for the re-measurement of the Q-values of several of the previously well-known cases [28]. This is particularly important because the new Ft-value for ^{46}V is beyond the one standard deviation zone of the world average value of Fig. 6. Most of the nuclides in question here

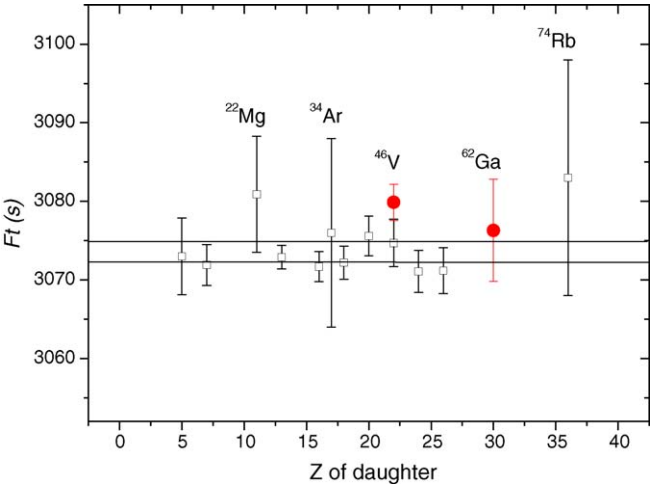

Fig. 6. Ft-values for the best-known superallowed beta emitters. Five most recently measured cases are labelled by the parent nucleus. Two horizontal lines denote one standard deviation around the world average Ft-value of 3073.5 ± 1.2 given in Ref. [22]. The newest values marked by filled circles for ^{46}V and ^{62}Ga are not included in this average.

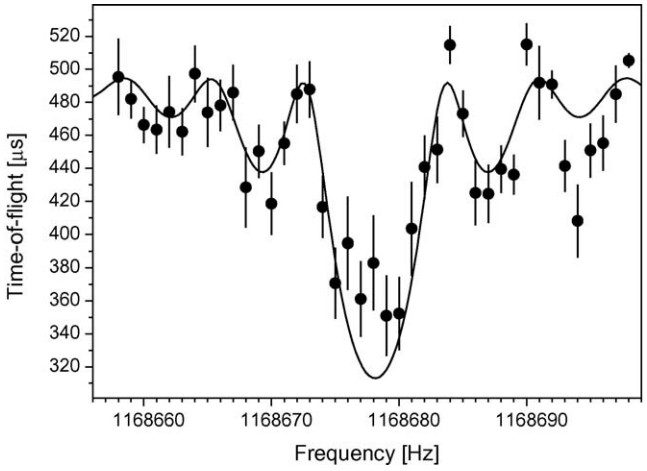

Fig. 7. A time-of-flight vs. frequency spectrum obtained for the isotope ^{92}Br.

(^{10}C, ^{14}O, ^{26m}Al, ^{34}Cl, ^{38m}Ca, ^{42}Sc, ^{46}V, ^{50}Mn and ^{54}Co) can be produced at IGISOL and their Q_{EC}-value can therefore be measured in the near future with a relative accuracy of $\sim 10^{-8}$ using the JYFLTRAP.

4.2. Mass measurements of neutron-rich fission products

The combination of IGISOL and the JYFLTRAP setup is particularly suitable for measuring masses of neutron-rich nuclei produced in fission. These nuclides belong to several refractory elements that are not available as mass-separated ion beams at any other type of ISOL facilities. Moreover, prior to the Penning trap era, the previous mass measurements have all been based on the beta-endpoint energy determinations. Often such measurements are in systematic error due to the fact that the mass determinations are relying on the long decay chains to the valley of stability and on an inadequate knowledge of the decay schemes. Therefore, the Penning trap technique has introduced a new era in the mass measurements of fission products and neutron-rich nuclides in general.

The first series of experiments at JYFLTRAP have focussed on neutron-rich strontium, zirconium and molybdenum isotopes [29]. They are known to possess interesting and rapidly changing nuclear structure features when the neutron number changes from 56 to 60. In the past, extensive spectroscopic studies have been employed to understand this shape transition and its relation to structural dynamic symmetries as well as to the underlying microscopic structures, proton–neutron interaction and to the role of neutron pairing. Despite thorough spectroscopic studies of these nuclei their masses are known rather poorly.

The comparison between the cyclotron frequency of an unknown ion with the frequency of a well-known reference ion will allow a precise mass determination as described in Chapter 2.1. Fig. 7 illustrates a typical TOF versus frequency spectrum measured for one of the studied isotopes, ^{92}Br. The experiments recently completed at JYFLTRAP have produced precise masses for over 80 neutron-rich isotopes, as shown in Fig. 8. The most neutron-rich nuclides of the studied isotope chains are presently ^{83}Ge, ^{92}Br, ^{97}Rb, ^{100}Sr, ^{101}Y, ^{105}Zr, ^{110}Mo, ^{111}Tc, ^{114}Ru, ^{118}Rh

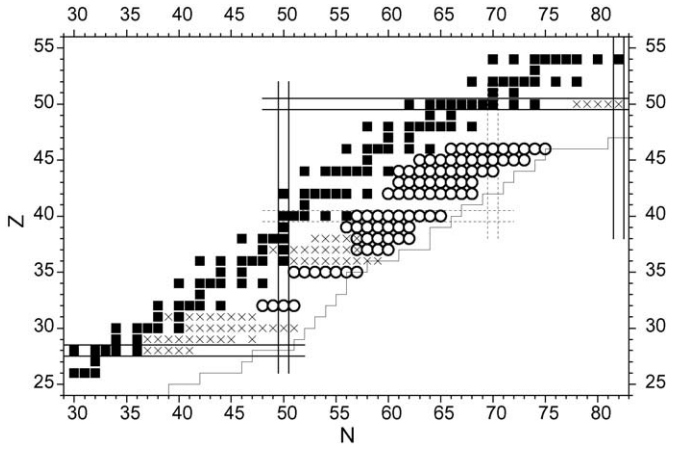

Fig. 8. Neutron-rich fission products whose masses have been recently measured by the ISOLTRAP (crosses) and JYFLTRAP (circles) mass spectrometers with precision of 10^{-7} or better. The experiments cover about 130 new masses. Most of these masses have not been published yet, but are in progress to be published within the coming year.

and ^{121}Pd. The data for the Sr, Zr and Mo isotopes have been submitted for publication recently. Together with the latest data from ISOLTRAP the knowledge of masses of fission products has been increased by more than 130 new precise values.

The data obtained at JYFLTRAP represents the first direct mass measurements of these refractory-element isotopes. Published data with a similar precision are available only for a very few other mass chains of neutron-rich nuclei. These are the Rb–Sr isotopes [30], Ni–Cu–Ga isotopes [31], Zn (Kluge et al., personal communications) and Kr and Sn isotopes [32] studied at the ISOLTRAP facility [33] of CERN. With the exception of ^{99}Sr new data show that neutron-rich Sr, Zr and Mo nuclei are significantly less bound than the tabulated values in the "Atomic mass evaluation 2003" [34]. The experimental values for the most neutron-rich isotopes studied can differ by as much as 1 MeV from the extrapolated values given in Ref. [34].

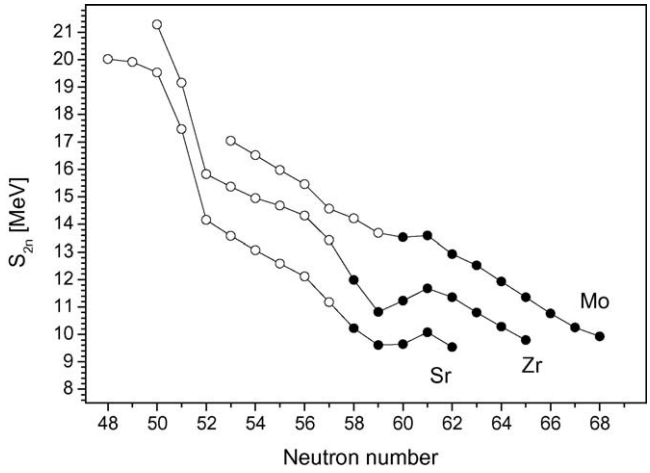

Fig. 9. Two-neutron separation energies for medium-mass fission products as recently measured by JYFLTRAP. Filled symbols are based on the new data from JYFLTRAP. All experimental errors are within the size of the symbols used.

New precision data provides the possibility to study the evolution of the two-neutron separation energy as a function of the neutron number (see Fig. 9). The data, which is still preliminary for Br, Rb, Tc, Ru, Rh and Pd isotopes, indicates a dramatic change in the behaviour of S_{2n} for Sr and Zr isotopes between $N=58$ and 60 which coincides with the known change of structure (deformation). This behaviour is still observable in the Rb and Mo isotope chains, thanks to the current precise data. Contrary to this, a smooth and almost linear behaviour of the experimental curves beyond $N=60$ indicates stability in the structure of these nuclei. This is in accordance with the prediction in the liquid drop model context, where such behaviour is produced by the asymmetry term only [35].

5. Laser ion source for IGISOL

The insensitivity of the ion guide to an element's chemistry has been essential to many of the spectroscopic studies made at JYFL. However, this property can become a disadvantage when working on rare isotopes very far from the line of stability, because the mass-separated beam may contain isobars of other elements produced with far greater abundances. In order to improve and extend the studies on exotic isotopes as highlighted in this paper a laser ion source project, FURIOS, has commenced which will provide improved isobaric purity and higher efficiency without compromising the universality and fast release inherent in the IGISOL system. Several techniques are being developed. One will be similar to the laser resonance ionization ion guide concept, IGLIS [7], where pulsed lasers produce ions within the gas cell volume. A second method will use counter-propagating lasers to selectively ionize atoms after they have flowed out of the gas volume, within a radio frequency guide located immediately after the ion guide. By repelling any non-neutral fraction at the entrance to the RF guide, any produced ion transported to the extraction and acceleration stage of the mass separator is guaranteed to be a resonantly produced ion and extremely high selectivity can be achieved. Full operation of this facility is keenly awaited.

6. Conclusions

JYFLTRAP coupled to the IGISOL facility is now fully operational and the first physics results on studies of exotic nuclei far from the valley of beta stability, using the novel ion manipulation instrumentation coupled to the IGISOL facility are very promising. The precision and sensitivity of experiments on rare radioactive isotopes have been improved by several orders of magnitude, allowing for experiments that could not have been thought of 5 years ago. As examples of these achievements, one can mention the high-precision mass measurements of short-lived isotopes with a precision better than 10^{-8} and laser spectroscopic measurements of rare radioactive isotopes of refractory elements.

It has been shown the JYFLTRAP can be employed also as a very high-resolution mass separator for decay spectroscopy. Its suitability for in-trap electron spectroscopy and for reaction yield(s) measurements by direct ion counting has been demonstrated.

A successfully initiated mass measurement program at JYFLTRAP has shown that accurate mass measurements are possible also for short-lived exotic isotopes of refractory elements. At IGISOL these measurements will be continued and can cover more than 200 neutron-rich nuclides produced in fission. These experiments will provide a novel way of studying the connections between the mass surface and nuclear structure far from the valley of beta stability.

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