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Ion manipulation and precision measurements at JYFLTRAP

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Abstract. Various ion manipulation tools based on ion trapping technologies have been implemented at the IGISOL-facility in JYFL. An RFQ ion cooler and buncher is used to enhance the sensitivity of collinear laser spectroscopy and as an injector to the Penning trap. Penning traps are utilized both in nuclear spectroscopy and for precision mass measurements, as explained in the paper. Atomic masses of neutron-rich Zr, Mo and Sr isotopes were found to be in disagreement with the Atomic-Mass Evaluation and two-neutron separation energies imply strong nuclear structure effects at the neutron number $N = 60$.

PACS. 07.75.+h Mass spectrometers – 21.10.Dr Nuclear structure: Binding energies and masses – 27.60.+j Properties of specific nuclei listed by mass ranges: $90 \leq A \leq 149$

1 Introduction

The mass of the ground state of a nucleus results from the structure of a complex quantum system. Therefore, an accurate determination of the nuclear mass surface can provide additional information compared to those obtained from excited states, such as the underlying symmetries and microscopic features like charge symmetry of nuclear interaction, shell effects, coexisting structures, pairing effects, spin-orbit interaction, and so forth. For this to be successful, measurements and theory have to be able to probe fluctuations in the order of 1 to 100 keV. Global correlations are typically variations due to closed shells and broad areas of deformation where the required accuracies in mass measurements are typically of the order of 100 keV. However, detection of local correlations such as those due to the presence of closed shell discontinuities, the local zones of deformation or those due to configuration mixing or shape mixing require mass accuracies preferably of the order of 10 keV [1].

Among neutron-rich nuclei, the binding energy data comes usually from beta endpoint measurements, since application of reaction studies is limited, although an advent of new radioactive ion beam facilities will partly change the situation. It is therefore of importance to perform direct mass measurements on neutron-rich side of the nuclide chart. In this paper we report on mass measurements applying ion trapping technologies in the Department of Physics in the University of Jyväskylä (JYFL).

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2 Ion manipulation in JYFLTRAP

An Ion Guide Isotope Separator On-Line (IGISOL) technique was developed more than twenty years ago at JYFL. Since then it has been applied in variety of spectroscopic studies both in Jyväskylä but also in different laboratories all over the world. For comprehensive compilation of past studies see [2].

In this study we have employed the fission reaction of ^{238}U induced by 30 MeV protons with typical intensity of a few μA. Due to its symmetric mass division, a proton-induced fission is well suited for the production of medium mass neutron-rich nuclei in the transitional Zr-Pd region.

Refractory elements are considered to be difficult cases for conventional ion sources. In the IGISOL-technique neither chemical nor physical properties affect the ionization efficiency. All reaction products recoiling out from the target are stopped in noble buffer gas, where they end up as singly-charged ions after numerous charge-exchange processes. Neutral buffer gas and singly-charged ions are rapidly transported out from the stopping volume through a small exit hole. An immediate differential pumping section with stepwise acceleration removes neutral atoms while ions are accelerated to 30 keV energy. For recent developments in the IGISOL-separator at JYFL see [3].

2.1 Radiofrequency ion cooler and buncher

Due to the rather large energy spread and the modest emittance of the ion beam extracted from the ion guide, a gas-filled radiofrequency quadrupole (RFQ) was introduced in to the beam line system [4]. Its main task is

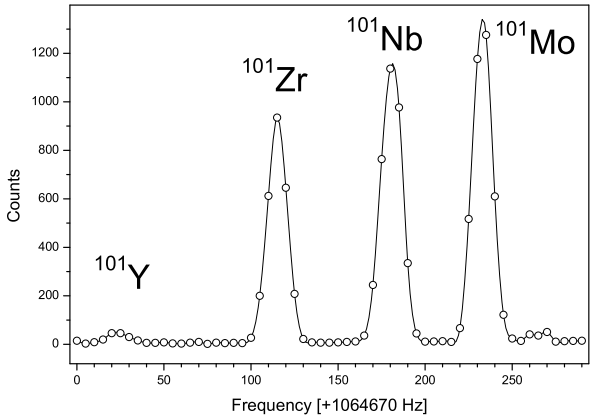

Fig. 1. Isobaric separation in the purification trap.

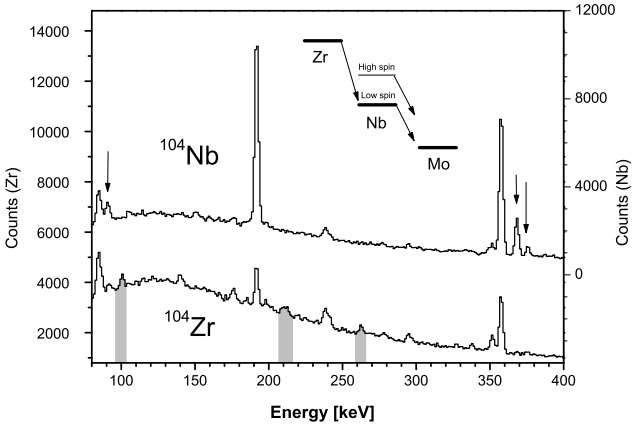

Fig. 2. Beta-gated gamma spectra obtained at $A = 104$ with mass purification favoring ^{104}Nb (an upper graph) or ^{104}Zr (lower graph). Shaded areas illustrate gamma-transition belonging to the beta decay of ^{104}Zr. Arrows point to gamma-lines belonging to the beta decay of high-spin isomer of ^{104}Nb.

to provide cooled and bunched beams for all experiments requiring improved ion optical properties. It has remarkably increased the sensitivity of the collinear laser spectroscopy by reducing Doppler broadening of optical resonances due to the smaller energy spread and by increasing signal-to-noise ratio due to the bunched structure of the ion beam [5]. The former leaves the resonance line shape dominated by the natural atomic line width and the latter allows gated photon detection synchronized by the arrival of the ion bunch suppressing the non-resonant background by a factor of $\sim 10^4$. The RFQ is also an ideal tool for bunched injection to the Penning trap system [6].

2.2 Tandem Penning trap

The ion trap installation at JYFL combines two Penning traps installed inside the warm bore of a single superconducting solenoid with a magnetic field of 7T. The magnet has been shimmed to provide two trapping sections, the first with magnetic homogeneity $\Delta B/B \sim 10^{-6}$ in one cm^3 and another with $\Delta B/B \sim 10^{-7}$. These regions are located in the center of the magnet 20 cm apart from each other. The first region is used for the isobaric purification and the second one for precision measurements [7].

2.3 Purification trap

An example of the scanning of the quadrupole excitation frequency over wide range is shown in fig. 1. By fixing the radial excitation frequency it is possible to remove other ions while the wanted ones are centered in the trap and transported to the precision trap [8]. The typical mass resolving power in the purification trap is $M/\Delta M \sim 10^5$.

A possibility to isobarically clean the ion sample provides an additional tool for conventional nuclear spectroscopy. In a recent decay study we have applied an isobaric purification in the decay study of ^{100,102,104}Zr. An example of mass purified γ-spectra obtained at $A = 104$ and in coincidence with β's is shown in fig. 2.

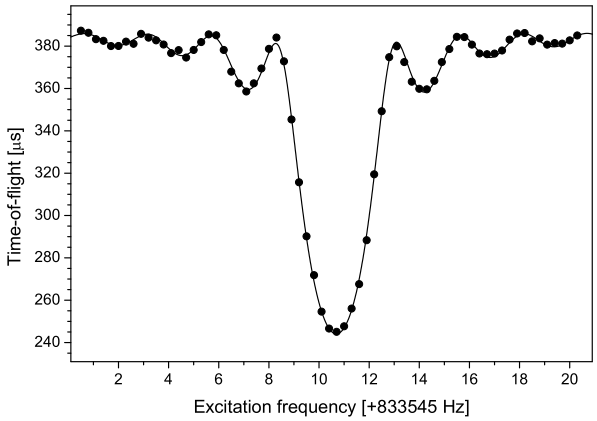

Fig. 3. A time-of-flight resonance obtained with the stable ^{129}Xe ions from the cross beam ion source.

2.4 Precision trap

In the precision trap, ions are first moved out from the center of the trap to larger radius and then resonantly excited with a quadrupole field. As a result, ions in resonance with the excitation frequency gain radial energy. While the ions are moving out from the magnetic field, the radial energy is transferred to axial energy in the field gradient. Thus the resonantly excited ions gain more axial energy and correspondingly their time of flight from the ion trap to the detection setup outside of the trap is shorter [8]. A reduction in the time of flight can be seen in the resonance curve, which is exemplified in fig. 3 for ^{129}Xe ions.

3 Mass measurements of refractory fission products

After the successful commissioning of the full trapping facility, we have performed systematical studies to characterize the optimum experimental conditions as well as to

learn about systematic uncertainties. Most of these studies have been performed with an ion beam from a cross beam ion source or by using nuclides with well-known mass produced on-line. Such a preparatory work is needed for a reliable evaluation of the data obtained in on-line mass measurements in unexplored regions of the nuclide chart.

Our first mass measurements of exotic nuclei were performed for isotopic chains of Zr, Mo and Sr isotopes produced in fission. During these measurements, the reference ion ^{97}Zr was obtained from fission in conditions similar to those for the unknown masses. The statistical uncertainties related to these measurements were of the order of a few keV at maximum and systematic errors taken into account in similar manner than described in [9]. Systematic errors considered in the analysis were the following.

- The uncertainty of the mass excess of ^{97}Zr, which was chosen as a reference for all measurements, was taken from the Atomic-Mass Evaluation table AME03 [10], $ME(^{97}\mathrm{Zr}) = (-82946.6 \pm 2.8)$ keV. This uncertainty does not affect the uncertainty of the frequency ratio $x = \frac{\omega_{c,\mathrm{ref}}}{\omega_{c,\mathrm{meas}}}$, but only that of the mass excess.
- The uncertainty related to magnetic field fluctuations was deduced using all measurements of ^{97}Zr done during the run. From this, the fluctuation of the cyclotron frequency due to magnetic field variations could be estimated to result in an uncertainty of about $4 \cdot 10^{-8}$ of the frequency ratio x, corresponding to about ± 4 keV in this mass region.
- A large number of ions in the precision trap can cause the measured cyclotron frequency to shift due to ion-ion-interactions in the trap. In order to reduce this effect, it was attempted to keep the countrate below 20 ions per bunch after purification. When necessary, the beam intensity was reduced by inserting slits of variable opening before the RFQ. The countrate effect had been examined during a previous online run using ^{58}Ni. For the countrates used in this experiment, it was found to give an uncertainty of ± 0.1 Hz on the measured frequency. In a separate measurement for ^{99}Sr, the countrate was lower resulting in an estimated uncertainty of ± 0.05 Hz.
- Another possible source for errors is the mass difference between the measured ion and the reference ion. An estimation for the mass dependent uncertainty could be obtained during an offline measurement by comparing the measured frequencies for ^{132}Xe and O_2-molecules. The uncertainty was found to be $\frac{x_{\mathrm{exp}} - x_{\mathrm{AME}}}{x_{\mathrm{AME}}} = 7 \cdot 10^{-10}(m - m_{\mathrm{ref}})$, with x_{AME} being the frequency ratio calculated from mass table values.

3.1 Systematic errors

3.2 Preliminary results

In fig. 4 we show a typical resonance curve obtained for the reference ion and examples of resonance curves obtained for ions whose masses have been measured for the first time in this experiment.

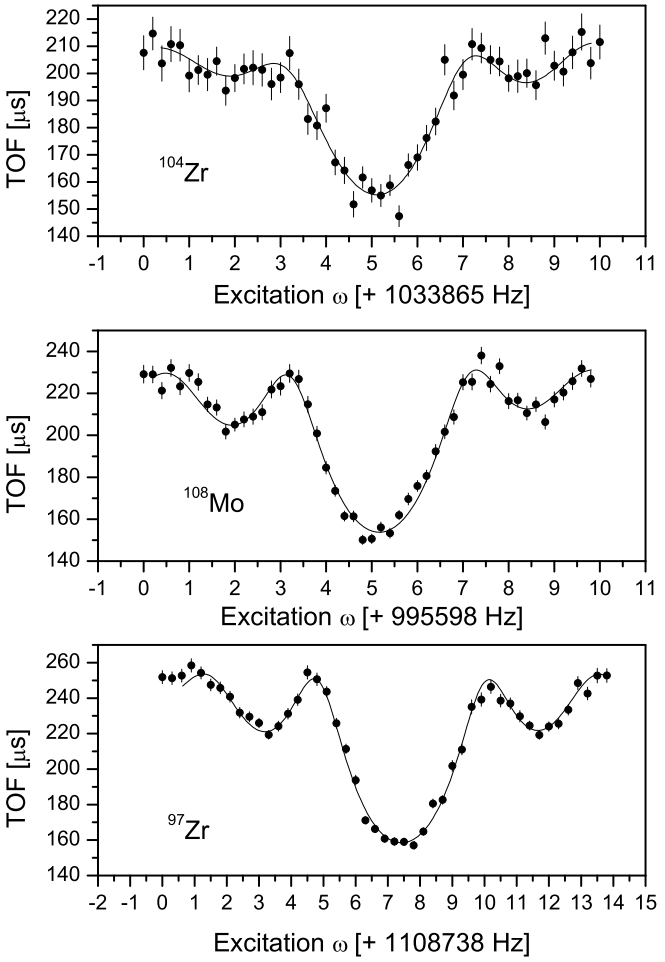

Fig. 4. TOF-resonance for reference ion ^{97}Zr and for measured ions ^{108}Mo and ^{104}Zr.

The mass excess data obtained in this measurement will be given in more detail in [11], but in this paper we show the comparison to AME2003 [10] for Zr isotopes, see fig. 5. It clearly shows a good agreement in less exotic nuclei where tabulated values originate from reactions and are rather precisely known already. Another observation is a noticeable deviation of the measured masses from the tabulated ones when moving further from the stability. There the old values are based on the long chains of beta endpoint measurements.

Apart from the mass excess it is of interest to derive the two neutron separation energies S_{2n}. The two-neutron separation energy is a useful quantity to extract information on local correlations of the binding energy surface. In fig. 6 we show two-neutron separation energies for Zr isotopes. This plot reflects clearly the change of deformation on S_{2n} at $N = 58$–60.

4 Conclusions

Our first set of precision measurements in neutron-rich nuclei illustrates two facts. Firstly, the old data found in the literature and entering to AME, can often be

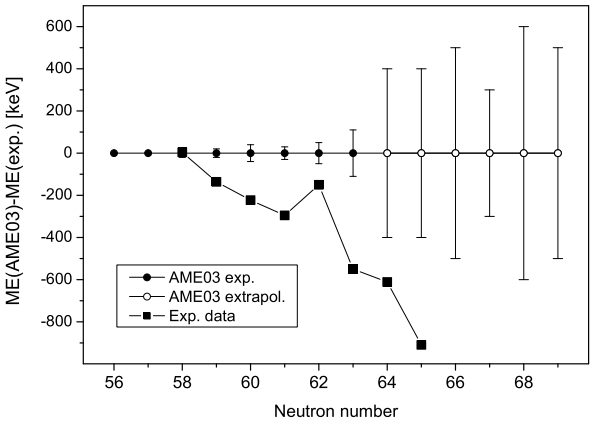

Fig. 5. Comparison of the experimental mass excesses and AME2003 [10] values for Zr isotopes. Error bars in the baseline corresponds to uncertainty of AME2003 values. Solid circles are tabulated values based on the experimental data and open circles corresponds to those isotopes, whose AME2003 value is based on the extrapolation as described in AME2003 [10].

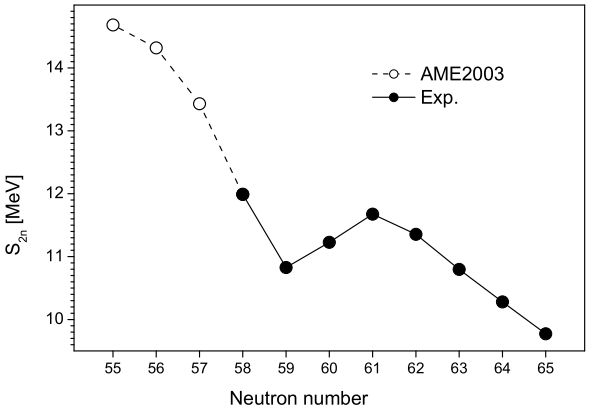

Fig. 6. Two-neutron separation energies for Zr isotopes. Errors of individual points are of the size of the symbol.

erroneous. Secondly, by taking a closer look at the mass surface around ^{100}Zr, we have observed a clear indication of nuclear structure correlation. By combining new data to those obtained with laser spectroscopy studies and comparing to modern theoretical models, the observed correlations can be traced to nuclear deformation effects.

The IGISOL facility has been upgraded recently and we have inititated a project to construct a laser ion source based on the ion guide method. With these improvements together with an optimization of the trap, precise mass measurements have a promising future at the IGISOL facility in coming years.

With an easy access to neutron-rich nuclei, also for refractory elements, we will extend these studies to selected areas in the element range of $Z = 28$–50, *i.e.* between two closed proton shells. In addition to systematical mapping of the mass surface, these studies will shed light on many nuclear physics questions, like binding in the vicinity of the doubly magic ^{78}Ni, nuclear structure effects at $N = 60$, possible magicity of ^{110}Zr and shell-quenching while approaching $N = 82$.

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