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ABSTRACT

A mass spectrometer has been set up at the on-line isotope separator ISOLDE at CERN, Geneva. Mass-separated radioactive ions are stored in a Penning trap. Their mass is determined by a measurement of the cyclotron frequency in the magnetic field of a superconducting magnet. A resolving power of up to 300.000 and a precision of some 10 keV were determined in case of mass measurements of neutron-deficient Rb and Cs isotopes. The resonance of the isobars ^{88}SR and ^{88}Rb were clearly resolved and evidence was obtained for an isomer in ^{122}Cs.

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INTRODUCTION

Masses of nuclei far from stability are key input parameters for nuclear models and serve as test for nuclear-mass predictions needed in astrophysical calculations. Until now, precise direct mass determinations are restricted to the valley of stability or its direct neighbourhood[1]. Far away from this valley nuclear binding energies are measured indirectly by means of mass differences obtained as Q values from nuclear decays or reactions. The only exceptions up to now are a series of direct mass measurements on alkali isotopes performed by the Orsay group at ISOLDE by means of a Mattauch-Herzog spectrometer[2,3] and very recently performed time-of-flight experiments at Los Alamos[4] and GANIL[5,6] on light isotopes.

Mass measurements of heavier isotopes far away from stability by a determination of Q values suffer from errors introduced by summing up the errors of the many mass differences which link the mass of the isotope under investigation to that of a well known mass and, in addition, from uncertainties due to an insufficient knowledge of the nuclear level schemes of nuclei far away from stability. Hence, a method is very desirable where the masses are directly determined, i.e. independently of the knowledge of level schemes and masses of neighbouring isotopes. This can be achieved by measuring the cyclotron frequency of ions stored in a Penning trap. Such a system which can be loaded with ions delivered from an on-line isotope separator has been developed at Mainz and recently

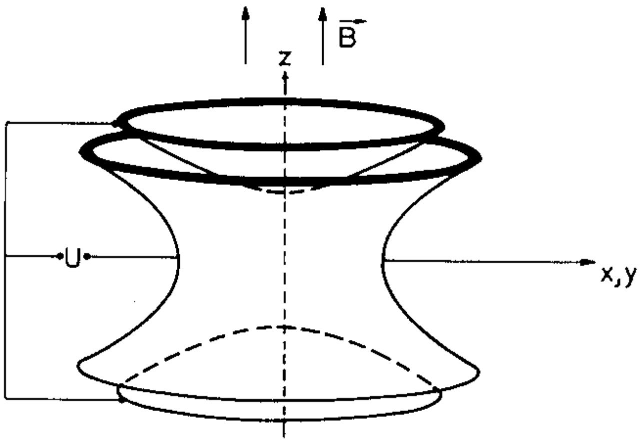

Figure 1: Scheme of a Penning trap. The shapes of the electrodes are hyperbolical with rotational symmetry around the z axis which is also the direction of the magnetic field.

installed at the ISOLDE facility at CERN[7]. First test measurements were carried out on *Rb* isotopes in December 1986 at the ISOLDE facility at CERN/Geneva[8,9], where the isobars ^{88}Sr and ^{88}Rb were resolved. In June 1987 further tests were done with neutron-deficient *Cs* isotopes. The results are reported in this contribution. Evidence was obtained for the first resolution of an isomeric state in a direct mass measurement.

PRINCIPLE OF THE MASS MEASUREMENTS AND EXPERIMENTAL SET-UP

Particles with charge e and mass m perform a cyclotron motion in a homogeneous magnetic field B given by

$$\omega_c = (e/m)\,B. \tag{1}$$

In order to achieve a high resolving power $R = \nu_c/\Delta\nu_c$, the cyclotron frequency ν_c should be as large and the line width $\Delta\nu_c$ as small as possible. According to the uncertainty priciple the ultimate line width depends on the coherent interaction time T_{RF} with the applied radio frequency field ($\Delta\nu_c \simeq 1/T_{RF}$). Hence, it is straightforward to use a Penning trap (Fig. 1) in the magnetic field of a superconducting magnet because it combines long confinement time with maximum ν_c.

A combination of static, magnetic and electric fields is used to establish a three-dimensional trapping potential[10,11]. Due to the presence of an electrostatic field, the cyclotron frequency is modified. Nevertheless the undisturbed cyclotron frequency ν_c can be measured by inducing a two-quantum transition[12]. In resonance the trapped ions gain energy out of the applied radio frequency (RF) field. This is detected by a time-of-flight (TOF) method[13]: The charged particles are ejected out of the trap, drift to a channel plate detector (MCP) and their TOF is determined. The mean TOF as a function of the RF shows a resonance which gives the mass of the stored ions (Fig. 2).

The ion storage technique has not yet been used in nuclear physics for the study of short-lived nuclei. The reason is an experimental difficulty: The ions investigated so

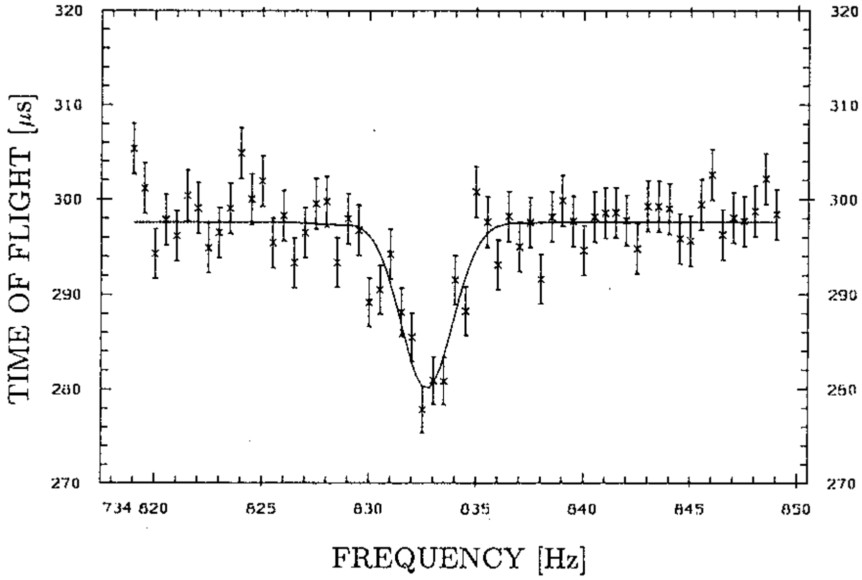

Figure 2: Cyclotron resonance of ${}^{124}Cs$ ($T_{1/2} = 30.8\,s$) as obtained by the mean time of flight as a function of the frequency of the applied RF field.

far in an ion trap were generally created inside the trap. However, in case of the study of short-lived isotopes these rare species have to be produced outside the trap and then guided with high efficiency into the trap. We have developed and tested a technique which allows to capture in-flight a bunch of ions in a Penning trap. Details can be found in Ref. 14.

The experimental set-up for the mass measurements is shown in Fig. 3. It is connected with a beam-line at the on-line separator ISOLDE/CERN and has a tandem configuration. A Penning trap in an electromagnet is used to collect the ions after reionization from a Re foil in which the ISOLDE ion beam is implanted. The ions are transfered into a second Penning trap installed in the 5.7 T field of a superconducting magnet. Here, the measurement of the cyclotron frequency takes place. Details are given in Ref. 14.

MASS MEASUREMENTS AND PERFORMANCE

The first test experiments with radioactive isotopes have only be performed recently and concerned neutron-deficient *Rb* and *Cs* isotopes, which are produced at ISOLDE with high yields up to 10^{11} mass-separated ions per second and mass number[7]. The isotopes with the shortest half life investigated were ${}^{124}Cs$ ($T_{1/2} = 30.8\,s$) and ${}^{122}Cs$ with $T_{1/2} = 4.2\,min$ and $21.0\,s$. The aim of these experiments was to check the performance of the apparatus under the realistic conditions of a beamtime at an on-line isotope

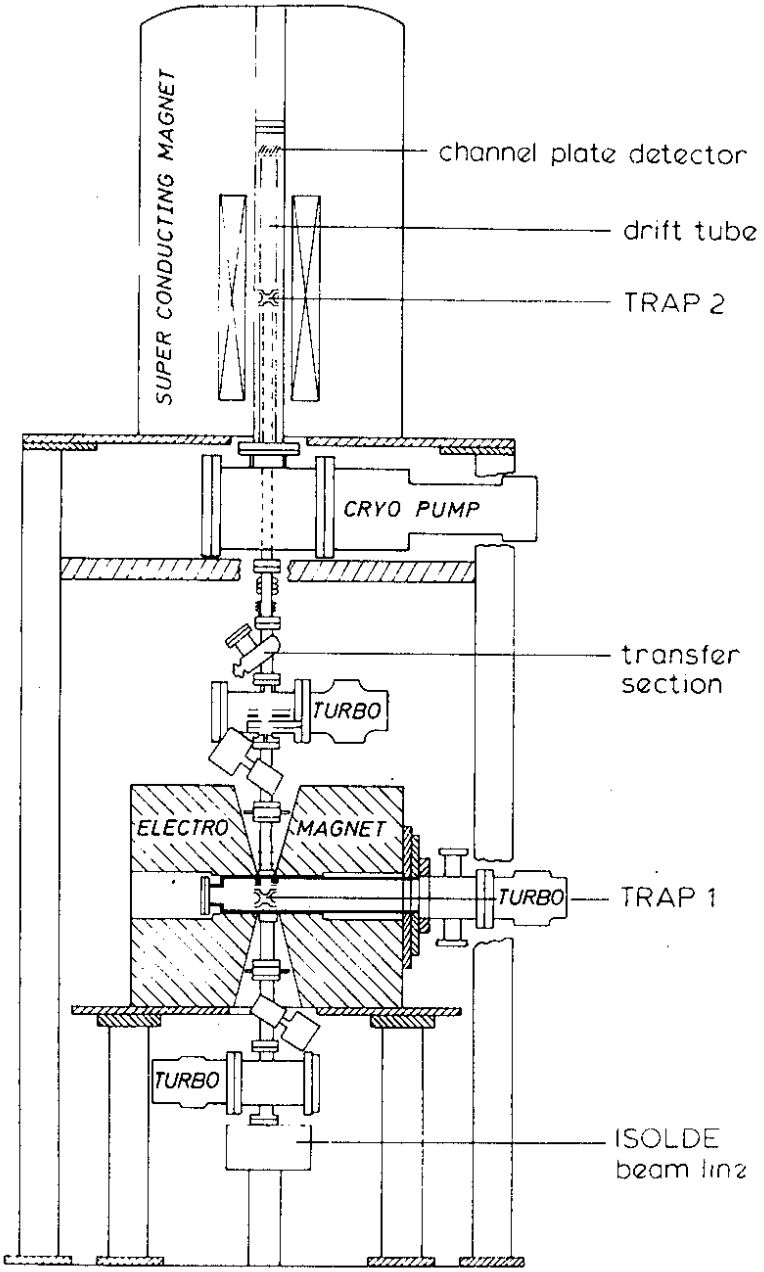

Figure 3: Experimental set-up used for direct mass measurement of radioactive isotopes at the on-line isotope separator ISOLDE at CERN. Trap 1 acts as a bunching device for the continuous 60 keV ion beam delivered by ISOLDE. The bunch of 1 keV ions extracted out of trap 1 is transfered to and captured in-flight in trap 2 where the mass measurement takes place. After inducing the radiofrequency the ions are ejected out of trap 2 and time-differentially counted by the channel plate detector.

separator. The results given below were obtained during a 2-days run in December 1986 ($^{77,78,85,86,88}Rb$ and ^{88}Sr) and a 8-hour run in June 1987 ($^{122,124,125,127,135,136}Cs$). A further test run is scheduled for September 1987.

Up to now the following performance has been achieved:

Trapping Efficiency: Up to 70 % of an ion bunch ejected out of trap 1 can be retarded and captured in-flight in trap 2. More details are given in Ref. 14.

Sensitivity: Typically 50 ions were stored in trap 2 at a time for the measurement of the cyclotron frequency. Since the detection scheme for the resonance by TOF is destructive, the trap has to be refilled after each cycle. The cycle time is about 1 s. Minimum 10^4 to 10^5 stored and detected ions are required for a resonance curve with sufficient statistics. Hence one mass measurement typically takes 30 *min* to 1 *hour*. The overall efficiency was determined to be $\varepsilon = 5 \cdot 10^{-6}$ defined as the ratio between the number of ions implanted into the foil of trap 1 to those detected by the MCP. Since the trapping efficiency for a bunched ion beam in trap 2 is up to 70 %, the main losses are clearly due to evaporation, ionization, trapping and ejection in the bunching trap 1. Much better efficiencies will be obtained if a laser ion source is installed at the on-line mass separator which directly delivers a pulsed ion beam[15] or the continuous beam of the on-line separator is bunched in a Paul trap as proposed and tested by one of us (R.B.M.).

Storage Time: The storage time of trap 2 has been determined to be $\tau \simeq 15\,min$ for Cs ions at a vacuum pressure of $p \leq 10^{-9}\,mbar$.

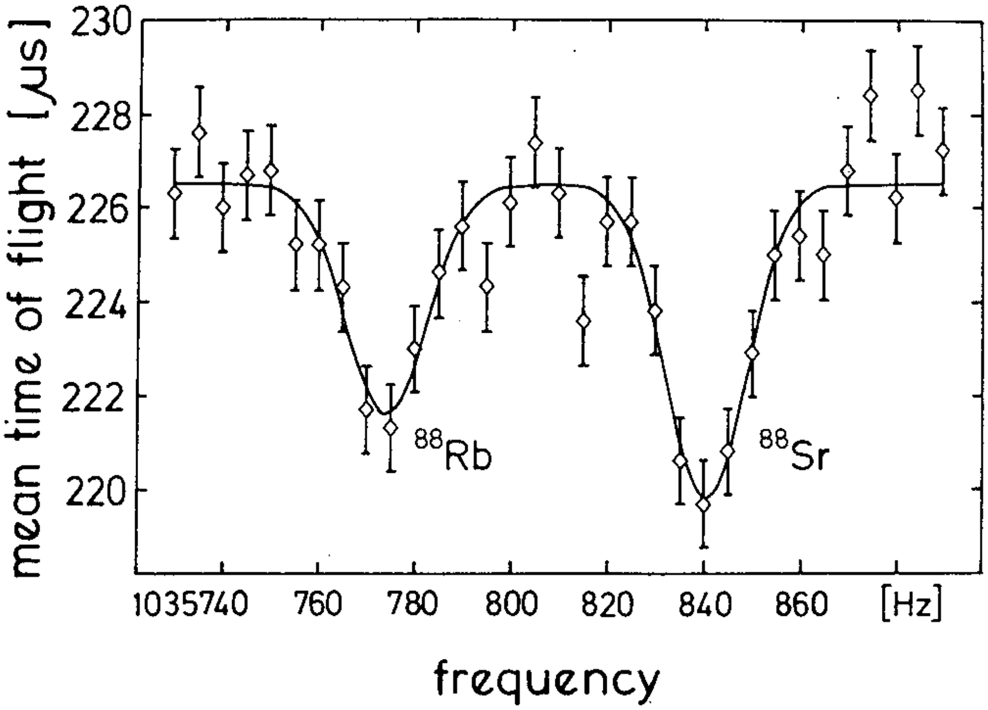

Figure 4: Simultaneously recorded cyclotron resonance of the isobars ^{88}Rb and ^{88}Sr which have a mass difference of 5.3 MeV. The power-broadened line width is due to higher RF power used during this measurement.

Resolution: A resolving power of $3 \cdot 10^5$ for K and Cs has been achieved in the on-line experiments. This corresponds to 130 keV and 440 keV and allows to resolve the cyclotron frequencies of isobars and in many cases also of isomers. Very recently, test experiments with stable ^{133}Cs yielded a resolving power of 760 000 corresponding to a $FWHM = 180\,keV$. Fig. 4 shows the signal obtained for the isobars $^{88}Rb/^{88}Sr$ which have a mass difference of 5.3 MeV. Both were produced at ISOLDE with comparable yields and cannot be separated by the ISOLDE mass separator. Although the resonances are broadened to $FWHM = 20\,Hz$ by RF power broadening they are clearly resolved owing to the still high resolving power of the Penning trap technique.

The Orsay group has investigated a number of isomeric states in neutron-deficient Cs isotopes by laser spectroscopy[16]. The same group could not resolve in their mass experiments[2,3] the ground and isomeric states. We have observed in a measurement at $A = 122$ a broadened structure (Fig. 5), which can be fitted by two Gaussians with center frequencies differing by 3 Hz (500 keV), line widths of 2.7 Hz and heights of 3 and 6 %. Two half-lives are known for ^{122}Cs ($T_{1/2} = 4.2\,min$ and $T_{1/2} = 21.0\,s$). The signals of Fig. 5 were obtained by starting the experiment immediately after collection of the $A = 122$ ions on the foil. If the start of the experiment was delayed by some minutes, the resonance at lower frequency disappeared and we observed only one resonance with a line width of about 2 Hz and a height of the typical magnitude of 7 %. Hence, there is strong evidence that we have resolved the resonances of the ground and isomeric states for the first time in a mass experiment. Due to lack of beam time, the measurement could not be repeated in June 1987.

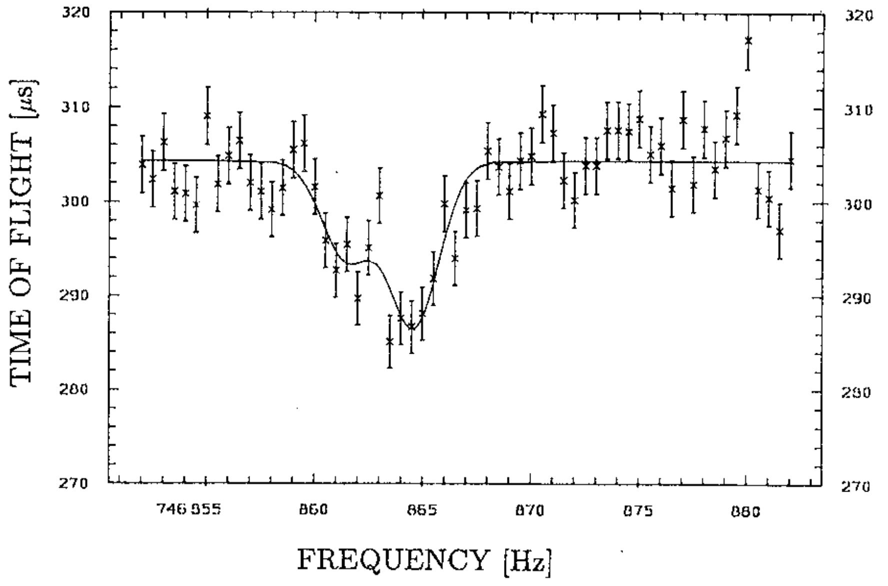

Figure 5: Mean time of flight of ^{122}Cs ions as a function of applied RF frequency. The resonance at lower frequency (higher mass) is attributed to the $T_{1/2} = 21$ s isomer.

Accuracy: The statistical uncertainty of the centroid of the resonances is about 5 % of the line width corresponding to $\Delta\nu_c/\nu_c \leq 2{\cdot}10^{-7}$ or 20 keV for ions with mass number $A = 100$. The magnetic field at the place of trap 2 is repeatedly measured by the determination of the cyclotron frequency of a stable alkali isotope. In test experiments with those reference isotopes it was found that the ratios of the cyclotron frequencies coincide with the tabulated mass ratios within the statistical uncertainties. However, sometimes there are jumps by 0.3 to 0.5 Hz (60 to 80 keV) in the resonance frequencies between groups of consistent data. The reason is not known until now but presumably due to changing magnetic fields in the environment at the ISOLDE/synchro-cyclotron site. Similar results were obtained in case of the test experiments with short-lived isotopes. In almost all cases the masses determined by the Penning trap technique coincide with the Orsay results within one standard deviation. It should be noted, however, that the accuracy of the Penning-trap results are more or less the same for all isotopes independent of the distance from the valley of stability. The errors of the Orsay experiments[3] are a factor of 2 smaller near stability ($A \geq 127$), comparable at $A \simeq 125$ and a factor of 2 to 3 larger at $A \leq 124$.

CONCLUSION

We were able to demonstrate that the Penning-trap technique is well suited to mass measurements far away from the valley of stability. After calibration of the magnetic field the masses are measured in an absolute way without the necessity of knowing the masses of neighbouring isotopes. The high resolving power of the technique enables to avoid problems and uncertainties by the isobaric impurities of on-line beams and even allows to separate resonances of isomers and groundstates. The accuracy of the technique is better than 100 keV for $A \simeq 100$ and sufficient for tests of nuclear models by masses of nuclei far from stability.

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