FIRST ABSOLUTE MASS MEASUREMENTS OF SHORT-LIVED ISOTOPES

G. Bollen, P. Dabkiewicz^{*)}, P. Egelhof, T. Hilberath, H. Kalinowsky,
F. Kern, H. Schnatz, L. Schweikhard and H. Stolzenberg
Institut für Physik, Universität Mainz, Mainz, Fed. Rep. Germany

R. B. Moore
Foster Radiation Laboratory, McGill University, Montreal, Canada

H.-J. Kluge
CERN, Geneva, Switzerland
and Institut für Physik, Universität Mainz, Mainz, Fed. Rep. Germany

G. M. Temmer^{**)}, G. Ulm^{***)}
and
the ISOLDE Collaboration
CERN, Geneva, Switzerland

^{*)} Present address: Technische Universität, Hamburg-Harburg,
Fed. Rep. Germany

^{**)} Senior US Scientist Awardee, Alexander von Humboldt Foundation.
Permanent address: Nuclear Physics Laboratory, Rutgers University,
New Brunswick, N.J., USA

^{***)} Present address: Physikalisch-Technische Bundesanstalt, Berlin,
Fed. Rep. Germany

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ABSTRACT

Absolute mass measurements of short-lived isotopes have been performed at the on-line mass separator ISOLDE at CERN by determining the cyclotron frequencies of ions confined in a Penning trap. The cyclotron frequencies for $^{77,78,85,86,88}\text{Rb}$ and ^{88}Sr ions could be determined with a resolving power of 3×10^5 and an accuracy of better than 10^{-6} , which corresponds to 100 keV for mass $A = 100$. The shortest-lived isotope under investigation was ^{77}Rb with a half-life of 3.7 min. The resonances obtained for the isobars ^{88}Rb and ^{88}Sr were clearly resolved.

1. Introduction

The aim of the experiment is to extend systematic high-precision measurements of nuclear masses to nuclei far from the valley of β stability. The mass as a fundamental bulk property represents a key input parameter for nuclear-matter calculations. Until now, direct precise mass determinations were restricted to the valley of stability or its immediate vicinity. 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 exception so far was a series of direct mass determinations on alkali isotopes performed by the Orsay group [1,2] using a Mat- tauch-Herzog spectrometer.

This paper reports on the first absolute mass measurements of short-lived isotopes which do not require the mass measurement of neighbouring isotopes and are deduced from frequency ratios. The experiments were performed at the on-line isotope separator ISOLDE at CERN in Geneva [3]. The principle of our method is to determine the cyclotron frequency in a known magnetic field while the isotope under investigation is stored in a Penning trap. Until now, this method has only been applied to light and stable particles [4,5]. Furthermore, we were able to load the Penning trap with ions from the outside world [6], whereas in earlier experiments the ions were created inside the trap.

2. Experimental procedure and set-up

The experimental set-up is shown in fig.1. The apparatus is directly connected to one of the vertical beam lines of ISOLDE. It consists of a Penning trap (trap 1) placed in the pole gap of an electromagnet, a transfer line with a number of electrostatic lenses and deflectors, a Penning trap (trap 2) placed in the stable ($10^{-8}/d$) and homogeneous ($10^{-7}/\text{cm}^3$) field of a superconducting magnet, a drift tube, and finally a channel-plate detector. The first trap is essentially a bunching device for the continuous 60 keV ion beam of the ISOLDE mass separator. The second trap is used for high-precision measurements of the cyclotron resonance. In this latter trap ultra-high vacuum, excellent homogeneity of the magnetic field and perfect geometry are essential. These requirements could be fulfilled with the chosen tandem trap configuration which is described in more detail in ref. [6].

2.1 Trapping the ions from ISOLDE

In order to confine the ions from the ISOLDE ion beam in trap 2, the ions coming from below the apparatus are stopped on a rhenium foil placed in the lower end cap of trap 1. After collecting a sample the foil is turned and heated for 500 ms by a d.c. current to temperatures of 1400 °C. The re-evaporated and surface-ionized ions are trapped and stored for 100 ms. In a following step the potential applied to the ring electrode is increased by a pulse so that the ions are ejected from trap 1 as a bunch. After leaving the trap the ion bunch is accelerated to 1 keV

by some electrodes. A system of electrostatic lenses guides the bunch into the fringe field of the superconducting magnet in such a way that the radial energy is not increased. This is most important for the mass measurements, where a very small energy spread of the trapped ions is required. In trap 2 the ion bunch is captured in flight after it has been retarded to a few eV before entering the trap. Figure 2 shows schematically the capture process of the ions. The potential of the lower end cap of trap 2 is switched to the potential of the ring electrode of this trap before the ion bunch arrives. When the ions pass the centre of trap 2, the potential of the end cap is raised again and the ions can no longer escape. Now the ions, which can be stored for periods exceeding 10 s, are available for mass spectrometry.

2.2 Determination of the cyclotron frequency

The mass of the ions is determined by a measurement of the cyclotron frequency of the stored ions in the homogenous magnetic field of trap 2. In order to measure this frequency, a radio-frequency (RF) field is applied to the trap for 200 ms. The ions are then ejected from the trap and allowed to drift to the channel-plate detector. During resonance the trapped ions have gained radial energy from the applied RF field. When drifting through the inhomogeneous part of the magnetic field this radial energy is transferred into longitudinal energy. This leads to a reduction of the time of flight (TOF) of the ions needed to drift from trap 2 to the channel-plate detector [4]. Figure 3 shows this reduction in the TOF for the case of ^{39}K ions. The figure shows the TOF spectra for these ions on- and off-

resonance with the RF field. The two spectra correspond to the points indicated in fig. 4, which shows the mean TOF of the potassium ions as a function of the applied RF.

3. Mass measurements

At the on-line mass separator ISOLDE, neutron-deficient Rb and Sr isotopes are produced with a maximum yield of 10^{11} ions per second from a Nb powder target with a tungsten ionizer. The yield curve shown in fig. 5 is obtained from our own measurements and earlier results [7].

In the test experiment reported here, the cyclotron frequencies for the isotopes $^{77,78,85,86,88}\text{Rb}$ and ^{88}Sr could be determined. As an example, fig. 6 shows a resonance curve obtained in the case of ^{77}Rb . The mean TOF is plotted as a function of the frequency of the applied RF field. At resonance the TOF is reduced by about 7%. A least-squares fit to this curve yields a value of 1,183,621.91(40) Hz for the centre of the resonance curve and a half-width of 3.74(63) Hz (FWHM). This leads to a resolving power of 3×10^5 and an energy resolution of 220 keV for mass $A = 77$. Since these measurements were performed as recently as December 1986, the data on the other isotopes are still under evaluation but will probably yield similar results [8]. By calibration of the magnetic field with the measured cyclotron frequency of 2,336,969.24(18) Hz for ^{39}K (fig. 4) one obtains an atomic mass of 76.930,270(27) u, corresponding to a mass excess of -64954(25) keV for ^{77}Rb . The quoted errors correspond to the accuracy with which the centres of the resonance curves are determined. The meas-

ured mass excess agrees fully with the adopted value of $-64950(40)$ keV [2] and leads to a relative deviation of the mass values of 6×10^{-8} . This is in agreement with earlier test measurements on stable Rb and Cs isotopes. For comparison all these values are listed in table 1, which also contains the cyclotron frequencies for ^{39}K used to calibrate the magnetic field.

About 10^{11} ions from ISOLDE were used in order to obtain the data of the curve shown in fig. 6. From this sample, 3×10^4 ions were detected by the channel-plate detector. Hence an overall efficiency of the apparatus of 3×10^{-7} is determined. This value differs from those obtained in earlier test measurements [6] by a factor of about 300. The reason for this discrepancy is presumably a slight misalignment of the apparatus. Because of this low efficiency we were limited in the last run in our investigation of shorter-lived isotopes. The shortest-lived isotope that could be measured is the case discussed earlier of ^{77}Rb with a half-life of 3.7 min.

The resonances for the isobars ^{88}Rb and the stable ^{88}Sr have been measured in order to demonstrate the capability of the method used. These isobars were produced with comparable yields (fig. 5) and cannot be separated by the ISOLDE mass separator. Figure 7 shows the simultaneously recorded resonances for the two isobars, which have a mass difference of 5.3 MeV. Although the resonances are broadened to about 20 Hz FWHM owing to RF power broadening they are clearly resolved owing to the still high resolving power of the Penning-trap technique.

4. Conclusion

We were able to demonstrate that the Penning-trap technique is well suited to mass measurements far 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 resolving power of 3×10^5 corresponds to mass differences of about 250 keV for mass $A = 80$. This is high enough to separate the resonances of most isobars and therefore to avoid problems and uncertainties caused by the isotopic impurities of on-line ion beams. At the moment the line width of the cyclotron resonances is broader than expected. Presumably this is due to a residual inhomogeneity of the magnetic field. Compensating this inhomogeneity one can further increase the resolving power and separate even the resonances of ground and isomeric states. The precision actually achieved of better than 10^{-6} enables mass measurements far from stability with an accuracy better than 100 keV for mass $A = 100$.

Bringing the efficiency of our apparatus back up to the value already obtained we will be able to investigate isotopes produced with much lower yields and with half-lives of the order of seconds. Furthermore, isotopes can be investigated which are not produced directly by an on-line isotope separator but obtained as daughters in the nuclear decay. This can be achieved by allowing the parent isotope to decay on the foil. The restriction of the method to the investigation of surface-ionizable elements can be overcome in future by the use of new techniques for bunching ion beams. Such techniques are already being tested [10,11] or are under development [12]. Then, the Penning-trap method would be the most general technique for mass spectrometry of nuclei far from stability with very high resolution, precision, and sensitivity.

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Figure Captions

- Fig. 1 Experimental set-up used for the absolute mass measurements of Rb and Sr isotopes at the on-line isotope separator ISOLDE at CERN.
- Fig. 2 Principle of trapping an ion bunch in-flight in a Penning trap. The electrical potential along the magnetic-field axis is sketched.
- Fig. 3 Time-of-flight spectra obtained for ^{39}K ions in and out of resonance with the applied RF field. The spectra correspond to the indicated points (a,b) in fig. 6.
- Fig. 4 Cyclotron resonance of ^{39}K ions as obtained by the mean time of flight as a function of the frequency of the applied RF field. This resonance has been used to calibrate the magnetic field.

Fig. 5 Yield curve of Rb and Sr isotopes produced at the on-line isotope separator ISOLDE at CERN. In the actual experiment the yield of Sr ion beams is reduced by almost 3 orders of magnitude by lowering the temperature of the target and the ion source.

Fig. 6 Cyclotron resonance of ^{77}Rb ions as obtained by the mean time of flight as a function of the frequency of the applied RF field. The resolving power is 3×10^5 . The indicated points a and b correspond to the time of flight spectra shown in Fig. 3.

Fig. 7 Simultaneously recorded cyclotron resonances of the isobars ^{88}Rb and ^{88}Sr which have a mass difference of 5.3 MeV. The increased line width is due to RF power broadening which occurred during this measurement.

TABLE 1

Accuracy and resolution of the mass measurements of ^{77}Rb and of stable alkali masses measured earlier¹.

ISOTOPE	ν_c [Hz]	$\delta\nu_c/\nu_c$ [10^{-7}]	FWHM/ ν_c [10^{-7}]	$(\nu_c - \nu_c^{\text{lit}})/\nu_c^{\text{lit}}$ [10^{-7}]
^{39}K	2313616.9	1.3	13	-
^{85}Rb	1061648.0	4.5	32	3.3
^{87}Rb	1037248.4	2.2	30	2.3
^{133}Cs	678273.3	2.5	47	0.2
^{39}K	2336969.2	0.8	37	-
^{77}Rb	1183621.9	3.4	32	0.6

¹ The table gives the following quantities: the measured cyclotron frequencies ν_c , the accuracy $\delta\nu_c/\nu_c$ of the determination of the centre of the resonance curve by a least-squares fit and the resolution defined as the ratio of FWHM and ν_c . The last column indicates the reliability of the mass measurement by giving the difference between the measured ν_c and ν_c^{lit} calculated from data given in the literature and divided by ν_c^{lit} . For the stable isotopes the masses given in ref. [9], and for ^{77}Rb that in ref. [2] were used to calculate ν_c^{lit} . The cyclotron frequencies for ^{39}K were determined to measure the magnetic field. The data of ^{39}K to ^{133}Cs were taken beginning 1986, the $^{39}\text{K}/^{77}\text{Rb}$ data in December 1986.

Fig. 1

Fig. 2

Fig 3

frequency

Fig. 4

Fig. 5