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IN - FLIGHT CAPTURE OF IONS INTO A PENNING TRAP+

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Abstract: A bunched beam of alkali ions with a pulse length of about 10 μs and an energy of 1 keV has been retarded electrostaticaly and captured in flight in a Penning trap. A trapping efficiency of up to 70% has been determined. Subsequently the cyclotron resonance was induced. In case of K a line width of the resonance of 4 Hz was measured at a resonance frequency of 2.3 MHz. This enables mass determinations of unstable nuclei produced at on-line mass separators with an accuracy in the sub-ppm region.

1. Introduction

Storing of ions in an ion trap [1] offers a number of important advantages: The trapped particles are almost at rest in space, confined in a small volume, essentially free of any undesired perturbation, and at hand for almost infinite times. Hence the confinement in a trap is idealy suited for precision spectroscopy. In the past many experiments made use of the ion trap technique for the investigation of stable isotopes and led to a variety of high-precision experiments [2]. These experiments include laser spectroscopy on single ions [3], [4], accurate mass measurements [5], [6], ultra-high resolution microwave spectroscopy [7], and the determination of the g factors of the electron and positron [8] which represents the most accurate fundamental constant known today.

The ion storage technique has not yet been used in nuclear physics for the study of nuclear properties as for example the determination of masses and moments of short-lived nuclei. The reason is an experimental difficulty: All ions investigated so far in an ion trap were created inside the potential well produced by the quadrupole field. However in case of the invesigaton of short-lived isotopes these rare species have to be produced outside the trap, cooled, eventually mass separated and then guided with high efficiency into a trap.

In this paper we report on the first in-flight capture of ions in a Penning trap. Simultaneously and independently Alford et al. [9] have achieved to capture bunches of cluster ions in a similar device which will allow detailed spectroscopy on stored clusters. The in-flight capture of charged particles is also an essential ingredient of two recent proposals to measure the inertial [10] and the gravitational [11] mass of the antiproton.

This letter concentrates on the aspect of the confinement of outside created ions in an ion trap, and the trapping efficiency. The final aim of our investigations is to extend systematic high-precision measurements of the nuclear mass to nuclei far away from the valley of β stability. The mass represents as a fundamental gross property a key input parameter for nuclear matter calculations. Until now, precise direct mass determinations are restricted to the valley of stability or its direct neighbourhood. 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 until now is a series of direct mass determinations on alkali isotopes performed by the Orsay group [12], [13] at ISOLDE by means of a Mattauch-Herzog spectrometer.

The principle of our method is to measure the cyclotron frequency in a known magnetic field while the isotope under investigation is stored in a Penning trap [5].

2. Experimental procedure and setup

The experimental setup is shown in Fig.1. The apparatus consists of an alkali ion source, a Penning trap (trap 1) placed in the pole gap of an electro magnet, a transfer line with a number of electrostatic lenses and deflectors, a Penning trap (trap 2) placed in the stable and homogeneous 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 beam of the ion source. The second trap is used for high-precision measurements of the cyclotron resonance. Hence ultra high vacuum, excellent homogeneity of the magnetic field and perfect geometry of the trap are essential. Table 1 gives the relevant parameters of both traps. Since the operating conditions of the bunching trap are incompatible with those of the precision trap (see below), the layout of Fig. 1 was chosen with two completely separated traps connected only by a transfer tube (distance between the centers of the two traps = 166 cm). This configuration allows efficient differential pumping between trap 1 and 2 and the installation of electro-optical devices for steering the ion beam.

BUNCHING TRAP: Alkali ions delivered by the ion source are implanted into a tungsten foil mounted in one endcap of the Penning trap, then surface ionized by heating the foil, trapped [14], [15], and finally ejected by a sudden change of the trapping potential.

More elegant procedures for trapping a continuous ion beam have been proposed [16], [17], [11], but not yet realized. In any case our approach avoids severe technical problems like floating the whole apparatus on the potential of the ion source (i.e. 60 keV in case of ISOLDE) or building a RF buncher and decelerator.

In case of the test experiments with potassium ions the foil was heated for 250 ms. After another 250 ms the ions were ejected out of trap 1 as a bunch by raising the potential applied to the ring electrode to that of the endcaps. The bunching efficiency has been determined to 6×10^{-4}.

TRANSFER TUBE: 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. Extensive electro-optical calculations have been performed to find an optimum design [18]. This is most important for the mass measurements requiring a very small energy spread of the trapped ions. The transmission of the transfer tube has been determined to 80 % (including the transmission through the holes in the endcaps of trap 2). At the entrance of trap 2 the length of the bunch is shorter than 30 μs.

PRECISION TRAP: Here the bunched ion beam is captured in flight by retarding it to a few eV just before entering the trap. The potential of the lower endcap of trap 2 is switched to the potential of the ring electrode just at the moment the ion bunch arrives. When the ions pass the center of trap 2 the potential of the endcap is raised again and the ions can no longer escape. It has been determined that up to 70% of the ion bunch ejected out of trap 1 and transfered to the entrance hole of trap 2 can be trapped.

Fig.2 illustrates the bunching by trap 1 and the trapping efficiency of trap 2. Fig. 2a shows the time-of-flight spectrum of the ion bunch ejected from trap 1. The ions were guided through the holes of trap 2 to the channelplate detector on top of the apparatus. In this case the endcaps and the ring electrode were on the same potential. Hence no trapping effect can be expected. Fig.2b shows the distribution when the potential of the upper endcap of trap 2 was raised just before the majority of the ions were leaving this trap. In this case most of the ions were reflected and did not reach the detector. If the potential of the lower endcap was raised with a typical delay of 15 μs in respect to the voltage rise of the upper one, the ion bunch was trapped. The second peak in Fig.2c was obtained, when the potential of the ring electrode was pulsed with a further delay of 250 ms to eject again the stored ions. Changing the delay between trapping and ejec-

tion allows to determine a lower limit of the storage time. No change of the number of the trapped ions was observed at a maximum delay of 1.5 s. Fig. 2d shows the time-of-flight spectrum of K ions obtained after trapping for 250 ms.

CYCLOTRON RESONANCE: In resonance the trapped ions gain energy out of the applied radio frequency field. This is detected by a time-of-flight method described in Ref. [5]. Until now only the masses of light ions (e^-, p, ^{3}He) have been measured by this technique. In test measurements we extended the time-of-flight technique [5] to ions of noble gasses as heavy as ^{136}Xe created inside trap 2 by electron bombardement [19]. Fig. 3 shows a cyclotron resonance measured for potassium. These ions were implanted into the foil of trap 1, bunched in this trap and transfered to trap 2. The line width of the cyclotron resonance is 4 Hz at 2.3 MHz for the case of K. Hence a resolving power of 5×10^5 is achieved. Calibrating the magnetic field of trap 2 by ^{85}Rb, one obtaines agreement with the tabulated mass of K within 2×10^{-7} corresponding to an uncertainty of the K mass of less than 10 keV.

3. Discussion

We have demonstrated that a bunched ion beam can be captured in flight in a Penning trap with high efficiency. Using trap 1 for bunching an overall efficiency of 10^{-4} has been determined for K ions. This efficiency is defined as the ratio of the number of stored ions in trap 2 to the number of ions implanted initially by the ion source into the tungsten foil in trap 1. It can be expected that this efficiency can still be increased. Already without any further improvements the setup is well suited for the investigation of radioactive isotopes at on-line mass separators as ISOLDE, where maximum production rates of up to 10^{11} atoms per second and mass number are available. Far away from β stability the yields decrease. In this case the ion beam of the mass separator can be accumulated on the collecting foil in trap 1. Furthermore isotopes can be investigated which are not produced directly but obtained as daughters in the nuclear decay. This can be achieved by allowing the mother isotope to decay while it is implanted in the foil.

The technique will be applied first to measurements of nuclear masses of isotopes produced at the ISOLDE facility. At present the method is restricted to the investigation of ions which can be surface ionized. This limitation can be overcome by using ionization by electrons or photons. An alternative is to trap in flight ion beams which are already bunched in the ion source of the mass separator. Meanwhile studies are under way for a pulsed ion source using resonance ionization spectroscopy [20].

Finally it should be mentioned that there might be other interesting nuclear-physics applications of a superconducting solenoid with a large room temperature bore and an ion trap. Placing an annular γ detector around the

ion trap with a hole of sufficient radius for the spiralling β particles to escape, one achieves a γ spectrometer capable of measuring γ spectra with very high efficiency down to very low energy with very little background from β activity. By combining this with a β detector on the solenoid axis one achieves a very powerful β-γ coincidence spectrometer. Confinement of radioactive ions in a trap instead of implantation into a solid would avoid the scattering of β's from the mounting material leading to much cleaner low-energy regions of the observed spectra. Also, because the recoil energy of the nucleus in β decay is usually much greater than the holding potential of the Penning trap, it becomes feasible to do experiments in which this recoil is observed. Such experiments can remove ambiguities about the actual nuclei with which an observed β decay is associated. Furthermore by laser or RF techniques it would appear feasible to polarize the radioactive ions in a Penning trap for observation of angular correlations. Such measurements relate to the Gamow-Teller versus Fermi components in β decay and to possible tests of the CVC hypothesis.

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TABLE 1

Geometry and operating conditions of the traps used for bunching and in-flight capture of an ion beam

	Trap 1	Trap 2
Type	Penning trap	Penning trap
Purpose	bunching of continuous ion beam	Precision measurement of cyclotron resonance
Distance between endcaps	28.3 mm	11.3 mm
Diameter of entrance hole	5 mm	2 mm
Diameter of exit hole	5 mm	2 mm
Quadrupole potential inside trap	distorted by collecting foil	to be optimized by correction electrodes
Voltage between electrodes	8 V	8 V
Magnetic field	0.7 T	5.8 T
Inhomogeneity	~ 10^{-3} T/cm^3	< 10^{-7}/cm^3
Stability	~ 10^{-5} T/h	5×10^{-8} T/d
Vacuum	< 10^{-7} mbar	< 10^{-9} mbar
Pumps	turbo molecular	cryogenic and turbo molecular

Figure Captions

Fig. 1 Experimental set up for direct mass determination of externally created ions.

Fig. 2 Time-of-flight spectrum of potassium ions detected by the channel plate. (a) An ion bunch is ejected out of trap 1. No trapping potential is applied to trap 2. (b) As before but the potential of the upper endcap of trap 2 is raised when the ion bunch passes trap 2. Hence a large fraction of the ions are repelled by the potential applied to the upper endcap and do not reach the detector. (c) As before but with trapping potential applied to the electrodes of trap 2. After a delay of 250 ms the trapped ions are ejected out of trap 2. (d) High-statistics time-of-flight spectrum of K^+ ions after being captured in flight and confined in trap 2 for 250 ms.

Fig. 3 Cyclotron resonance of K ions as obtained by the mean time of flight as a function of the frequency of the applied rf-field. The resolving power obtained is 5×10^5.

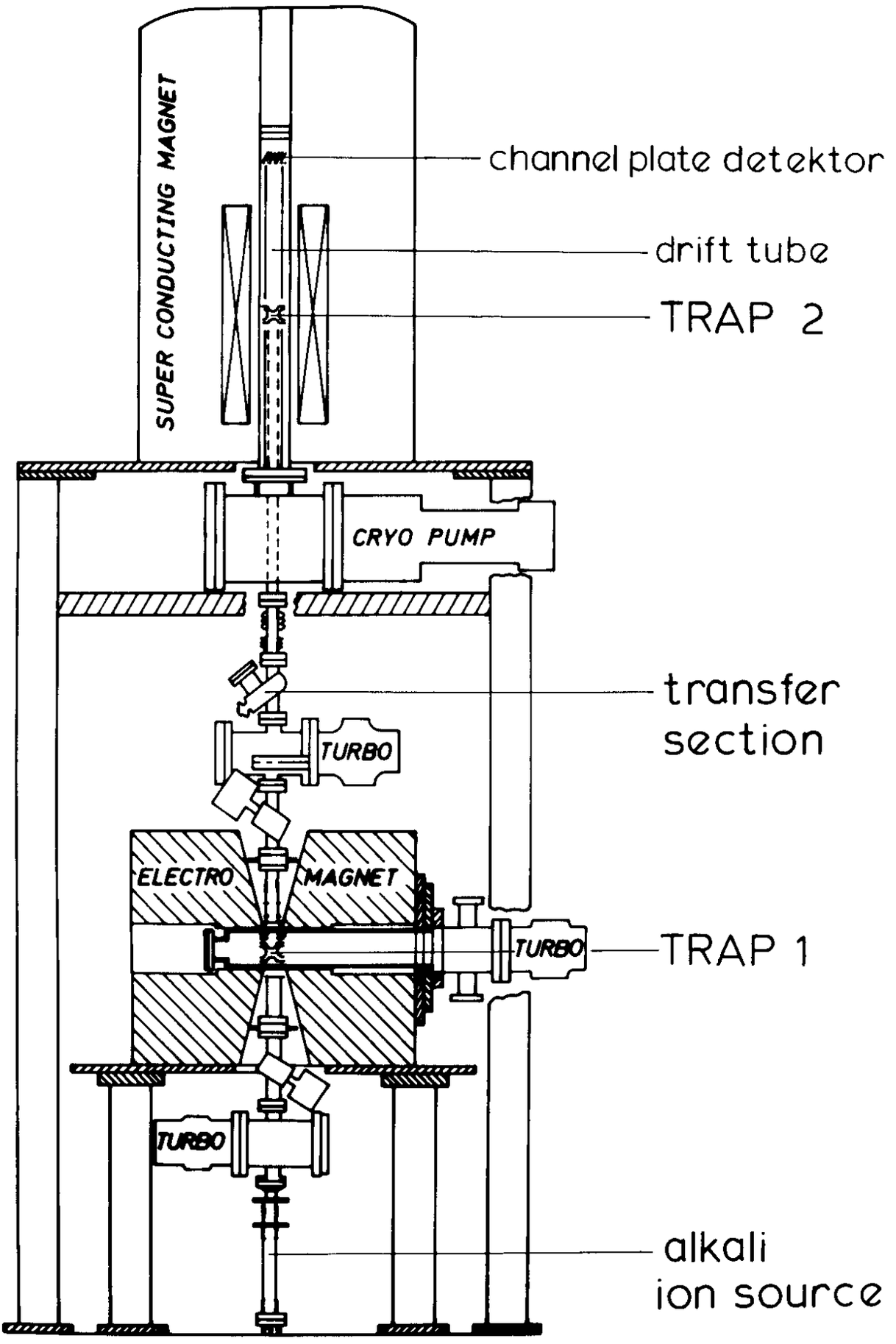
SUPER CONDUCTING MAGNET
channel plate detektor
drift tube
TRAP 2
CRYO PUMP
transfer section
TURBO
ELECTRO
MAGNET
TURBO
TRAP 1
TURBO
alkali ion source

Fig. 1

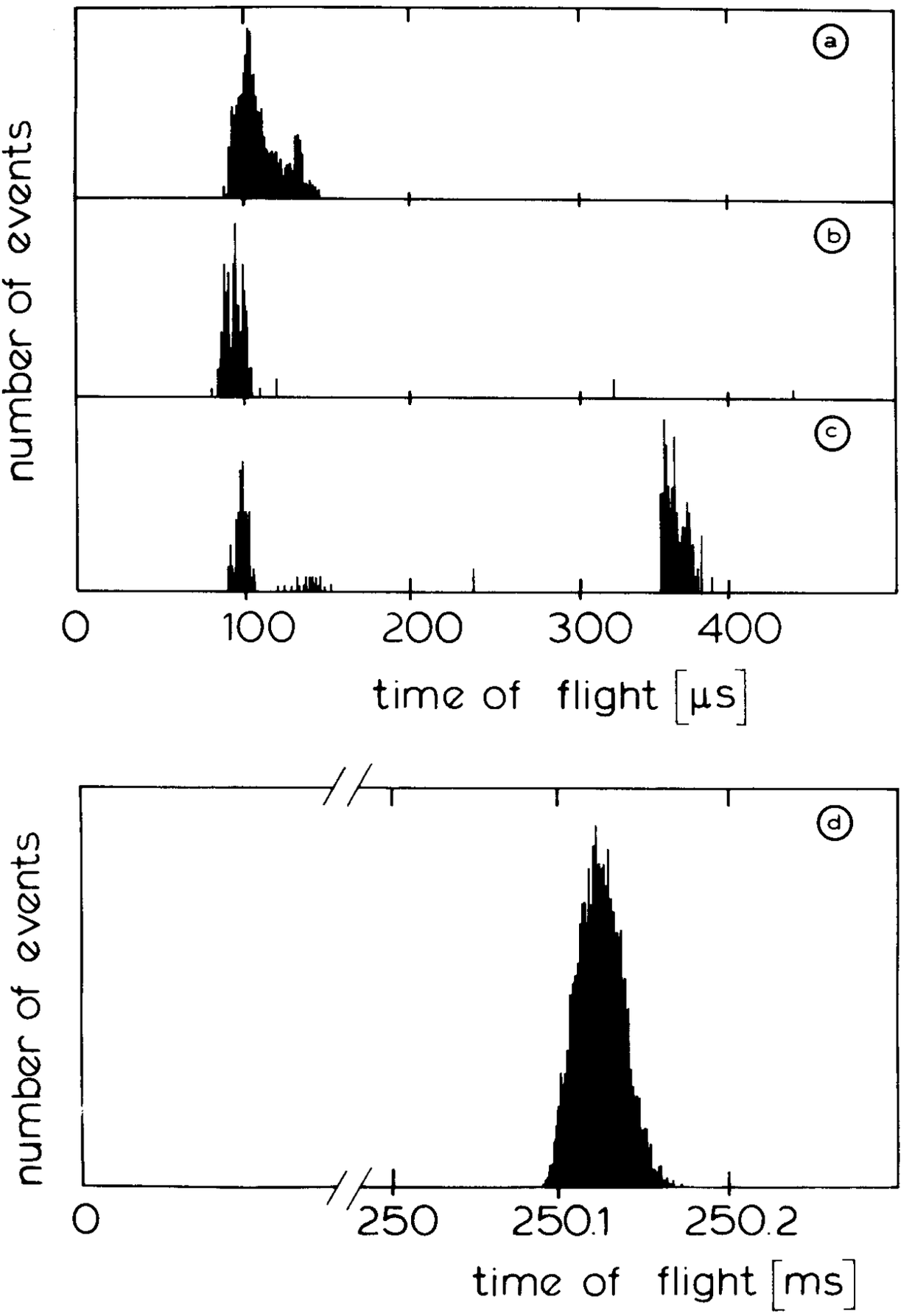
number of events
a
b
c
0
100
200
300
400
time of flight [μs]
number of events
d
0
250
250.1
250.2
time of flight [ms]

Fig. 2

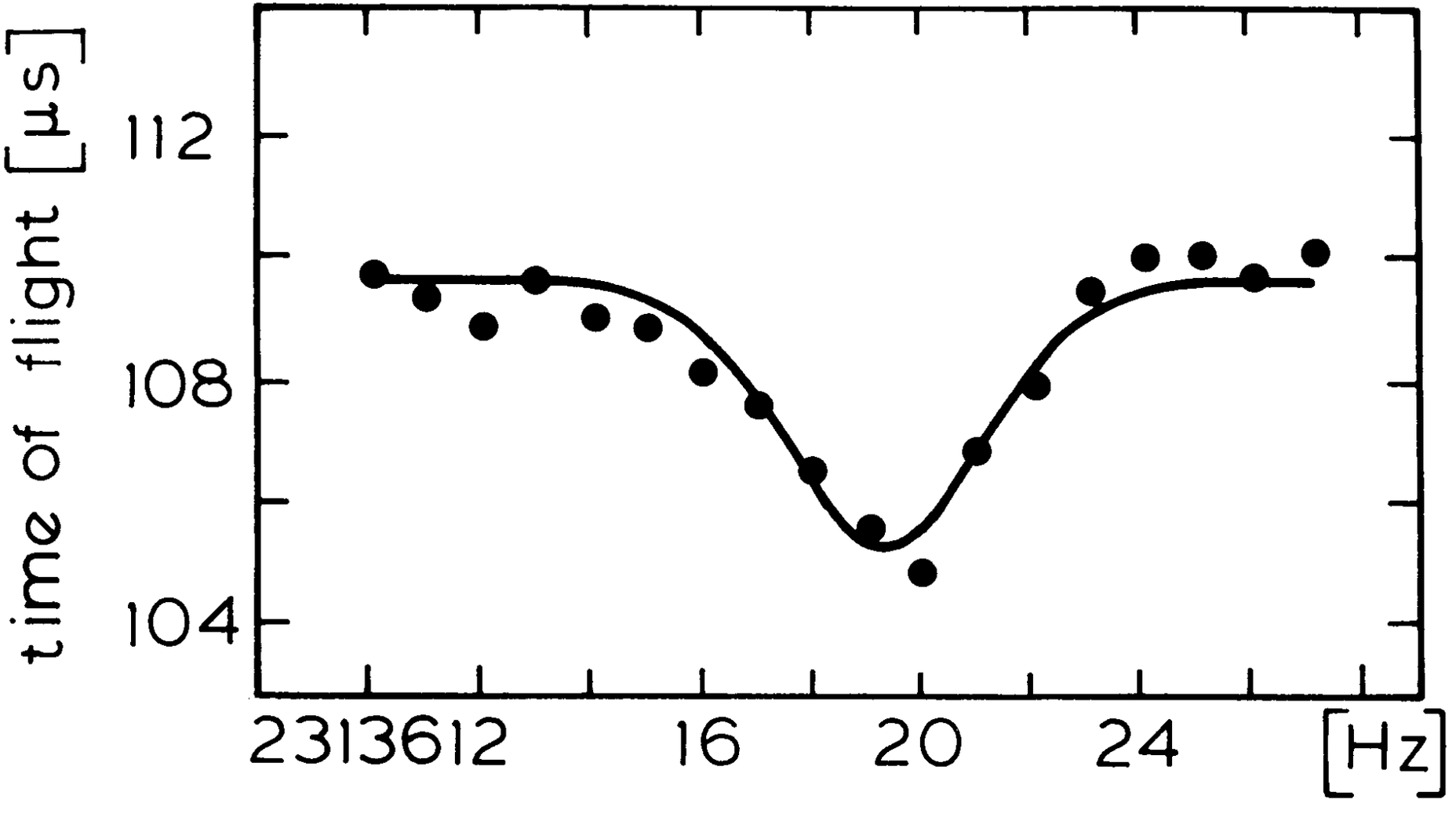
time of flight [μs]
112
108
104
2313612
16
20
24
[Hz]
cyclotron frequency

Fig. 3