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First investigation of phase-shifted Ramsey excitation in Penning trap mass spectrometry

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ABSTRACT

The excitation with time-separated oscillatory fields of the ion's cyclotron motion inside a Penning trap is used to improve the precision of mass measurements. In this work at TRIGA-TRAP the effect of a phase shift of the radio frequency field between the two Ramsey excitation pulses on the resulting ion-cyclotron-resonance time-of-flight line shape is investigated and compared with theoretical predictions.

1. Introduction

The mass and its direct connection to the binding energy reflects all forces between the nuclear constituents. Therefore, a precise knowledge of the mass is required in many physical applications with accuracies ranging from $\delta m/m = 10^{-5}$ down to $\delta m/m = 10^{-12}$ [1,2]. Penning trap mass spectrometers like TRIGA-TRAP [3] achieve high precision by converting the mass measurement into a frequency measurement of an ion's cyclotron frequency $\nu_c = qB/(2\pi m)$ with charge-to-mass ratio q/m, which is stored in the superposition of a strong homogeneous magnetic field B and a weak electrostatic quadrupole field V [4]. ν_c is in this case determined by the excitation of the ion's radial eigenmotions and the measurement of its time-of-flight to a detector outside the magnetic field [5]. The so-called time-of-flight ion-cyclotron-resonance (TOF-ICR) [6] is obtained by measuring the ion's time of flight as a function of the excitation frequency which is scanned around ν_c. The shape of the resonance curve depends greatly on time structure and phase between the excitation pulses. Thus, the influence of these parameters has to be examined systematically to optimize precision and to cancel out certain systematic errors.

In 1989, Ramsey received the Nobel Prize for the invention of the separated oscillatory fields method [7], which was used in Penning traps for the first time in 1992 for the excitation of the cyclotron motion [8,9]. Later on, the theoretical line shape of the corresponding TOF-ICR resonance was derived [10] and tested experimentally at different facilities with mass measurements of short-lived nuclides including a demonstration of an additional significant gain in precision compared to a continuous excitation, see, e.g. [11–14]. The effect of phase shifts in the oscillatory fields on molecular beams was already discussed by Ramsey in 1951 [15]. Experimental studies of the effect on ions in Penning traps and on the measured TOF-ICR line-shape which is theoretically addressed in [10] have not been performed yet. In this report, the results of experimental tests of the theory concerning phase shifts between the two rf pulses used to excite ions in a Penning trap are presented.

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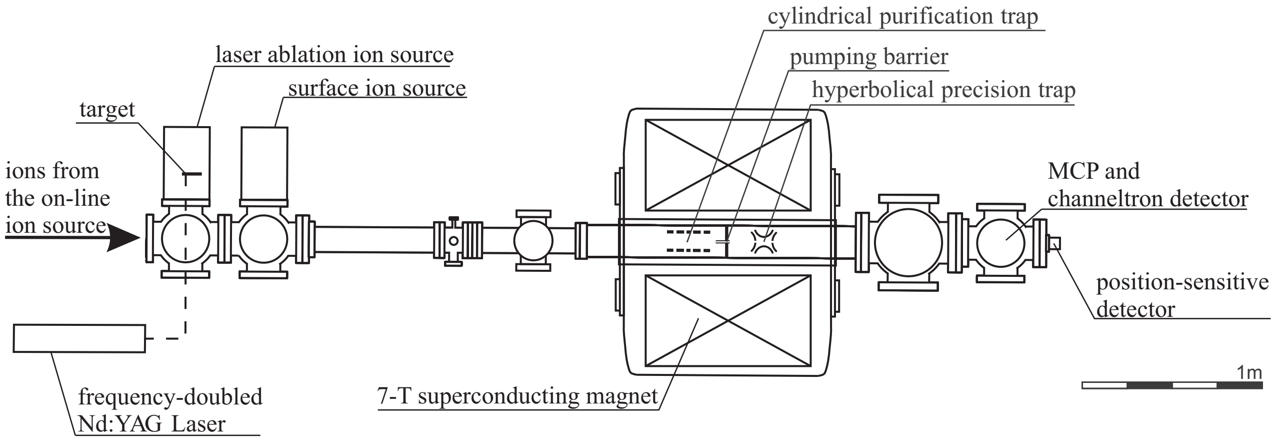

Fig. 1. Top view on the TRIGA-TRAP setup [3] with the ion sources on the left and the 7-T superconducting magnet with the two Penning traps in the middle. The detectors used for the time-of-flight ion-cyclotron measurement are on the right.

2. Experimental setup

The phase-shifted Ramsey excitation in a Penning trap was investigated at the double Penning trap mass spectrometer TRIGA-TRAP located at the research reactor TRIGA Mainz. TRIGA-TRAP is part of the TRIGA-SPEC experiment dedicated to determine ground-state properties of short-lived radioactive nuclides at the research reactor TRIGA Mainz [3]. A sketch of TRIGA-TRAP is presented in Fig. 1. The short-lived radionuclides are extracted from the reactor using a gas-jet system [16], which is connected to an ECR ion source [17]. Furthermore, two off-line ion sources are available: a surface ion source for alkali ions and a non-resonant laser-ablation ion source for the production of carbon cluster ions $^{12}C_n^+$ $(7 \leq n \leq 24)$ used for calibration purposes [18]. The latter was used for the studies presented here. Also other stable and sufficiently long-lived isotopes can be ionized with the laser-ablation ion source which was used for the first mass measurement at TRIGA-TRAP on ^{197}Au [19].

The ions are injected into the first trap placed inside a 7-T superconducting magnet where q/A selection is carried out by means of mass-selective buffer-gas cooling [20]. For this, the motional amplitude of all ions is increased with a mass-independent dipolar excitation of the magnetron motion. Subsequently, the desired ions are centered in the trap by a mass-dependent quadrupolar excitation and transported to the second trap through a differential pumping barrier [21]. The actual mass measurement is performed by the destructive TOF-ICR technique [6]. Therefore, the ions are resonantly excited by dipolar and quadrupolar rf fields inside the second trap to convert their magnetron motion into cyclotron motion. Afterwards, they are ejected to a microchannel plate (MCP) or channeltron electron multiplier detector (CEM) [22] outside the magnetic field. On their flight path to the detector, the ions are accelerated in axial direction due to the interaction of their motional magnetic moment with the magnetic field gradient.

3. The Ramsey excitation technique

In general the ion motion was excited continuously for a time τ with a constant amplitude (see Fig. 2a)(top). The conversion prob-

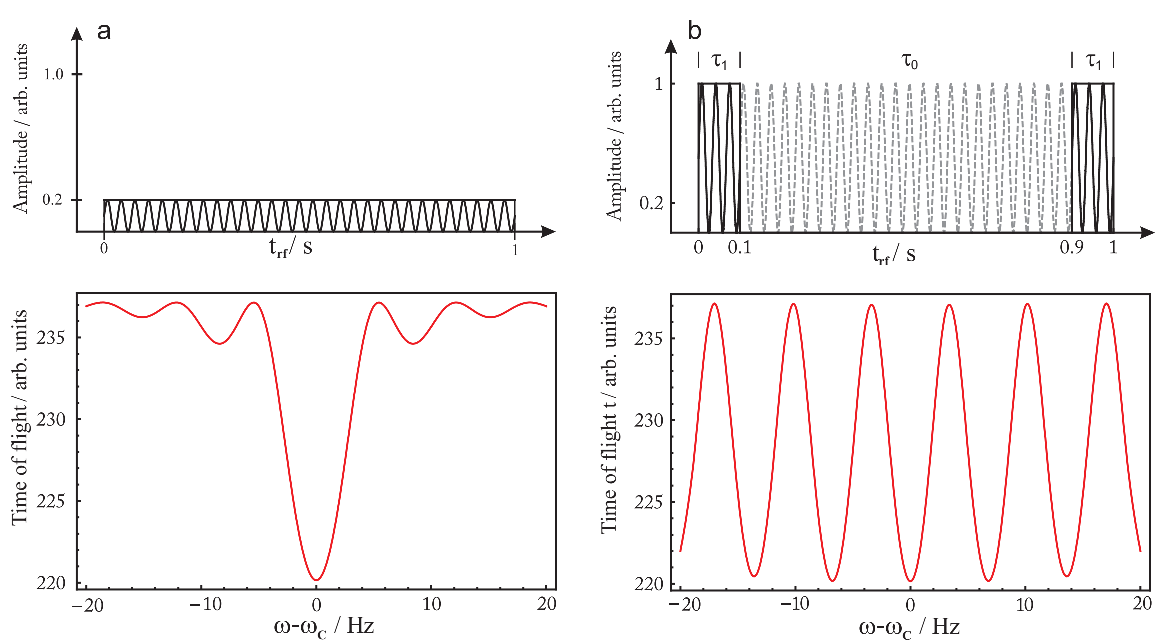

Fig. 2. Typical excitation schemes and the resulting time-of-flight resonances. (a) Continuous excitation for 1 s. (b) Ramsey excitation with τ_0 = 800 ms waiting time and two excitation pulses of τ_1 = 100 ms length. The dashed line between the pulses represents the time evolution of the rf signal during the waiting time. For details see text.