A Multi-Pass Time-of-Flight Mass Separator for Beam Purification

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Abstract

Using the flight path in an energy-isochronous time-of-flight mass spectrometer repeatedly the overall long flight distance becomes large and allows high mass resolving powers. In a proof of principle system that has an overall length of ≈400mm we have achieved mass resolving powers m/Δm ≥40,000 for 1500eV ions of mass 28u. The transmission is ≈40% as long as the overall flight distance is shorter than the vacu-um free-path-length. Because of the relatively high kinetic energies of the stored ions, such systems can analyze bunches of large numbers of ions without being severely limited by space-charge effects. If ions of several keV are used, the mass analysis of a heavy ion requires only ≈1ms so that most neutron-rich nuclei can be investigated. We propose to develop techniques that enable this system to be used as a mass separator to study the decay of neutron rich nuclei. Such a system can also be used as a beam purifier.

1. Introduction

To determine the decay of exotic short-lived nuclei one is faced with the problem that all actions must happen in a time that is comparable to the life-time of the nuclei of interest and that these nuclei are produced together with large numbers of nuclei of neighboring isobars and neighboring elements. In order to observe decays of the nuclei of interest, it thus is necessary to use some means of on-line separation. One common method is to use an Isotope Separator On Line (ISOL) [1] that can separate ions of different isobars. To separate ions of the different elements within one isobar one must provide additional selectivity that can be provided by element-selective ion sources or by special production reactions. A more general solution can be expected, however, from a second-stage mass separator whose mass resolving power m/Δm is larger than a few 10,000. Such a separator could separate of ions whose masses differ only by a few MeV, the magnitude of the Q_β-values for the decay of a [N+Z]-nucleus to a [(N-1)+(Z+1)]-nucleus.

2. Time-of-flight mass separators of high mass resolving power

There are two types of systems that can separate short-lived ions of different masses:

1. Laterally dispersive systems in which use is made of the fact that ions of different masses move along different radii in a magnetic field
2. Longitudinally dispersive systems in which use is made of the fact that ions of different masses need different times to pass through the system.

Because of the often low production rates of exotic nuclei such mass separators must provide high transmissions, i.e. they must treat ion beams of large transversal phase-space areas $\varepsilon_x = \Delta x * dx/dz$ and $\varepsilon_y = \Delta y * dy/dz$. Here z denotes the coordinate along the ion beam axis and Δx as well as Δy denote the transversal extension of the ion beam [2] perpendicular to z. For transversally dispersive systems the demand of high transmission, i.e. large $\varepsilon_y * \varepsilon_x$, is in conflict with the demand on a high mass resolving power m/Δm which

requires narrow slits 2Δx and reasonably small angles of divergence 2dx/dz and 2dy/dz. For longitudinally dispersive systems, i.e. in time-of-flight mass analyzers, there is no such conflict [2,3] since in such systems a high mass resolving power requires only short ion pulses 2Δt and reasonably small spreads 2ΔK in kinetic energy, but no limits on the transversal extension of the ion beam. In most cases thus several 10% of the initially produced ions can pass through the mass analyzer as long as the continuously produced ions can be stored for the duration of one mass spectrum [4] and bunched to a time of a few ns.

To achieve high mass resolving powers a mass separator must be able [2] to differentiate between ions of equal charge but masses $m_0+\Delta m = m_0(1+\delta_m)$ with $|\delta_m|\ll 1$ even though these ions have different energies $K_0+\Delta K=K_0(1+\delta_K)$ with $|\delta_K|\ll 1$. In case of a longitudinal dispersive system thus the ion flight times $t =t_0+\Delta t =t_0(1+\delta_t)=\ell/v$ must become energy-isochronous. Since the ion velocity $v=v_0\sqrt{[(1+\delta_K)/(1+\delta_m)]}$ with $v_0=\sqrt{[2K_0/m_0]}$ depends on the ion energy, ions of increased energy must be sent along properly dimensioned detours, i.e. that they move along trajectories of length $\ell=\ell_0(1+\delta_K)$ that increase with energy. In this case the overall flight time is $t =\ell/v \approx(\ell_0/v_0)(1-\delta_m/2 +\ldots.\delta_K^2\ldots)$.

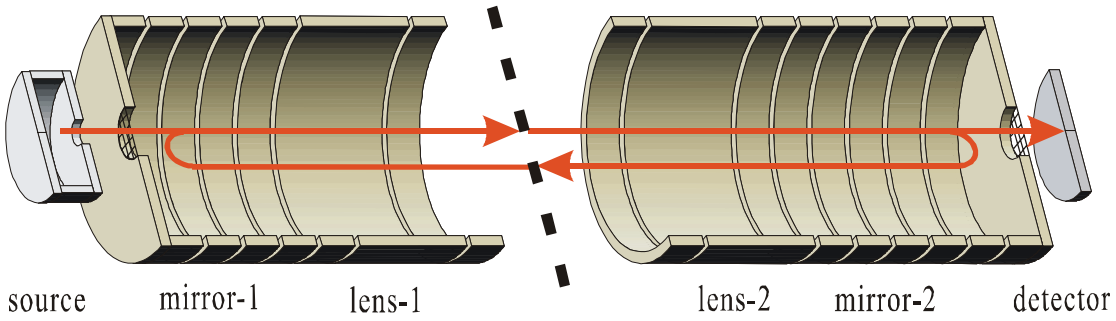

Fig1. Sketch of our proof-of-principle multi-pass time-of-flight mass spectrometer (MTOF-MS) that consists of a pulsed storage ion source, a fast ion detector and coaxially arranged electrostatic ion mirrors and lenses all built from ring electrodes. The ion mirrors do not contain grids though grids have been placed in the back of both mirrors since the ions pass through those only once when entering or leaving the "race track".

Since the ions start at slightly different times $\pm\Delta t^*$ the mass resolving power $m/\Delta m = t_0/2\delta_t$ is limited to $t_0/2\Delta t^*$. High mass resolving powers thus require either large values of t_0 or small values of Δt^*. This Δt^* can not be reduced below certain limits, but t_0 can be increased for instance by increasing ℓ_0 the length of the ion flight path for instance by using the physically given flight path N times. Thus a "race track" is established through which the ions pass again and again. Such systems we refer to as multi-pass time-of-flight mass spectrometers (MTOF-MS). There are two types of such systems:

1. Those that use magnetic or electrostatic sector fields to form a ring [2,3,5] or
2. Those that reflect ions repeatedly between ion mirrors [6,7].

Both systems can achieve energy isochronicity, in which case ions of higher energy are sent along detours: in sector fields they move along radii ρ that grow with δ_K while in mirror systems they penetrate deeper into the repeller fields.

2.1 An MTOF mass analyzer that uses coaxially arranged electrostatic ion mirrors

We have built an overall 400mm long proof-of-principle mirror-type MTOF-MS. It contains two coaxially arranged rotationally symmetric electrostatic ion mirrors (see

Fig.1) each of which consists of 8 ring-electrodes that can be aligned with high precision. In this "race track" the ions must pass through N laps, for each of which the ions must pass once through each mirror and twice through the field-free region between the mirrors, an overall flight path of ≈ 600mm.

To test this MTOF-MS we used N_2^+ and CO^+ ions whose masses differ by about 10.5MeV. These ions were produced from gas samples over ≈1ms in an electron impact storage ion source [4] accelerated to ≈1500eV and bunched to pulses of ≈3ns duration. At the beginning of a measurement cycle the upper mirror in Fig.1 was opened for ≈2μs so that the ions could enter the "race track". After a time, that allowed these ions to complete N laps in this race track, the lower mirror in Fig. 2 was opened for ≈2μs so that the ions could be recorded in a double channel plate detector. The recorded mass spectra are shown in Fig. 2 illustrating [8] that after ≈121 laps mass resolving powers ≥20,000 could be reached and after ≈255 laps mass resolving powers ≥40,000. For N≈50 the ion transmission was ≈40%. There were noticeable losses in transmission, however, for larger values of N. The reason was, that for so many laps the length of the ion flight path exceeded the vacuum free path length, since the pumping system was insufficient.

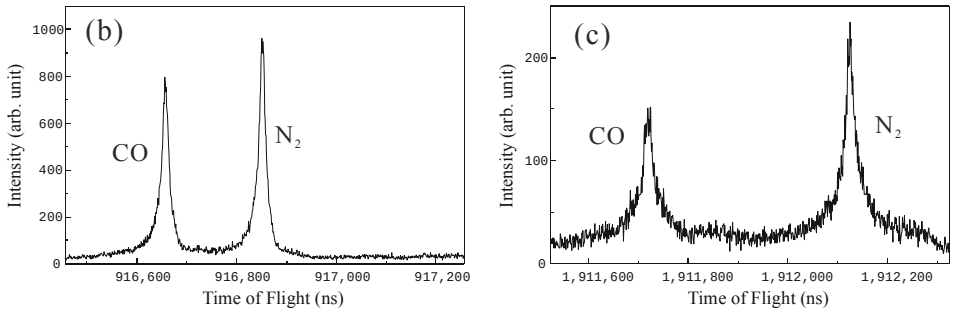

Fig. 2. The mass spectrum of a mixture of N_2 and CO as obtained in the MTOF-MS after 121 and 255 laps. Note that the masses of these two molecules are both ≈28 mass units or ≈28,000MeV while the mass difference between them is only ≈10.5MeV. Note also that the lower mass spectrum has a noticeably reduced intensity since many additional ions have undergone angle scattering events.

2.2. An MTOF Mass Separator

So far the MTOF system has only been used as a mass spectrometer. It should be usable, however, also as a mass separator [9] in which case we would use instead of the ion detector a beam deflector whose voltage we would increase with time. In this case the ions of different masses would experience different fields when passing through this deflector. Thus ions of one mass would pass undisturbed through this deflector while ions that would come earlier or later would be deflected. Placing radiation detectors around an ion collector one thus would record any decays of the ions of a desired mass optimally while those of ions of other masses would be eliminated or at least attenuated. Since this attenuation factor changes if the timing and/or the amplitude of the rampvoltage is varied, the corresponding γ-spectra would be attenuated while the γ-spectra ions of the desired mass would stay undisturbed. Thus one should be able to study the decay of ions whose mass differences are so small that they could not be fully resolved if the MTOF system would be used as a mass spectrometer.

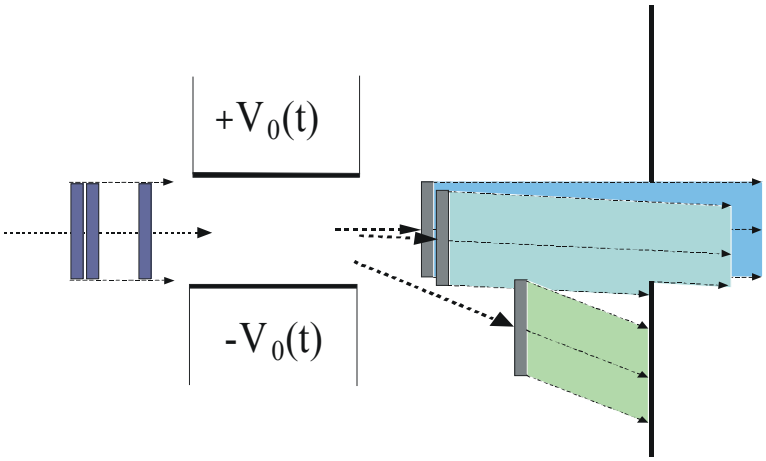

Fig. 3. Sketch of the deflector that, if supplied with a ramped deflector voltage, can deflect ions differently if they at slightly different times. Shown are 3 bunches of ions arriving at the left side. The ions of interest here are assumed to pass with full intensity through the shown aperture at the right side, while ions that reached the deflector much or only slightly earlier are fully or partially eliminated, respectively.

Using an improved MTOF system at UNISOR we hope to be able to study even the decay of isomers. If that should prove feasible, one could also consider using such an MTOF system at a future RIA facility where it then could be feasible to separate out or at least enhance and then accelerate only those ions of nuclei that are in some isomeric state.

3. Injecting ions of short-lived nuclei into an MTOF mass separator

At some ion source separator facility [10] like the Holifield Radioactive Ion Beam Facility (HRIB) in Oak Ridge it should be possible to decelerate ions by electrostatic fields such that they can be injected into an MTOF separator. The use of more energetic ions as formed in heavy ion reactions should also be possible but would require to decelerate the ions in a gas cell [11,12] from which they must be extracted again. In both cases it would be desirable to pass the ions through a beam cooler [13,14]. This is a gas-filled electric multipole – in most cases a quadrupole – in which the ions experience transverse RF-fields that accelerate and decelerate them perpendicularly to the multipole axis. In collisions with the residual gas atoms and molecules the ions thus loose energy until they have only a few times the thermal energies of the residual gas atoms or molecules. These transversal RF-fields cause the ions to approach the multipole axis along which they move with constant velocity under the force of a longitudinal DC-field.

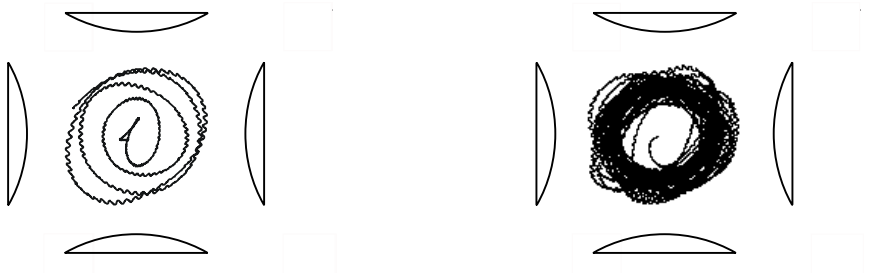

Fig.4. Calculated ion trajectories in a "rotating field" gas-filled quadrupole [15] as seen when looking down the quadrupole axis after times ΔT and $8\Delta T$. All the ions had been assumed to start from the multipole axis with small transversal energies. Under the action of the RF-fields these ions then were assumed to be pulled to larger and larger quasi-circles the magnitudes of which did not grow beyond the shown maximal excursions, however.

Whether the ions of interest are formed in an ion source or whether they emerge as low velocity ions from a gas cell, they often exist as molecular ions together with other molecular ions of no interest. Because of ion-atom or ion-molecule collisions a certain percentage of these ions is fragmented early on in the beam cooler, though the rest moves with low velocities through the rest of the multipole. One way to enforce such fragmentations is [15] to apply to the first half of the multipole additionally to the standard RF-field a rotating azimuthal RF-field of lower frequency. The effect of this additional field is that the ions move away from the multipole axis and acquire an azimuthal velocity around it (see Fig.4). Together with the constant velocity along the axis caused by the mentioned longitudinal DC-field the ions move along corkscrew-like trajectories around the multipole axis. This azimuthal motion doubles the energy available for fragmentations [15] and allows to break also stronger molecular bonds. This technique should help to purify the ion beam for an MTOF analyzer but also for any other ion separator or spectrometer at RIA.

4. Outlook

The UNIRIB collaboration is proposing to establish at the online isotope separator [1] (UNISOR) at HRIBF a laboratory for the development of a system as described for the decay study of neutron rich nuclei. This system will be used to develop the injection as well as the extraction techniques. Enlarging the existing MTOF and supplying it with a ramped deflector should transform this mass spectrometer [7,8] into an MTOF separator. It seems feasible to decelerate ions of short-lived nuclei after a magnetic-sector mass separator and to introduce them into an MTOF separator of high mass resolving power. Adding a rotating field gas-filled multipole should allow to fragment molecular ions efficiently [15]. This may require, however, to introduce the ions into through an orthogonal beam pulser [16].

5. Acknowledgements

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