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Development of a high resolution isobar separator for study of exotic decays

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Abstract

A compact isobar spectrometer and separator, based on the multi-pass-time-of-flight (MTOF) principle, is being developed by the University radioactive ion beam (UNIRIB) Consortium. It consists of two coaxial, grid-free electrostatic mirrors with auxiliary injection, focusing and extraction elements. Ions of different mass are reflected multiple times between the mirrors and separated longitudinally. Using an electron beam impact ion source and N_2 as a sample gas, a mass resolving power of 110,000 (FWHM) has been achieved. In the near future, MTOF will be coupled to the on-line isotope separator UNISOR (University Isotope Separator – Oak Ridge) at Holifield radioactive ion beam facility using electrostatic beam deceleration, a radiofrequency beam cooler and a fast buncher. It will serve as a high resolution mass separator with a Bradbury–Nielsen gate, providing isotopically pure samples of exotic species in the ^{100}Sn region and later, of neutron rich nuclei, for use in decay studies.

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1. Introduction

In order to perform decay spectroscopic studies of exotic nuclei, samples consisting of only one chosen isobar are often a necessity. Magnetic sector field separators or combined electric and magnetic devices with a mass resolving power between a few hundred and a few thousand are used at many facilities and separation according to mass number is achieved. However, we are not aware of an ISOL-type nuclear physics facility where an electromagnetic separator provides isobarically pure samples of exotic nuclei on a routine basis, which requires a mass resolving power in excess of ~15,000, depending on the intensity and the desired suppression of the nearest contaminating isobar. Usually, additional techniques like resonant laser ionization or chemical means have to be employed.

The UNIRIB consortium is following a different approach. We are developing a longitudinally dispersive, energy-isochronous, multi-pass-time-of-flight (MTOF) isobar spectrometer and separator based on our experience with an earlier prototype device [1]. MTOF will be capable of isolating a chosen isobar from a mass separated beam as it is typically delivered by a magnetic sector field mass separator. In MTOF ions are reflected multiple times between electrostatic mirrors and longitudinal mass dispersion occurs. After the desired number of reflections, ions are directed onto a multi-channel plate detector and ToF spectra are recorded (MTOF as a spectrometer). In the future, ions will be directed towards a Bradbury–Nielsen gate [2], the desired isobar will be transmitted to a detector station, and all other isobars are discarded (MTOF as a separator).

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The advantages of such a device over an instrument containing magnetic sector fields are: (i) very high mass resolving power of ~100,000 or better, (ii) relatively small size and weight, (iii) device is transportable, (iv) good transmission, (v) low cost. On the downside, MTOF operates with a pulsed beam and the concomitant problems. A similar MTOF-based approach towards isobaric separation is presently being pursued by several other laboratories which perform studies of exotic nuclei, e.g. GSI [3], MSU [4], or RIKEN [5].

The technical development of MTOF is taking place at the UNISOR mass separator [6] at the Holifield radioactive ion beam facility. UNISOR will be used as a pre-separator for MTOF and routinely provides stable and radioactive mass separated beams. All results presented in this paper should be considered preliminary.

2. Technical description

The mechanical and electronics design of MTOF is based on results of detailed ion optical calculations, which are described elsewhere [7]. These calculations were used to optimize the MTOF mechanical design, and to determine tolerances for the mechanical precision and the stability of the high voltages which supply the individual mirror electrodes. Below, the main components of MTOF and their operation are described.

2.1. Electron beam impact ion source

This ion source is used for initial test measurements only and will be replaced in the future with beam line elements to inject radioactive ion beams (RIBs) into MTOF. Ions of stable gaseous elements are produced by impact of a continuous 70-eV electron beam. Ions are stored in a shallow potential well of ~0.5 V/mm field strength around a fine mesh and extracted through several apertures of ~2 mm diameter by using a solid state pulser. The ion source is operated at a potential of 1090 V. The pressure in the ion source chamber during operation is $\sim 5 \times 10^{-6}$ Torr, caused mainly by the gas load of the sample gas. The pressure inside the ion source itself is estimated to be ~1000–2000 times higher, based on conductivity estimates. The number of extracted ions per pulse is ~1, the repetition rate is several 100 Hz and is kept inversely proportional to the time ions spend in MTOF during the mass analysis process.

2.2. Injection optics

Ions enter the MTOF main vacuum chamber through a cylindrical opening of 10 mm length and 2 mm diameter. It limits the gas flow from the ion source chamber into the MTOF main chamber, which is at a pressure of $\sim 1 \times 10^{-7}$ Torr. An einzel-lens and a set of horizontal and vertical deflectors are used for matching the ion source emittance and MTOF isochronous acceptance and centering the beam, respectively.

2.3. Electrostatic mirrors and drift tube

Each electrostatic mirror consists of nine independent electrodes, which are mounted within a hollow aluminum tube with the aid of ceramic balls. The aluminum tubes are mounted on a support tray and their position can be adjusted. The first electrode of the entry mirror and the last electrode of the exit mirror are connected to their high voltage power supplies via directed energy DEI-4150 fast solid state HV pulsers, which switch voltages from ~1600 to 800 V in order to let ions in and out of MTOF. Despite their symmetric mechanical construction, the voltages on the entry and exit mirror electrodes are different, resulting in one electrically "short" and one "long" mirror. This appears to be advantageous if one wishes to achieve mass resolving powers $\gg$100,000. An hour-glass shaped electrode of the long mirror is used as a focusing lens with a potential of ~ -1800 V. The distance between the turning points of the ion motion in the two mirrors is ~1070 mm. All ion optical elements were aligned with respect to the optical axis with a precision of better than 0.2 mm by using insertable targets and a Taylor–Hobson beam line telescope.

2.4. MCP detector or Bradbury–Nielsen gate

For operation of MTOF as a spectrometer, an MCP detector of 20 mm diameter is placed behind the last electrode of the exit mirror, and ToF spectra are recorded using a precision instruments PI98063 TDC with multi-hit capability. In the experiments reported here, no constant fraction discriminator was used. The TDC start time is given by the ejection pulse of the ion source. For operation as a separator, the MCP will be replaced in the future by a Bradbury–Nielsen gate [2,8] with wires of 1/100 mm diameter and a wire spacing of 1/10 mm. We have developed electronics capable of applying voltages of ±50 V to the Bradbury–Nielsen gate within ~10 ns. An MCP detector located ~60 mm from the gate will be used to set the timing and to verify separation.

2.5. Electronics

All MTOF electrode voltages can be set and read back independently and remotely via a computer using the LABVIEW programming package and National Instruments NI-PXI-6704 DACs and NI-PXI-6284 ADCs, respectively. Since the 15 bit resolution of the NI DACs falls short of our desired voltage precision, we have combined two DAC channels using hardware produced by RIS corporation (Knoxville, TN) to achieve the equivalent of ~18 bit resolution. ISEG DPR series high voltage (HV) power supplies with 2 kV maximum voltage output are used and the HVs are additionally filtered using RC circuits mounted close to the electrodes inside the MTOF vacuum chamber. Great care was taken to avoid ground loops in the HV supply electronics and a star ground with the HV modules as

reference point was implemented. The resulting short term stability of the HVs is $\sim\pm 10$ mV. However, during extended operation, temperature drift of the ISEG HV supplies leads to a drift of the mass peaks observed in the ToF spectra. Therefore, HVs are monitored and manually adjusted during operation. All timing, such as ion ejection, opening and closing of the mirrors and start of the TDC, is controlled by a Stanford DG535 gate and delay generator.

3. Results

We have theoretically and experimentally investigated a large number of ion optical solutions for the ion motion in MTOF with the aim to optimize simultaneously the mass resolving power, the transmission and the isobaric suppression as determined by the ToF peak shape.

For a given set of "initial conditions", which comprises the desired number of reflections, the extraction field strength in the ion source, the initial parameters of the stored ions (ion cloud size and energy spread), an optimizing computer code [7] minimizes all ToF aberrations up to 5th order by varying the MTOF electrode voltages, including injection and extraction electrodes. In addition, using the code one can adjust transverse focusing properties and match the emittance of the injected beam with the MTOF isochronous acceptance. All ion optical solutions tested experimentally so far correspond to a transverse tune value of $Q = 0.80$, defined as the number of lateral oscillations per lap. We find consistently excellent agreement (<0.5 V) between the predicted and the experimentally found voltage settings for best resolution. The sole exception is the potential of the ion source (or the ions's kinetic energy) that must be adjusted by a larger value to fit the MTOF energy acceptance.

3.1. Mass resolving power

Measurements were performed using air as sample gas with the number of laps ranging between 20 and 300, corresponding to flight paths between 43 and 642 m and ToFs (for N_2 molecules) between 665 μs and 9.707 ms, respectively. Fig. 1 shows a typical ToF spectrum for N_2 molecules after 120 laps with electrode voltage settings simultaneously optimized for maximal mass resolving power and a small tail of the ToF peak extending to longer ToF. The mass resolving power in this spectrum is about 59,000 (FWHM). The small background on the right of the ToF peak is due to a continuous ion current from the present test ion source. A maximum value for the mass resolving power $M/\mathrm{d}M = T/2\ \mathrm{d}T$ of 110,000 (FWHM) was achieved after 300 laps. In this case, however, the tail of the ToF spectrum extending to longer ToF is somewhat larger than that one present in Fig. 1. Some of our experimental results are shown in Fig. 2. Apertures of 9 and 14 mm diameter were used, installed in the center of MTOF between the electrostatic mirrors. The results show the dependence of the mass resolving power (FWHM) on

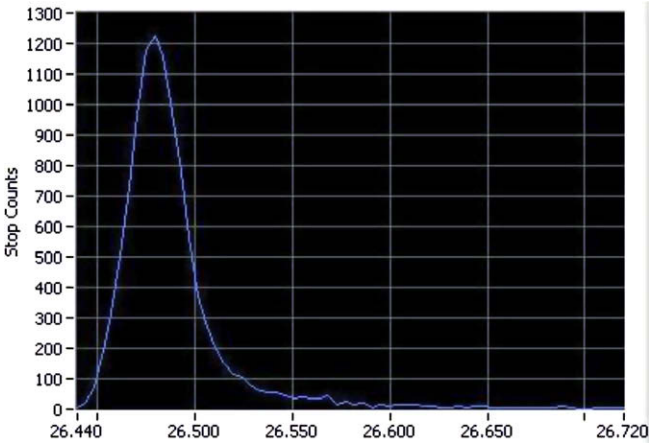

Fig. 1. ToF spectrum for N_2 molecules after 120 laps, ToF = 3901.2 μs. The time axis is (TOF − T_0) in microseconds, where T_0 is a physically irrelevant offset. FWHM is 33 ns, $M/\mathrm{d}M = 59{,}000$. The spectrum was optimized simultaneously for good resolving power and a small tail portion.

the number of laps and the size of the beam in the center of MTOF. We point out that the mass resolving powers quoted in this section refers to MTOF operated as a spectrometer, not as a separator.

3.2. MTOF acceptances and beam emittances

The transversal acceptance of MTOF can be adjusted with a set of apertures with diameters 4, 6, 9 and 14 mm installed in the center of the drift tube. Due to the periodicity of the ion motion between the mirrors, such apertures limit not only the beam size, but also the transverse angles and hence the beam emittance. For the tune $Q = 0.80$ currently used in MTOF operation the transverse acceptance can be calculated as $\varepsilon\ [\mathrm{mm\ mrad}] = 0.52\ \mathrm{d}^2[\mathrm{mm}^2]\,\pi$. For the $\mathrm{d} = 9$ mm diameter aperture, a transverse acceptance of 42 π mm mrad is obtained. The emittances of beams from our present test ion source do not exceed ≈44 π mm mrad (see dashed ellipse in the insert of Fig. 2), as it follows from simulations with the SIMION program. Given the excellent agreement between the calculated and experimental voltage settings for optimal resolution, we adopt calculated values for the MTOF isochronous energy acceptance of $\sim\pm 2.5\%$ and of ∼15 π mm mrad for the transverse isochronous acceptance. Within these acceptance limits, the optical limit for $M/\mathrm{d}M$ becomes >100,000.

We have not measured the energy spread and ion cloud size in the ion source. They are treated as free parameters and adjusted in order to reproduce the experimentally observed mass resolving power, and lie within accepted limits ($\Delta K \sim 0.2$–0.3 eV, $\mathrm{d}z \sim 1$–2 mm, $\mathrm{d}x = \mathrm{d}y \sim 1$ mm) and are approximately constant in order to reproduce results under various conditions.

The initial ion time spread resulting from the extraction process from the ion source can be decreased by increasing

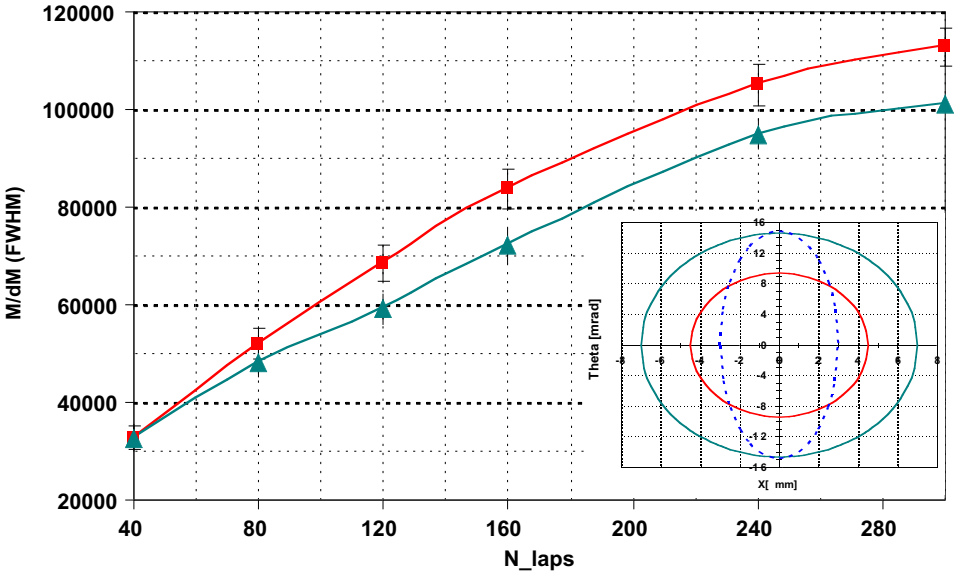

Fig. 2. Experimental mass resolving power versus number of laps measured for apertures with diameters 9 mm (red curve, squares) and 14 mm (blue curve, triangles) diameter, corresponding to 42 and 102 π mm mrad of transversal acceptance, respectively. Insert: Solid ellipses are calculated MTOF acceptance limits for the 9 mm (red, small ellipse) and 14 mm (blue, large ellipse) diameter apertures corresponding to the respective $M/\mathrm{d}M$ curves. The dashed ellipse is the emittance limit for the injected beam using the present test ion source.

the extraction field, thus decreasing the turn-around time. This comes at the expense of an increased energy spread due to the finite size of the ion cloud and does not improve the optical limit mass resolving power. However, the optical limit mass resolving power is approached at smaller number of reflections. Assuming a longitudinal ion cloud size of ~1 mm, an ion energy of 1090 V and using an extraction voltage of 36 V/mm the resulting energy spread of 36 V is within the calculated MTOF isochronous acceptance of ±2.5%. Therefore, most of our measurements were performed at 36 V/mm extraction field or less.

3.3. Isobaric suppression

Isobaric separation will be achieved by using the Bradbury–Nielsen gate [8] described earlier. Besides the performance of the Bradbury–Nielsen gate, the achievable isobaric suppression is given by the magnitude of the tail portion of the contaminating, lighter, isobar's ToF peak at the position where the heavier isobar of interest is located. For example, in our experimental ToF spectrum of N_2 with 120 laps (see Fig. 1), at a time of 200 ns after the N_2 ToF peak, the tail portion of the N_2 peak drops to an intensity of ~1% of the peak height. It is thus estimated that an isobaric suppression of ~100 can be reached for two isobars which are separated by 200 ns in ToF. This would be the case for a hypothetical pair of isobars with mass $A = 28$ and a mass difference of 4.3 MeV. Since MTOF itself is a purely electrostatic system, this estimate can be scaled to the mass $A = 100$ region, with the result that an isobaric suppression of ~1% can be expected after 120 laps for a pair of $A = 100$ isobars with a mass difference of ca. 12 MeV. (It is here assumed that the initial ion cloud parameters for mass $A = 28$ and $A = 100$ are the same). Such an isobaric suppression would enable many decay studies which are impossible to perform today. We expect that the magnitude of the tail portion can be further reduced if a cooled ion population is injected into MTOF, which will be the case when MTOF is coupled to radioactive ion beam line.

3.4. Transmission

Measurements of the MTOF transmission made with the 9 mm diameter aperture and at a pressure of 1×10^{-7} Torr indicate that during the first 2 laps a large fraction (~50%) of ions coming from the ion source is lost. This is due to the mismatch between the transverse emittance of our present test ion source and the MTOF acceptance, and such losses will not be present with the RIB injection scheme described below. From 2 to 300 laps, ~50% of the remaining ions are lost due to collisions with residual gas atoms. Such losses can be reduced by improving the vacuum in the MTOF main chamber.

4. RIB injection at UNISOR

We have developed a complete conceptual design for RIB injection into the MTOF isobar separator. We will commission MTOF at the UNISOR mass separator and perform at UNISOR a first series of proof-of-principle and "real" physics driven experiments on the proton and later, on the neutron rich side of the valley of stability. The UNISOR mass separator will act as a pre-separator to MTOF and isolate a particular mass chain. After exiting the mass separator, the ions of 30–40 keV will be slowed

down to 60–120 eV by a set of electrostatic electrodes before being injected into two radiofrequency quadrupoles, one acting as a storage and cooler quadrupole and the other as a final cooler and bunching device. The RFQ's and MTOF will be located on a high voltage platform at the same elevated potential as the target ion source. The design of each of these components is based on known technologies and existing devices with published results e.g. [9–11], which ensure that a RIB injection with high transmission and supporting a high mass resolving power in MTOF can be constructed.

Preliminary estimates for the possible throughput limited by the space charge range from 10^3 to 10^4 ions per pulse without loss of resolving power, corresponding to DC beam currents up to a few pA. While such a throughput is certainly sufficient for many decay spectroscopic studies, additional efforts may be required in cases where abundant stable contaminants are present in a mass chain. We will investigate the MTOF space charge tolerance in detail when the beam cooler and buncher become available.

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