High-resolution SHARAQ spectrometer at RI Beam Factory

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Abstract. The high-resolution SHARAQ spectrometer and the dedicated beam-line have been constructed at the RI beam factory. Cathode-readout drift chambers placed at the focal plane of SHARAQ and multi-wire drift chambers in the beam-line worked satisfactorily for heavy ion beams with $Z=1$–7 at 200–250 MeV/nucleon. By introducing a dispersion matched operation of the beam-line, we have achieved a momentum resolution of $\Delta p/p = 1/8100$ for a primary beam of $^{14}$N beam with a momentum spread of $\pm0.1\%$.

1. Introduction

The high-resolution SHARAQ spectrometer [1] and the dedicated beam-line [2] have been constructed at RI Beam Factory for magnetic analyses of radioactive isotope (RI) beams and their reaction products. A missing mass spectroscopy with RI beam induced reactions used

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as new probes to atomic nuclei is planned with the ion-optical system: Single and double charge reactions with large positive Q-values, such as \( ^{12}\text{N},^{12}\text{C} \) and \( ^{8}\text{He},^{8}\text{Be} \) reactions are expected to be quite efficient in populating highly excited states in a recoil-less manner. Experiments to investigate isovector spin monopole resonances and tetra neutron states by taking this advantage of the RI beam induced reactions are planned. RI-beam induced reactions also provide us a variety of spin-parity selectivities which are missing in stable-beam induced reactions. An interesting example is the \( ^{10}\text{C},^{10}\text{B}(0^+;\text{IAS}) \) reaction which selectively populates isovector \((\Delta T = 1)\) non-spin-flip \((\Delta S = 0)\) modes in nuclei. We are planning to apply the \( ^{10}\text{C},^{10}\text{B}(0^+;\text{IAS}) \) reaction to search for isovector non-spin-flip monopole resonances in \(^{90}\text{Zr}\).

In the reaction studies, energy and momentum-transfer resolutions are of particular importance. The SHARAQ spectrometer and the beam-line are designed to achieve energy and momentum-transfer resolutions of \( \Delta E_x \sim 500 \text{ keV} \) and \( \Delta q \sim 0.1 \text{ fm}^{-1} \), respectively.

![Figure 1. Schematics of the SHARAQ spectrometer.](image)

2. SHARAQ spectrometer
The SHARAQ spectrometer, shown in Fig. 1, is designed to achieve a momentum resolution of \( \Delta p/p = 1/14700 \) and an angular resolution of \( \Delta \theta \sim 1 \text{ mrad} \) for particles with a magnetic rigidity of 1.8–6.8 Tm. It is of a \( QQDQD \) configuration: The first quadrupole doublet (SDQ) consists of two superconducting magnets with effective lengths of 1000 and 500 mm. The cold bore radius and maximum field gradient are as large as 170 mm and 14.1 Tm. The quadrupoles are used to adjust the beam envelope so that the required energy resolution and acceptance can be
achieved. The first (D1) and second (D2) dipoles are normal-conducting magnets with bending angles of $32.7^\circ$ and $60^\circ$. The bending radius is 4.4 m. The entrance edge of D2 has the shape of a 3rd order polynomial to minimize higher-order aberrations. The third quadrupole magnet (Q3) between the dipoles is used to achieve a zero vertical magnification ($y|y$). The vanishing vertical magnification is essential in obtaining a vertical angular resolution better than 1 mrad for a large emittance beam. The details of design specifications are described in Ref. [1].

The focal plane of SHARAQ is equipped with two cathode readout drift chambers (CRDC). They have an effective area of 550 mm × 300 mm to cover the focal plane of SHARAQ. The CRDCs are operated with a pure isobuthane gas at a pressure as low as $P_{\text{gas}} \sim 2–4$ kPa in order to minimize multiple scattering effects. They were tested with heavy ions beams with $Z = 1–7$ at $E = 200–250$ MeV/nucleon in the commissioning run of SHARAQ. Detection efficiencies were found to be almost 100% at anode high voltages of 650–950 V. Horizontal position resolution was as good as 0.42 mm (FWHM) for each plane, resulting in a resolution of the focal plane position of $\Delta x = 0.3$ mm.

3. High-resolution beam line
Since a secondary RI beam have a momentum spread on the level of 1%, we can not perform a high-resolution measurement only with the high-resolution spectrometer. The high-resolution beam line was designed to enable a dispersion-matched operation with the SHARAQ spectrometer [2], with which we can cancel effects originating from the beam momentum spread.

**F3**: double achromatic focus

**F4**: dispersive focus (H), focus(V)

**F5**: focus(V)

**F6**: dispersive focus (H), focus (V)

**FH7**: dispersive focus(H), focus (V)

**FH9**: dispersive focus (H), focus (V)

**Target**: dispersive focus, focus (V)

**FP**

**Figure 2.** A layout of the high-resolution beam line.

Fig. 2 represents a layout of the high-resolution beam line. The beam line has 7 focal planes, F3–FH9 and the SHARAQ target position. Among them, dispersive focal planes of F4, F6, FH7,
FH9 have values of dispersion in the range of 1.9–22.6 m. A number placed on each quadrupole multiplet is a serial number of the element. Ten superconducting triplet quadrupole (STQ7–15 and 19)\cite{4} and three normal conducting quadrupole magnets are used to transport the RI beams.

In the figure, horizontal beam trajectories in the dispersion matched mode for the $x_{F3} = \pm 3$ mm, $\theta_{F3} = \pm 10$ mrad, and $\delta = \pm 0.3\%$ are shown, where $x_{F3}$, $\theta_{F3}$, and $\delta$ indicate position, angular, and momentum deviations from the central ray at F3\cite{2}.

Low-pressure multi-wire drift chambers (MWDC) placed on the focal planes are used to determine trajectories of RI beams. The MWDCs are operated with a pure isobuthane gas at a pressure of 10–30 kPa and can determine the particle trajectories with a position resolution better than 300 $\mu$m \cite{5}.

4. Dispersion matching

Commissioning runs of the SHARAQ spectrometer and the high-resolution beam-line were carried out in March and May of 2009. In the commissioning runs, ion-optical properties of the SHARAQ spectrometer and the beam-line were examined by measuring particle trajectories with the tracking detectors described above and the specifications were found to be compatible with the designed values.

It was also found that correlations of beam trajectories at different dispersive focal planes serves as measures to diagnose focus and dispersion matching conditions. We are being establishing a beam tuning method which uses the correlations as diagnostic criteria\cite{6}.

![Figure 3](image.png)

**Figure 3.** Correlations of a position at the dispersive focal plane FH7 $x_{FH7}$ with a position $x_{FP}$ (a) and an angle $a_{FP}$ (b) at the final focal plane of SHARAQ.

When lateral and angular dispersion matching conditions are satisfied, the position $x_{FP}$ and the angle $a_{FP}$ at the final focal plane get independent of the beam momentum. Since a position at the dispersive focal plane in the beam-line directly corresponds to the beam momentum, correlation between the position and $x_{FP}$ ($a_{FP}$) provides a performance measure of the lateral (angular) dispersion matching. We chose the position at the focal plane FH7, $x_{FH7}$, as a monitor of the beam momentum. The focal plane FH7 has a momentum dispersion as large as 7.3 m. Figure 3a shows a correlation between $x_{FP}$ and $x_{FH7}$ for a primary $^{14}$N beam at 250 MeV/nucleon, after a dispersion-matching tuning. The upright correlation indicates that $x_{FP}$ is independent of the beam momentum, which is a clear manifestation of achievement of
5. Summary
The high-resolution SHARAQ spectrometer and the dedicated high-resolution beam-line have been constructed at the RI beam factory. The ion-optical system is equipped with thin tracking detectors, the CRDCs at the focal plane of SHARAQ and MWDCs in the beam line, with which we can determine particle trajectories with a position resolution of $\sim 300 \mu m$. Correlations of the beam trajectories can serve as measures in beam-transport diagnosis. In the dispersion matched mode, a momentum resolution of $\Delta p/p = 1/8100$ was achieved for a primary beam of $^{14}$N with a momentum spread of $\pm 0.1\%$. We plan a series of experiments by taking advantages of novel RI-beam induced charge exchange reactions.

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