Development of Ring-imaging Cherenkov Counter for Heavy Ions

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Up to this day, RICHes have been mainly used for high energy experiments to identify leptons and mesons. On the other hand, the number of Cherenkov photons is proportional to square of the atomic number, so that application of a RICH for heavy ions is expected. Then we are developing a ring-imaging Cherenkov counter for heavy ions (HI-RICH). The experiment was performed at NIRS-HIMAC. As for the primary beam (^{132}Xe with an energy of 420 MeV/u), a velocity resolution $\Delta\beta/\beta = 0.050\%$ (standard deviation σ) and a detection efficiency $\varepsilon = 99.9\%$ were achieved. Regarding to the secondary beam, a particle identification was successfully performed with HI-RICH and an ion chamber.

The 26th International Nuclear Physics Conference
11-16 September, 2016
Adelaide, Australia

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1. Introduction

The ring-imaging Cherenkov counter (RICH) is a velocity detector for incident charged particles. RICHes have been mainly developed and used for experimental particle physics. For example, the first RICH tested at CERN [1] was performed with ionization process and the *Aerogel RICH counter* in the KEK Belle II experiment [2] which is going to start in 2017 will be used to separate kaons from pions and to provide discrimination between pions, muons and electrons. In nuclear physics experiments, on the other hand, GSI developed a RICH for heavy ions with a liquid C_6F_{14} radiator and a MWPC as a photon detector in 1999 [3], but this is a rare case. A velocity resolution of this was measured to be $\Delta\beta/\beta = 0.03\%$ (σ) for Ru^{44+} particles of $\beta \simeq 0.85$.

Also we have developed a RICH for heavy ions with several hundreds MeV/u energy (*HI-RICH*). The conventional velocity measurement for heavy ions is time-of-flight method (TOF), which requires large space and high costs for high accuracy. In contrast, HI-RICH requires only decades of centimeters, so that this is expected to be a new compact and low-cost velocity detector.

The velocity β of ions can be deduced by measuring the Cherenekov angles θ_C ($\cos\theta_C = (n\beta)^{-1}$, where n is the refractive index of a radiator). For measuring θ_C, bottom face rings of the Cherenkov cones should be reconstructed. Note that this angular distribution spreads mainly due to energy loss of incident particles in a radiator, optical dispersion $n(\lambda)$ of emitted radiation and finite thickness of a radiator. The number of photons emitted per unit wavelength λ per unit length of radiator x is then,

$$\frac{dN}{d\lambda\, dx} = \frac{2\pi\alpha Z^2}{\lambda^2}\left(1 - \frac{1}{n^2\beta^2}\right), \tag{1.1}$$

where α is the fine structure constant and Z is the atomic number of the incident particle.

## 2. Experiment

2.1 Beam line

The experiment was performed at NIRS-HIMAC, with medical accelerator for Heavy ions. Several detectors including HI-RICH were placed on the last focal plane (F3) in the SB2 course which is shown in Ref. [4]. The primary beam was ^{132}Xe with a kinetic energy of 420 MeV/u which is equivalent to a velocity $\beta = 0.725$. As for the secondary beam experiment, the production target was a 2 mm-thick beryllium.

2.2 Detector setup

Figure 1 shows a top view of the detector setup. The size of the plastic scintillator was 50 mm × 50 mm × 1 mmt, whose signals were read by coincidences of two PMTs. It was used as a common trigger. The ion chamber is an energy loss ΔE detector which was used for particle identifications.

2.3 HI-RICH design

Figure 2 shows a schematic view of HI-RICH, which is consist of a radiator and three pairs of 8×8 multi-anode photomultiplier tubes which are placed perpendicular to the beam line. The PMTs are covered with band-pass filters with wavelength peaks of 360 nm. Radiators can be moved along the beam line.
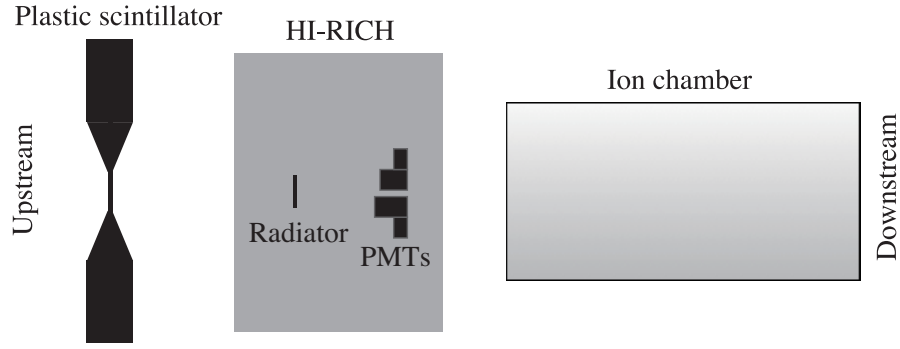
Figure 1: Top view of the detector setup
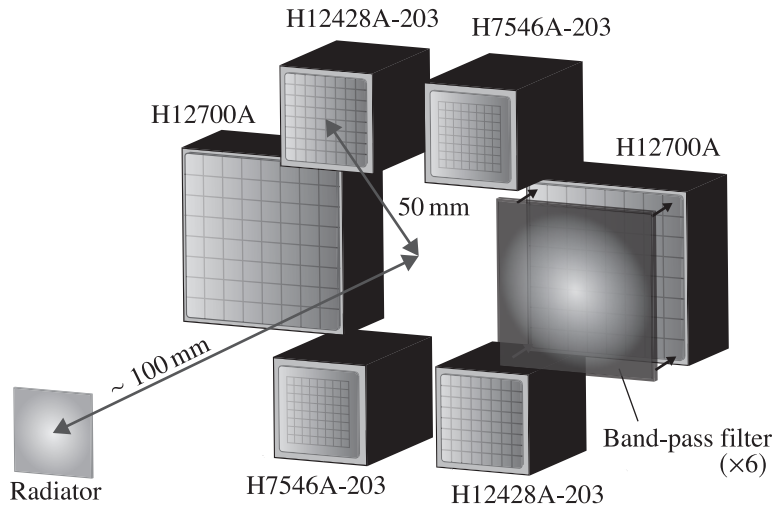
Figure 2: Schematic view of HI-RICH

## 2.4 Photomultiplier tubes

The model number of the PMTs are *H7546A-203*, *H12428A-203* and *H12700A* which are made by *Hamamatsu Photonics*. As shown in Fig. 2, they are 8×8 multi-anode models. The maximum quantum efficiencies of the PMTs are about 30–40% and the peak wavelengths of them are 350 nm.

2.5 Radiator

As for radiators, synthetic quartz (SiO_2) and BK7 were used. Refractive indexes of SiO_2 and BK7 are about 1.48 and 1.54 respectively. Each optical dispersion $n(\lambda)$ is as follows:

$$
\begin{aligned}
n_{\text{quartz}}(\lambda) &= 1.45 + 0.24 \exp[-0.0064\lambda] + 18.93 \exp[-0.032\lambda], \\
n_{\text{BK7}}(\lambda) &= 1.51 + 0.1 \exp[-0.00566\lambda] + 0.213 \exp[-0.0078\lambda].
\end{aligned}
\tag{2.1}
$$

A graph of them in a range of 300–400 nm are shown in Fig. 3. A red line and a blue dashed line show BK7 and SiO_2 respectively.
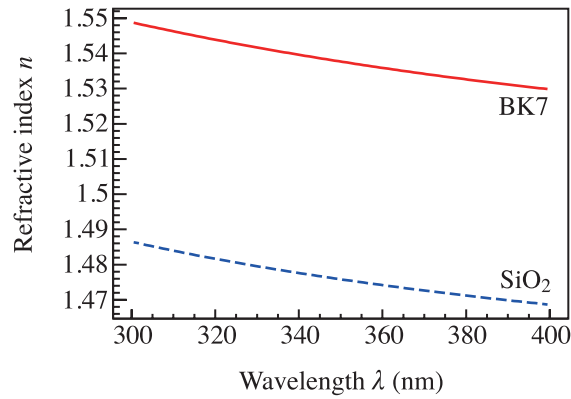
**Figure 3:** Optical dispersion of radiators

2.6 Filter

There are band-pass filters with a thickness of 2.5 mm. As shown in Fig. 2, The PMTs are covered with them. The model number is *UV U-360* made by *Edmund Optics*. They suppress spreads of angles of emitted photons by optical dispersion. In the wavelength dependence of the transmission, the peak wavelength is 360 nm and the FWHM is 45 nm. A graph of this is shown in Ref. [5].

3. Results and discussion

As an example, 2D plots of detected Cherenkov photons of all events seen from upstream are shown in Fig. 4. This is a result of the primary beam with a SiO_2 radiator with a thickness of 0.48 mm. Figure 5 shows a time spectrum of a channel. The time information is differences between signals of the HI-RICH PMTs and common trigger signals of the plastic scintillator. The FWHM of the spectrum is 0.38 ns, which is consistent with the catalog value of a transit time spread of 0.35 ns.
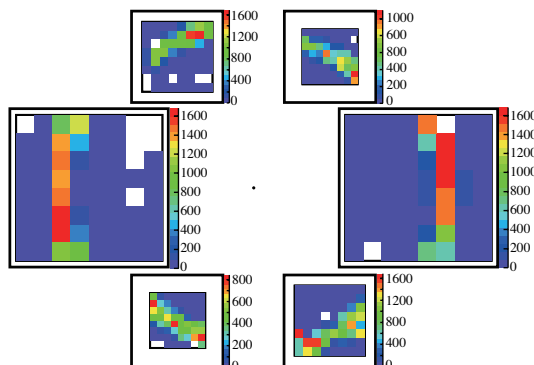
Figure 4: Detected Cherenkov photons (all events)
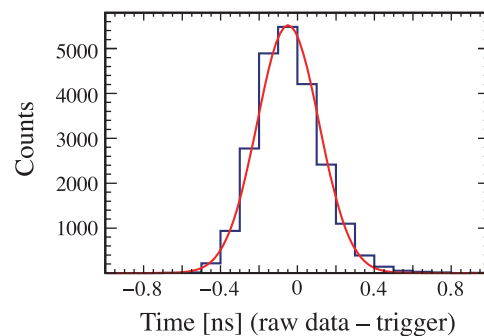
Figure 5: Time spectrum of a HI-RICH channel

3.1 Monte Carlo simulation

In order to understand the property of HI-RICH, We simulate HI-RICH. Since results will be compared with Monte Carlo simulations in this paper, we explain the methods of the simulations briefly.

Fluctuations taken into consideration are as follows:

- Energy loss of beams in a radiator
  This is the most dominant fluctuation and was calculated with *LISE++*.

- Angles of emitted photons by optical dispersion
  A spread of wavelength was considered as a rectangular distribution. The center and the full width of it was 360 nm and 45 nm which is approximation of the wavelength dependence of the transmission of the band-pass filter [5]. Optical dispersion was defined as Eq. (2.1).

- Positions of emitted photons in a radiator
  Because of radiator thickness, positions of emitted photons is uncertain.

The number of photoelectrons was considered as a Poisson distribution. If a photoelectron reached a position of a PMT channel, the channel was considered to be hit. This process was repeated with all photoelectrons.

3.2 Primary beam

The primary beam was ^{132}Xe with an energy of 420 MeV/u and the estimated velocity just before HI-RICH was $\beta = 0.712$.

Table 1 shows experimental results of the velocity resolutions and detection efficiencies about two kinds of thicknesses of SiO_2 radiators. The experimental velocity resolutions are compared with the simulation in Fig. 6. The simulated detection efficiencies are 100%. If a radiator is too thick, velocity resolution will be large primarily because of energy loss in it. If a radiator is too thin, however, velocity resolution will be large too owing to lack of the number of photons. Data points and a blue line are experimental and simulation results respectively. The experimental data of the velocity resolutions are not achieved to the simulation. This is because the real number of photoelectrons is fewer than the theoretical number of them owing to discriminating signals. Because the number of photons is approximately proportional to the radiator thickness, so is the number of photoelectrons. Then a red dashed line shows simulation results performed as the actual number of photoelectrons. These are consistent with experimental results. A velocity spectrum with a radiator thickness of 0.95 mm is shown in Fig. 7.

Table 1: Experimental results of β resolution and the detection efficiency

| SiO_2 radiator thickness	0.48 mm	0.95 mm
$\Delta\beta/\beta$ (%) (σ)	0.0547(3)	0.0497(3)
Detection efficiency ε (%)	99.39(6)	99.86(3)
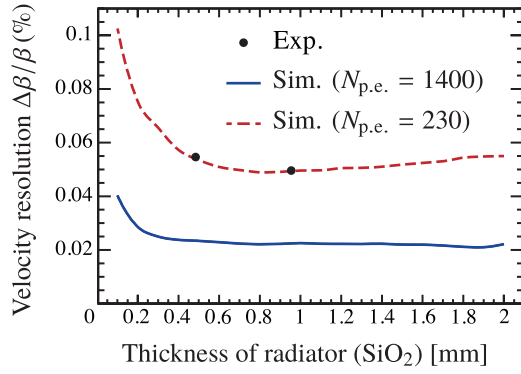
Figure 6: SiO$_2$ radiator thickness dependence of the velocity resolution
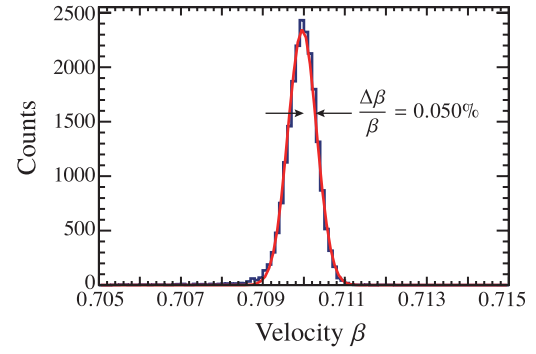
Figure 7: Velocity spectrum with a radiator (SiO$_2$) thickness of 0.95 mm

Figure 8 shows a comparison of multiplicity dependence of the velocity resolution between the simulation and experimental results. Multiplicity is defined as the number of hit channels in an event. A red line and black points are the simulation and experimental data respectively. A blue histogram is an experimental multiplicity spectrum. As for experimental data points, some events were selected by multiplicity gates of each point. The simulation well reproduces the experimental data.
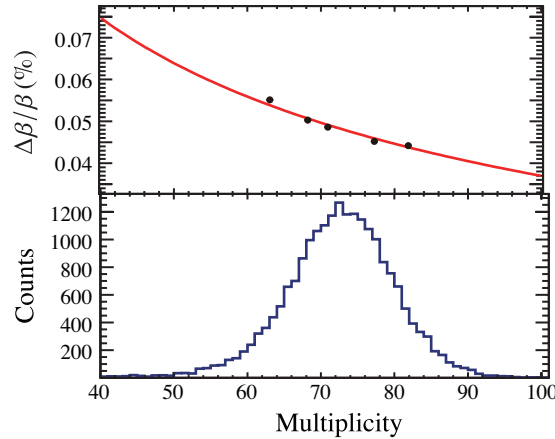

Figure 8: Multiplicity dependence of the velocity resolution

With the 0.95 mm-thick radiator, a velocity resolution of 0.050% and a detection efficiency of 99.9% were achieved with $\beta = 0.71$ and an atomic number $Z = 54$. This is equivalent to TOF resolution at a distance of 60 m with two detectors of $\sigma = 100$ ps which is a typical time resolution of plastic scintillators.

3.3 Secondary beam

In the secondary beam, the target material was a 2 mm-thick beryllium and the radiator was BK7. A particle identification was successfully performed with HI-RICH and the ion chamber which is an energy loss ΔE detector. Figure 9 shows PID plots of the atomic number Z and the velocity β. Z was deduced by the ion chamber and HI-RICH. As can be seen, nuclides are separated

clearly. In terms of ^{113}Sn as a typical example, a velocity resolution of 0.086(1)% was achieved which is equivalent to 5.3σ separation about the mass number as shown in Fig. 10. All detection efficiencies were 100%.
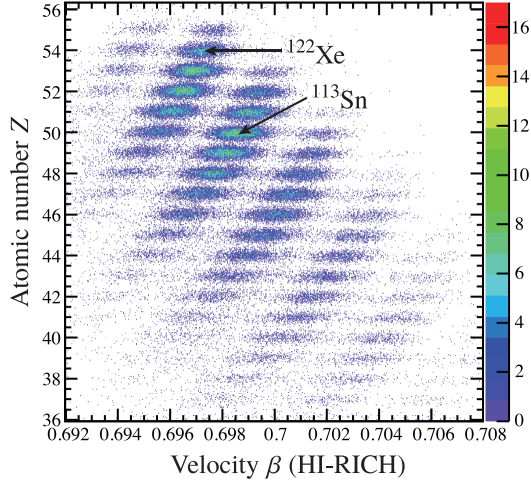

Figure 9: PID plots of the atomic number and the velocity
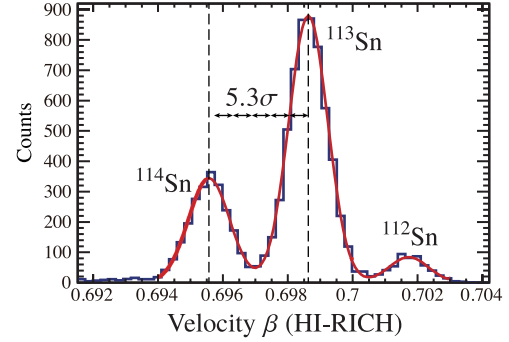
Figure 10: Projection of PID plots at Sn^{50+}

Figure 11 shows a relation between the number of photons which is estimated by the experimental multiplicity and $Z^2 \sin^2 \theta_C$ which is a term of Eq. (1.1). These nuclides are selected from the line including ^{113}Sn. According to Eq. (1.1), the number of photons is theoretically proportional to $Z^2 \sin^2 \theta_C$, so that it can be said that the result is consistent.
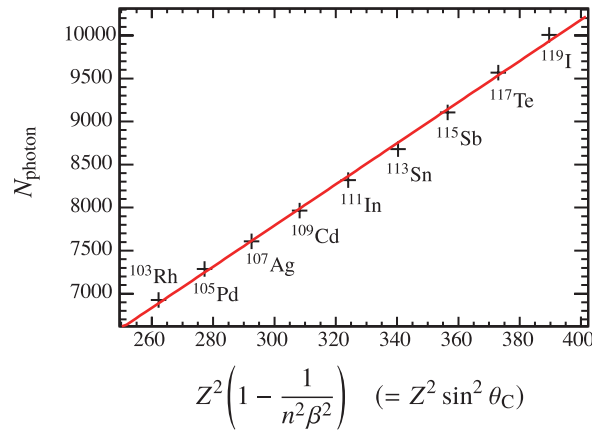
Figure 11: Relation between the number of photons and $Z^2 \sin^2 \theta_C$ which is a term of Eq. (1.1)

4. Summary

We have developed a RICH for heavy ions with several hundreds MeV/u energy. The experiment was performed at NIRS-HIMAC. HI-RICH is consist of a radiator and three pairs of

8×8 multi-anode photomultiplier tubes which are covered with band-pass filters to suppress optical dispersion. The nucleus of the primary beam was ^{132}Xe with an energy of 420 MeV/u. In the secondary beam experiment, the target material was a beryllium with a thickness of 2 mm.

As for the primary beam, a velocity resolution $\Delta\beta/\beta = 0.050\%$ (σ) and a detection efficiency $\varepsilon = 99.9\%$ were achieved. In regards to the secondary beam, a particle identification was successfully performed. In terms of typical nucleus ^{113}Sn, 5.3σ separation about the mass number was achieved.

References

[1] J. Seguinot; T. Ypsilantis. Nucl. Instrum. and Meth. 142 (1977) 377–391.

[2] S. Iwata, et al. Prog. Theor. Exp. Phys. 2016, no.3, 033H01.

[3] R. Gemhauser, et al. Nucl. Instrum. and Meth. A. 433 (1999) 217–221.

[4] M. Kanazawa, et al. Nucl. Phys. A 746 (2004) 393–396

[5] Edmund Optics. "U-360 UV Bandpass Filter Coating Performance".
    `http://www.edmundoptics.com/document/download/353912`