Observation of anisotropic collective flow of charged particles and neutrons in heavy-ion collisions at beam energies of 400 MeV/nucleon

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The anisotropic collective flow of protons and neutrons in heavy-ion collisions is expected to provide experimental information on the equation of state (EOS) of high-density and neutron-rich nuclear matters because it reflects the symmetry energy at the high-density region.[1)] The anisotropy is expressed by the distribution function of particle emissions observed from the reaction plane as

$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}\left(1 + 2\sum_n v_n \cos n\varphi\right), \qquad (1)$$

where φ, N_0 and v_n represent the emission angle of the particles observed from the reaction plane, normalization constant, and the anisotropic strength, respectively. The difference between the v_1 (directed flow) of neutrons and of protons is theoretically expected to be highly sensitive to EOS around target rapidity[2)] even though only a few experimental data are available.

A pilot experiment (H355) was conducted at HIMAC by impinging 400 MeV/nucleon ^{132}Xe beam on a CsI target (500 mg/cm^2) at a high intensity of 10^6 particles/spill to measure the proton and neutron flows precisely. In this experiment, 32 plastic scintillators (EJ299-33, $30 \times 55 \times 127$ mm^3) were used to identify neutrons using pulse-shape discrimination. The detectors were placed parallel to the beam axis and in a cylindrical configuration to detect particles at target rapidity. Charged and neutral particles can be identified by combining these detectors called NiGIRI (Neutron, ion, and γ-ray identification for radioactive isotope beam) and charged particle veto scintillators. Figure 1 shows the prototype NiGIRI array.[3)] Energies of the detected particles are deduced from the time-of-flight between the CsI target and NiGIRI detectors. Another set of 32 plastic scintillators called the Kyoto-array were used to cover the mid-rapidity region. The emitted angles of the charged particles were measured for determining the reaction plane. The plane was determined by the beam axis and $\boldsymbol{Q}$ vector obtained using

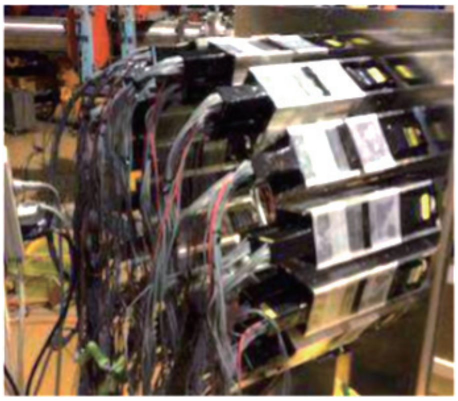

Fig. 1. NiGIRI detectors[3)] (16 arrays 2 layers).

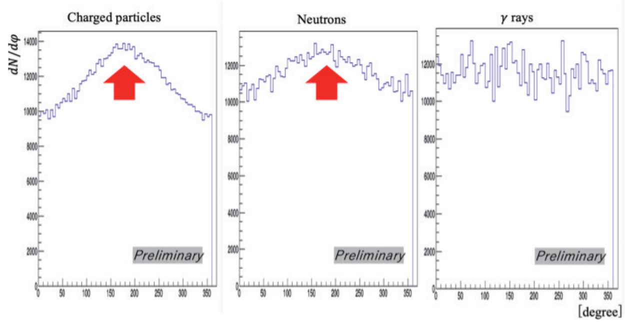

Fig. 2. Measured distribution functions dN/φ of charged particles (left), neutrons (center), and γ rays (right). The spectra were integrated over momentum and impact parameter.

$$\boldsymbol{Q} = \sum_k \begin{pmatrix} \cos\theta_k \\ \sin\theta_k \end{pmatrix}, \qquad (2)$$

where θ_k denotes a hit angle of Kyoto-array; the summation is taken over the number of detected particles. The cross-talk events observed in the Kyoto-array were mostly rejected in the $\boldsymbol{Q}$-vector determination to minimize the detector bias.

Emission angles of charged particles, neutrons, and γ rays with respect to the angle of $\boldsymbol{Q}$ vector were studied at target rapidity using the data of NiGIRI. Figure 2 shows the measured distribution functions ($dN/d\varphi$) of the charged particles, neutrons, and γ rays. The results indicate a clear anisotropy for charged particles and neutrons, and show flatter distribution for γ rays; the results are expected to indicate collective flow, particularly v_1, and therefore a pressure gradient is observed in the high-density region in heavy-ion collisions.

To the best of the author's knowledge, this experiment prooves for the first time that it is possible to directly compare the collective flow among light charged ions and neutrons around target rapidity. An upgraded experiment with a higher resolution of the reaction plane detector arrays will be performed at HIMAC and possibly RIBF in the future.

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