The centrality and energy dependence of the elliptic flow of light nuclei and hadrons in STAR

Outline
- Introduction & motivation
- STAR experiment at RHIC
- Results
- Summary

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Azimuthal anisotropy

\[ \frac{\partial P}{\partial x} > \frac{\partial P}{\partial y} \]

Interactions

Pressure (P)

Azimuthal distribution of produced particles can be described as a Fourier series. The second order coefficient,

\[ \langle \cos(2(\phi - \psi_R)) \rangle = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle \]

- Sensitive to early times in the evolution of the system

An estimate of \( \psi_R \), namely Event Plane (\( \psi_2 \)) is calculated using produced particles in mid-rapidity.

Motivation

- Particle anti-particle $v_2$ shows difference.

→ How does the difference depend on centrality and energy?

- hadron $v_2$ show constituent quark (NCQ) scaling.

- Nuclei are expected to form at a later stage due to their low binding energy

→ Can we expect mass number scaling of nuclei $v_2$ ?

→ How does nuclei and anti-nuclei $v_2$ compare?

→ Is there any centrality dependence of nuclei $v_2$ ?


The STAR experiment

1. Time Projection Chamber (TPC)
   pseudo-rapidity window: $-1.0 < \eta < 1.0$
   full azimuthal coverage.

2. Time of Flight (ToF)
   pseudo-rapidity window: $-0.9 < \eta < 0.9$
   full azimuthal coverage

Using TPC and ToF $\pi$, $K$, $p$ can be identified up to $p_T \sim 3.0$ GeV/c,

Light nuclei identification using TPC $d$, $d$-bar, triton: $p_T \sim 1.0$ GeV/c, and $^3$He up to 4.5 GeV/c

Light nuclei identification using ToF $d$, $d$-bar, triton: $p_T \sim 4.0$ GeV/c,
Measurement of nuclei $v_2$

- Elliptic flow of $d$, $\bar{d}$, $t$, $^3$He, $\overline{^3}$He measured at mid-rapidity.
- $\eta$ sub-eventplane method was used with $\eta$-gap = 0.1

$\sqrt{s_{NN}}$ from 19.6 GeV to 200 GeV

$\sqrt{s_{NN}} = 19.6$ GeV, $\sqrt{s_{NN}} = 11.5$ GeV, $\sqrt{s_{NN}} = 7.7$ GeV, $\sqrt{s_{NN}} = 39$ GeV, $\sqrt{s_{NN}} = 62.4$ GeV, $\sqrt{s_{NN}} = 200$ GeV

Centrality: 0-80%

STAR Preliminary

Mass ordering of $v_2$

$\bar{v}_{NN} = 200$ GeV

$\bar{v}_{NN} = 62.4$ GeV

$\bar{v}_{NN} = 39$ GeV

$\bar{v}_{NN} = 27$ GeV

$\bar{v}_{NN} = 19.6$ GeV

$\bar{v}_{NN} = 11.5$ GeV

$\bar{v}_{NN} = 7.7$ GeV

$\rightarrow$ Nuclei $v_2$ shows mass ordering at low $p_T$ similar to hadrons

\( v_2 \) of triton (t) and \(^3\text{He}\)

\[ v_2 \text{ of } t \text{ and } ^3\text{He} \text{ are of similar magnitude (within statistical uncertainty)} \]
$v_2$ of particles and anti-particles

$\Delta v_2$ for 10-40% centrality is similar to minimum bias result

$\Delta v_2$ relative to proton $v_2$ shows a centrality dependence

Nuclei and anti-nuclei $v_2$ shows a difference at 200 GeV

Statistical uncertainties large at lower beam energies to make definite conclusions.
Centrality dependence of nuclei $v_2$

$\sqrt{s_{_{NN}}}$ = 200 GeV
$\sqrt{s_{_{NN}}}$ = 62.4 GeV
$\sqrt{s_{_{NN}}}$ = 39 GeV
$\sqrt{s_{_{NN}}}$ = 27 GeV

$\sqrt{s_{_{NN}}}$ = 19.6 GeV
$\sqrt{s_{_{NN}}}$ = 11.5 GeV
$\sqrt{s_{_{NN}}}$ = 7.7 GeV

$\to$ Nuclei $v_2$ shows centrality dependence for all energies

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NCQ scaling of hadron $v_2$

- NCQ scaling observed for particle and anti-particle groups separately for beam energy $\geq 19.6$ GeV
- Scaling holds for $1.5 < p_T < 5.0$ GeV/c
- More statistics is needed for 7.7 and 11.5 GeV/c

Precision measurement of $v_2$ of $\phi$ and $\Omega$

- Mass ordering observed for $p_T < 2.0$ GeV/c
- Baryon – meson splitting for $2.0 < p_T < 5.0$ GeV/c

→ High precision measurement of $\phi$ and $\Omega$ $v_2$ agree with the previous physics conclusion of partonic collectivity at 200 GeV
Nuclei $v_2$ show mass number scaling for $p_T/A \sim 1.5$ GeV/$c$ for all beam energies

$\Rightarrow$ Support the general idea that nuclei are formed by coalescence of nucleons
Coalescence model results


\[ \text{Coalescence model agrees with data} \]

→ Another indication of coalescence of nucleons to form nuclei

- Probability for producing a nucleus is given by the overlap of nucleon phase-space distribution with the Wigner phase-space function of nucleons inside the nuclei.
- Nucleon phase space information used from a transport (AMPT) model.


Summary

(A) New Measurement presented:
✓ Energy ($\sqrt{s_{NN}} = 7.7, 11.5, 19.6, 27, 39, 62.4$ and $200$ GeV) and centrality dependence of nuclei $v_2$ presented.
✓ Centrality dependence of difference in $v_2$ of proton and anti-proton at $\sqrt{s_{NN}} = 7.7, 11.5, 19.6, 27, 39, 62.4$ presented.

(B) Observation and Physics conclusion:
1. Nuclei $v_2$ versus $p_T$ shows a clear centrality dependence and mass ordering when compared to identified hadrons at all beam energies studied
   → Mass ordering of $v_2$ occurs naturally in a hydrodynamic model.
2. Nuclei $v_2$ versus $p_T$ shows mass number scaling upto $p_T/A = 1.5$ GeV/c and the magnitude of nuclei $v_2$ versus $p_T$ are reproduced by a Coalescence model.
   → Both these support the physics picture of coalescence of nucleons as the dominant mechanism of nuclei production.
3. The difference in $v_2$ of proton and anti-proton is observed to be similar at all collision centralities studied for the BES energies. A centrality dependence appears when this difference is normalized to proton $v_2$ at the respective beam energies
   → The results implies hadronic interactions play an important role at lower beam energies.
Other interesting results on flow from STAR (Posters):

- Triangular Flow of Identified Hadrons in Au+Au Collisions at $\sqrt{s_{NN}} = 39$ and 200 GeV
  - Xu Sun  *(Poster Id: H-37)*

- Measurement of higher harmonic flow of $\phi$ meson in STAR at RHIC
  - Mukesh Sharma  *(Poster Id: H-03)*

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Back up is here…
Centrality dependence of hadron $v_2$

Anti-particles:

particles:
Baryon meson ratio

\[ v_2 \times m_T - m_0 \text{ data fitted} \]

\[ v_2 \text{ baryon to } v_2 \text{ meson ratio taken at } m_T - m_0 = 2.0 \text{ GeV/c for baryons and (2/3) of that value for mesons} \]

- Splitting larger for particles than for anti-particles
- Centrality dependence only for anti-particles
- No energy dependence