Probing properties of pion- and kaon-emitting sources at NICA energies

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The QCD Phase Diagram

Main goals

• Explore QCD phase diagram, study the Equation of State (EoS) and transport properties of the medium
• Search for the 1st-order phase transition and critical point
• Study turn-on and turn-off signatures of sQGP

How to study

• Collisions of ions at various energies
  • BES-I and BES-II programs at RHIC
  • MPD and BM@N experiments at NICA
  • NA61/SHINE experiment at SPS
Searches for the First-order Phase Transition

- **Softening of the EoS**
  - Could be observed in the $dv_1/dy$ slope
  - Strong softening: consistent with the 1st-order phase transition
  - Weaker softening: likely due to crossover

- **Time delays of the particle emission**
  - Could be observed using femtoscopy technique

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D.H. Rischke, M. Gyulassy. NPA 608 (1996) 479

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Correlation Femtoscopy

- Two-particle correlation function (CF):
  \[ \text{CF}(p_1, p_2) = \int d^4r \, S(r, k) \, |\Psi_{1,2}(r, k)|^2 \]
  \[ r = x_1 - x_2 \text{ and } q = q_{\text{inv}} = p_1 - p_2 \]
- Experimentally:
  \[ \text{CF}(q) = A(q)/B(q) \]
  - A(q) – contain quantum statistical (QS) correlations and final state interactions (FSI)
  - B(q) – obtained via mixing technique (does not contain QS and FSI)

The relative pair momentum can be projected onto the Bertsch-Pratt, out-side-long system:
- \( q_{\text{long}} \) – along the beam direction
- \( q_{\text{out}} \) – along the transverse momentum of the pair
- \( q_{\text{side}} \) – perpendicular to longitudinal and outward directions

Correlation functions are constructed in Longitudinally Co-Moving System (LCMS), where \( p_{1z} + p_{2z} = 0 \)

S. Pratt. PRD 33 (1986) 1314
Why Correlation Femtoscopy?

- Access to the spatial and temporal information about a particle-emitting source at kinetic freeze-out

- Different particle species are sensitive to various effects (Final State Interactions (FSI), transport properties, asymmetries, etc...)

- Femtoscopy provides strong model constraints

V.M. Shapoval et al. NPA 968 (2017) 391
D.H. Rischke, M. Gyulassy. NPA 608 (1996) 479

G. Nigmatkulov et al. NUCLEUS-2020

S. Pratt et al. PRL 114 (2015) 202301
Femtoscopy: World Systematics

- Precise measurements in a broad energy range (from 7.7 GeV to 2.76 TeV)
- Need more high-statistics measurements at low energies
- Precise measurements exist only with pions
  - Need heavier particles

G. Nigmatkulov et al. NUCLEUS-2020

R. Lacey. PRL 114 (2015) 142301


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Femtoscopy with Strange Particles

- Contain strange (anti)quark
- Enhancement of strange particle yields was one of the first suggested signatures of QGP
  J. Rafelski and B. Muller. PRL 48 (1982) 1066

- Interesting behavior was observed in $K/\pi$ ratios at NICA energies
- Could be sensitive to different production mechanisms at low collision energies

We would like to explore the quark-gluon matter at NICA/FAIR/RHIC energies using femtoscopy technique

This talk is dedicated to the study with
the UrQMD (micr. descr.) and
VHLLE (viscous hydrodynamics + resc.) models


J. Rafelski and B. Muller. PRL 48 (1982) 1066

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Correlation Functions from UrQMD

- Examples of the correlation functions of pions and kaons obtained for Au+Au collisions at \( \sqrt{s_{NN}} = 11.5 \) GeV

- Correlation functions were fitted with:

\[
C(q_{\text{out}}, q_{\text{side}}, q_{\text{long}}) = 1 + \lambda e^{-R_{\text{out}}^2 q_{\text{out}}^2 - R_{\text{side}}^2 q_{\text{side}}^2 - R_{\text{long}}^2 q_{\text{long}}^2}
\]

Where:

\( R_{\text{side}} \) – size of the emission region

\( R_{\text{out}} \) – sensitive to the emission duration

\( R_{\text{long}} \) – proportional to the system lifetime

| | \( q_{\text{other}} \) | < 0.05 GeV/c

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Correlation Functions from vHLLE

• Examples of the correlation functions for pions obtained for Au+Au collisions at $\sqrt{s_{NN}}=11.5$ GeV obtained for two equations of state:
  • XPT – cross over
  • 1PT – first-order phase transition

• Correlation functions were fitted with:

$$C(q_{out}, q_{side}, q_{long}) = 1 + \lambda e^{-R_{out}^2 q_{out}^2 - R_{side}^2 q_{side}^2 - R_{long}^2 q_{long}^2}$$

Where:

- $R_{side}$ – size of the emission region
- $R_{out}$ – sensitive to the emission duration
- $R_{long}$ – proportional to the system lifetime
Femtoscopic radii are sensitive to the type of the phase transition

Cross over EoS reasonably describes measured femtoscopic radii

$R_{\text{out}}/R_{\text{side}}$ (XPT) agrees with STAR data points at 7.7 and 11.5 GeV but then increases with increasing collision energy


P. Batyuk et al. NUCLEUS-2020
Femtoscopic Radii of Pions from UrQMD and vHLLE

- Femtoscopic radii of pions decrease with increasing transverse mass
  - Influence of radial flow
- $R_{side}$ increases going from peripheral to central collisions
  - Geometrical picture of ion-ion collision
- UrQMD shows similar results to vHLLE with 1PT
- vHLLE with XPT reasonably describe STAR data
Femtoscopic Radii of Pions and Kaons from UrQMD

- Femtoscopic radii of pions decrease with increasing transverse mass
  - Influence of radial flow
- $R_{\text{side}}$ values for pions and kaons are similar
  - Similar size of the particle-emitting region
- $R_{\text{long}}$ for kaons is generally larger than that for pions at the same $m_T$
  - Influence of resonances?
- $R_{\text{out}}$ pions and kaons behave differently
  - Different emission duration?
  - Change of the production mechanism?
• Pion and kaon results for the cross over (XPT) and 1st-order (1PT) phase transitions
• Femtoscopic radii of pions decrease with increasing transverse mass
  • Influence of radial flow
• $R_{\text{side}}$ values for pions and kaons are similar
  • Similar size of the particle-emitting region
• $R_{\text{out}}$ for both pions and kaons show similar behavior
  • Similar particle emission duration?
• $R_{\text{long}}$ for kaons is generally larger than that for pions at the same $m_T$
  • Influence of resonances?
Energy dependence of femtoscopic radii

- Estimated radii for NICA energy range ($\sqrt{s_{NN}}= 4$-11 GeV)
- Pion radii slightly increase with increasing collision energy
- Excitation function of $R_{\text{long}}$ suggests a slight increase of the system lifetime with increasing $\sqrt{s_{NN}}$
Summary

- We performed the first model estimation of kaons femtosopic radii using the UrQMD and vHLLE models.
- Pion femtosopic radii decrease with increasing transverse momentum.
- Experimental pion radii can be reasonably described by vHLLE with XPT.
- Kaon radii dependence as a function of transverse mass shows:
  - $R_{\text{side}}$ values for pions and kaons are similar for vHLLE and behaviour is different for UrQMD.
  - $R_{\text{long}}$ for kaons is generally larger than that for pions.
- Energy dependence of $R_{\text{long}}$ for both pions and kaons at NICA energies suggests a slight increase of the system lifetime.