Pion-kaon femtoscopy in Therminator 2 model

Paweł Szymański
pawel.szymanski.dokt@pw.edu.pl

Warsaw University of Technology
Faculty of Physics

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Phenomenological models

- Microscopic
  - Dynamic simulation of the collision process inspired by QCD
  - Tracking of individual objects
  - Propagation of individual particles through a cascade of collisions and decays

- Macroscopic
  - No consideration of the dynamics of individual objects in detail
  - Statistical description of multiparticulate system

What about generators?

Paweł Szymański (WUT)
Phenomenological models

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Microscopic

Macroscopic
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Macroscopic

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What about generators?
THERMINATOR generator

THERMAl heavy-IoN GenerATOR 2

- Generates collisions of relativistic ions
- Uses Monte Carlo methods
- Implements thermal models of particle production with single freeze-out

THERMINATOR: THERMAl heavy-IoN generATOR

THERMINATOR 2: THERMAl heavy-IoN generATOR 2

THERMINATOR is a Monte Carlo event generator designed for studying of particle production in relativistic heavy-ion collisions performed at such experimental facilities as the SPS, RHIC, or LHC. The program implements thermal models of particle production with single freeze-out.
Input file

[Ranges]
# Rapidity range
RapPRange = 4.0

# Spatial rapidity range
RapSRange = 8.0

[Model_parameters]
# Proper time at freeze-out [fm]
Tau = 9.91

# Maximum transverse radius [fm]
RhoMax = 7.43

# Transverse velocity [c]
VelT = 0.407

# Parameter A
ParA = 0.5

# Delay of the particle emition [fm]
Delay = 0.0

# Freeze-Out Temperature [MeV]
Temperature = 165.6

# Chemical potentials for Barion, Isospin (I_3), Strangeness and Charm [MeV]
MuB = 28.5
MuI = -0.9
MuS = 6.9
MuC = 0.0

[Subdirectory]
# subdirectory to store events of this model
EventSubDir = bwap/

Input file takes following information:

- The number of events
- Parameters:
  - Temperature [MeV]
  - MuB, MuI, MuS [MeV]
  - VelT
  - Tau, RhoMax [fm]
Input parameters

- Temperature (T) and chemical potentials: baryon ($\mu_B$), strangeness ($\mu_S$), third component of isospin ($\mu_I$) — thermodynamical parameters
- VelT (Vt) — a parameter specific to the Blast-Wave model, denoting velocity
- Tau, RhoMax — geometrical parameters

Vt, Tau and RhoMax affect the produced particles

The relation between RhoMax and Tau is:

$$\rho_{\text{max}}^2 \cdot \tau \simeq V$$

V is the volume of the source
Beam Energy Scan at STAR
BES goals

Developed to find answers for several questions:

- Search for turn-off of QGP signatures
- Search for the QCD critical point
- Search for the signals of phase transition/phase boundary
### Therminator generator adaptation to the conditions of RHIC and FAIR experimental complexes

<table>
<thead>
<tr>
<th>$\sqrt{s_{NN}} [GeV]$</th>
<th>$T$ [MeV]</th>
<th>$\mu_B$ [MeV]</th>
<th>$\mu_S$ [MeV]</th>
<th>$\mu_{I_3}$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.7</td>
<td>139.0</td>
<td>406.4</td>
<td>93.4685</td>
<td>-10.5677</td>
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<tr>
<td>11.5</td>
<td>150.1</td>
<td>303.2</td>
<td>69.9562</td>
<td>-7.9697</td>
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<td>156.2</td>
<td>196.8</td>
<td>45.6875</td>
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<tr>
<td>27</td>
<td>157.6</td>
<td>149.0</td>
<td>34.7938</td>
<td>-4.0845</td>
</tr>
<tr>
<td>39</td>
<td>158.4</td>
<td>106.9</td>
<td>25.1974</td>
<td>-3.0241</td>
</tr>
<tr>
<td>62.4</td>
<td>158.8</td>
<td>68.9</td>
<td>16.5409</td>
<td>-2.0676</td>
</tr>
</tbody>
</table>

"Therminator generator adaptation to the conditions of RHIC and FAIR experimental complexes",
Engineer’s Thesis, Monika Seniut
### Therminator for BES program

<table>
<thead>
<tr>
<th>$\sqrt{s_{NN}}$ [GeV]</th>
<th>$\tau$ [fm]</th>
<th>$\rho_{max}$ [fm]</th>
<th>$V_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.7</td>
<td>8.3</td>
<td>8</td>
<td>0.65</td>
</tr>
<tr>
<td>11.5</td>
<td>8.35</td>
<td>8</td>
<td>0.8</td>
</tr>
<tr>
<td>19.6</td>
<td>8.75</td>
<td>8.2</td>
<td>0.85</td>
</tr>
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<tr>
<td>62.4</td>
<td>9.4</td>
<td>9</td>
<td>0.75</td>
</tr>
</tbody>
</table>

"Adaptation of the THERMINATOR model for BES program", Quark Matter 2018, H. Zbroszczyk & P. Szymański
**Pion-kaon femtoscopy — asymmetry**

\[ C(q) = \int |\Psi(q, r)|^2 S(r) d^3r \]

\[ S(r) = \exp\left( -\frac{(r_{out} - \mu_{out})^2}{\sigma_{out}^2} - \frac{r_{side}^2}{\sigma_{side}^2} - \frac{r_{long}^2}{\sigma_{long}^2} \right) \]

\( \mu_{out} \) — asymmetry in the outward direction

assumption: \( \sigma_{side} = \sigma_{out}, \sigma_{long} = 1.3\sigma_{out} \)

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R. Lednicky, et al.  

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A. Kisiel  
Pion-kaon femtoscopy — asymmetry

\[ C(\vec{q}) = \int |\Psi(\vec{q}, \vec{r})|^2 S(\vec{r}) d^3r \]

known \hspace{1cm} unknown

\[ S(\vec{r}) = \exp \left( -\frac{(r_{out} - \mu_{out})^2}{\sigma_{out}^2} - \frac{r_{side}^2}{\sigma_{side}^2} - \frac{r_{long}^2}{\sigma_{long}^2} \right) \]

\( \mu_{out} \) — asymmetry in the outward direction

assumption: \( \sigma_{side} = \sigma_{out} \), \( \sigma_{long} = 1.3\sigma_{out} \)

\[ \beta_{particle} = \beta_f + \beta_t \]

\( \beta_f \) — collective (flow) velocity

\( \beta_t \) — thermal (random) velocity

Emission asymmetry arises in a system where both thermal and collective velocities exist and are comparable in magnitude.
SH representation of 3D correlation function as a set of 1D plots

\[ C(q) = \sum_{l,m} C_{l,m}(q) Y_{l,m}(\theta, \phi) \]

\[ C_{l,m}(q) = \int_{\Omega} C(q, \theta, \phi) Y_{l,m}(\theta, \phi) d\Omega \]

\( \Omega \) - full solid angle

\( Y_{l,m}(\theta, \phi) \) - spherical harmonic function

\( q = |q| \) - pair relative momentum

\( \theta \) and \( \phi \) - polar and azimuthal angle
Pion-kaon femtoscopy — Spherical harmonics (SH)

SH representation of 3D correlation function as a set of 1D plots

\[ C(q) = \sum_{l,m} C_{lm}^m(q) Y_{lm}^m(\theta, \phi) \]

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\( C_0^0 \rightarrow \) sensitive to the size of the emitting source (shapes same as correlation function)

\( C_1^1 \rightarrow \) sensitive to the spacetime emission asymmetry

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P. Danielewicz and S. Pratt.

Z. Chajecki and M. Lisa

A. Kisiel and D.A. Brown

A. Kisiel
Which particle...?

Like-sign particle combinations

- $C_0^0(k^*)$
- $C_1^0(k^*)$
- $C_1^1(k^*)$

Lighter particle emitted closer to the center and/or later.

Heavier particle emitted closer to the center and/or later.

$k^* [\text{GeV/c}]$

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$k^* [\text{GeV/c}]$
Pion-kaon femtoscopy

- visible emission asymmetry
- most of the pions are emitted closer to the center and/or later than most of the kaons
Average emission points

\begin{align*}
\langle x_{\text{out}} \rangle &= 3.87 \text{ fm} \\
\langle x_{\text{out}} \rangle &= 4.84 \text{ fm} \\
\langle x_{\text{out}} \rangle &= 5.16 \text{ fm}
\end{align*}

- visible emission asymmetry
- most of the pions are emitted closer to the center and/or later than most of the kaons
Fitting procedure using CorrFit tool. Gaussian source distribution assumed.

CorrFit use the full information of the interaction potential (both coulomb and strong interaction)

The "best-fit" correlation function is found through the minimum $\chi^2$ method

CorrFit - a program to fit arbitrary two-particle correlation functions
Pion-kaon femtoscopy

\[ C_0^i(k^*) \quad \text{(Input)} \]
\[ C_0^f(k^*) \quad \text{(Fit)} \]

\[ k^* \text{ (GeV/c)} \]

\[ \begin{aligned} R &= 10.0 \pm 0.5 \\ \mu &= -5.0 \pm 0.5 \end{aligned} \]

\[ \begin{aligned} R &= 8.0 \pm 1.0 \\ \mu &= -4.5 \pm 0.5 \end{aligned} \]
Pion-kaon femtoscopy

Fitting procedure using CorrFit tool. Gaussian source distribution assumed.

CorrFit - a program to fit arbitrary two-particle correlation functions

- smaller sizes than size measured in the STAR
- visible size dependence on collision energy
- smaller emission asymmetry than measured in the STAR
- visible asymmetry dependence on collision energy
All and primary particles SH components

$$\sqrt{s_{NN}} = 62.4 \text{ GeV}$$

![Graphs showing $C_0(k)$ and $C_1(k)$ for $\pi^+ K^+$ and $K^+ \pi$ for all particles and only primary particles.](image-url)
All and primary particles — 62.4 GeV

\[
C_0(k^*)
\]

**Input**

62.4 GeV

All particles

\[ R = 10.0 \pm 0.5 \]

**Fit**

\[ \mu = -5.0 \pm 0.5 \]

\[
C_0(k^*)
\]

62.4 GeV

Primary particles

\[ R = 7.0 \pm 1.0 \]

\[ \mu = -3.0 \pm 1.0 \]
Summary

- Obtained size of the source and emission asymmetry from THERMINATOR 2 for BES energies
- Observed clear signal of asymmetry in emission process:
  - pions emitted closer to the center and/or later than kaons
- Size and emission asymmetry show dependence on collision energy
- Source sizes smaller than in the STAR
- Emission asymmetry smaller than in the STAR
- Size and emission asymmetry are smaller for only primary particles
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Thank you for your attention!