Thermal Model for RHIC II: elliptic flow and HBT radii

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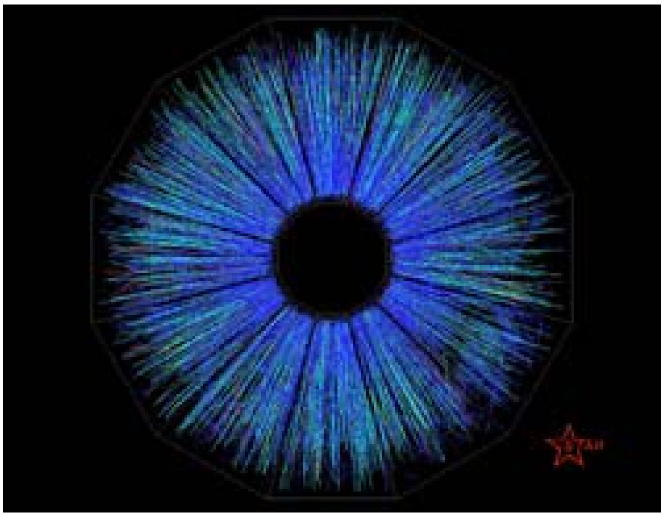


The iris of RHIC

Model at $b \neq 0$

Two empirical facts from RHIC:

1. $v_2 > 0$ (more particles in the reaction plane)

2. $R_{\rm side}$-measurement: the shape elongated out-of-reaction plane (early freeze-out in conflict with hydro)

Choice of parameterization taking this into account:

$$
\begin{aligned}
r_x &= \rho\sqrt{1-\epsilon}\cos\phi \\
r_y &= \rho\sqrt{1+\epsilon}\sin\phi
\end{aligned}
$$

r_z, t as for the symmetric case

$$
\begin{aligned}
u_x &= \frac{1}{N} r_x \sqrt{1+\delta}\cos\phi \\
u_y &= \frac{1}{N} r_y \sqrt{1-\delta}\sin\phi \\
u_z &= \frac{1}{N} r_z, \quad u_t = \frac{1}{N} t
\end{aligned}
$$

normalization N such that $u^\mu u_\mu = 1$

Azimuthal asymmetry

At $b \neq 0$ asymmetry of shape in the $x - y$ plane

$$\left.\frac{dN}{d^2p_\perp dy}\right|_{y=0} = \left.\frac{dN}{2\pi p_\perp dp_\perp dy}\right|_{y=0} (1 + 2v_2 \cos 2\phi + \ldots)$$

The elliptic-flow coefficient:

$$v_2 = \frac{\int_0^{2\pi} \left.\frac{dN}{d^2p_\perp dy}\right|_{y=0} \cos 2\phi \, d\phi}{\int_0^{2\pi} \left.\frac{dN}{d^2p_\perp dy}\right|_{y=0} d\phi}$$

$v_2 \neq 0$ is a signature of rescattering effects (final state interactions, flow, ...), since $\sum(p+p)$ symmetric

v_2 depends on the impact parameter b, $p_\perp$, and the type of particle

Centrality parameter:

WB+WF, PRC65 (2002) 024905

$$c \simeq \frac{b^2}{(2R)^2}$$

(for most central collisions $c = 0$!)

ϕ-averaged $p_\perp$-spectra at $b \neq 0$

Fit, ignoring δ and ϵ (effects are tiny %), at various centralities works as good as at $b = 0$

	PHENIX @130GeV				PHENIX+STAR @130GeV
c [%]	min. bias	0-5	15-30	60-92	0-5/0-6
τ [fm]	5.6	8.2	6.3	2.3	7.7
$\rho_{\max}$ [fm]	4.5	6.9	5.3	2.0	6.7
$\rho_{\max}/\tau$	0.81	0.84	0.84	0.87	0.87
$\beta_\perp^{\max}$	0.62	0.64	0.64	0.66	0.66
$\langle\beta_\perp\rangle$	0.46	0.47	0.47	0.48	0.48

Summary of v_2

1. Elliptic flow can be introduced
2. $\epsilon(c)$ can be taken from (future) data
3. $\delta(c)$ fitted to the v_2 – reasonable values
4. Predictions for various particles and the $p_\perp$ dependence
5. Resonances lower v_2
6. How to describe saturation at high $p_\perp$?

Hanbury Brown–Twiss (HBT) correlation radii

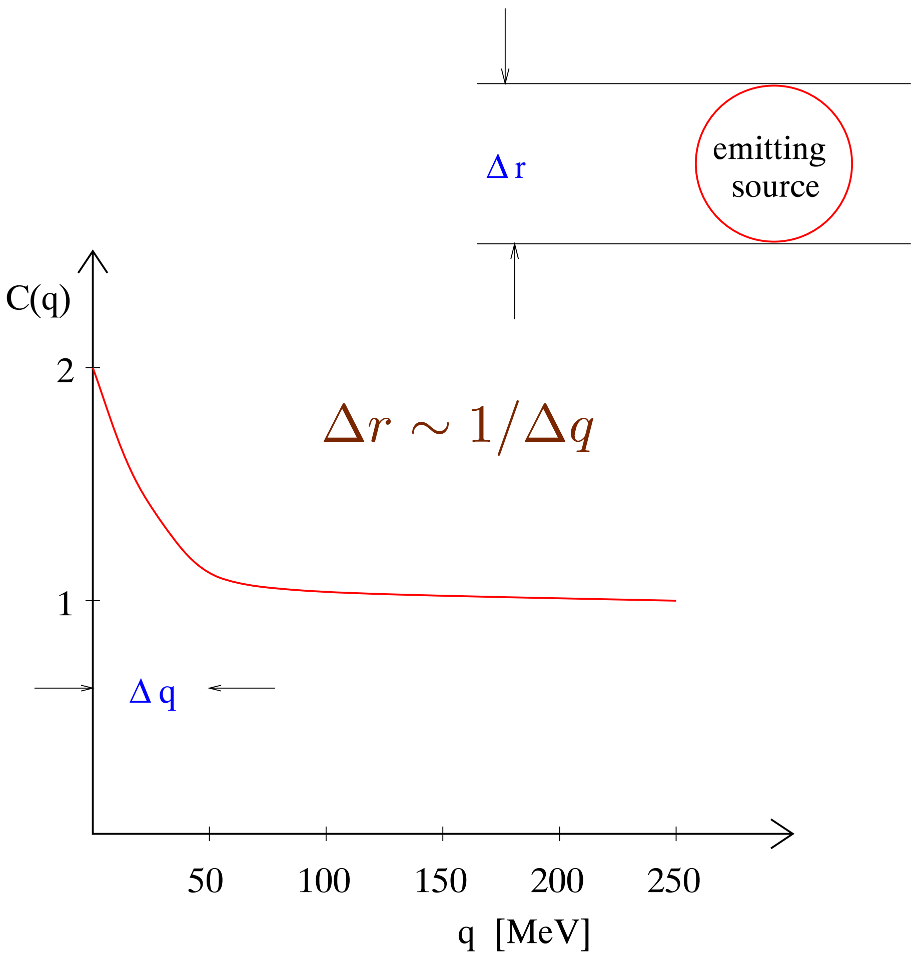
G. Baym, Acta Phys. Pol. B29 (1998) 1839

radioastronomy: measuring of correlations of signal intensities $\rightarrow$ angular sizes of radio sources

nuclear/particle physics: study correlations of identical particles $(\pi^+\pi^+,\ \pi^-\pi^-,\ \ldots)$

$$C(\vec{q},\vec{P}) = \frac{\{n_{\vec{p}_1} n_{\vec{p}_2}\}}{\{n_{\vec{p}_1}\}\{n_{\vec{p}_2}\}},$$

$\vec{q} = \vec{p}_2 - \vec{p}_1$, $\vec{P} = \vec{p}_1 + \vec{p}_2$, $\{\ \}$ – over events



Discovering the shape...

coordinates: $\vec{P}||\vec{x}, \quad \text{out} = x, \quad \text{side} = y, \quad \text{long} = z$

$$C(\vec{q}) = 1+\lambda e^{-\left(q_{\text{out}}^2 R_{\text{out}}^2 + q_{\text{side}}^2 R_{\text{side}}^2 + q_{\text{long}}^2 R_{\text{long}}^2 + 2 q_{\text{out}} q_{\text{long}} R_{\text{ol}}^2\right)}$$

with the geometric interpretation:

Bertsch-Pratt param.

$$\begin{aligned} R_{\text{side}}^2 &= < y^2 >, \quad R_{\text{out}}^2 =< (x - v_x t)^2 > \\ R_{\text{long}}^2 &= < (z - v_z t)^2 >, \; R_{\text{ol}}^2 =< (x - v_x t)(z - v_z t > \end{aligned}$$

Model evaluation (with some approximations):

$$C(\vec{q}) = 1 + \frac{\left| \int d\Sigma(x) \cdot u(x) e^{iq\cdot x} S(P \cdot u(x)) \right|^2}{\int d\Sigma \cdot u S((P + \frac{q}{2}) \cdot u(x)) \int d\Sigma \cdot u S((P - \frac{q}{2}) \cdot u(x))}$$

where the source function is

$$S(p{\cdot}u) = \frac{1}{(2\pi)^3} e^{-(p\cdot u - \mu)/T} + \text{contr. from resonances}$$

hydro/QGP: $R_{\rm out}/R_{\rm side} > 1$ (significantly)

experiment:

- R's of the order of target size
- $R_{\rm out}/R_{\rm side} \simeq 1$

MOST SURPRISINGLY, independent of the collision energy!

J/ψ

Prediction from the thermal model:

$$\frac{J/\psi}{\pi^-} = 0.12^{+0.16}_{-0.07} \times 10^{-6}$$

WB+WF, PRC 65 (2002) 064905

for $T = 165^{+7}_{-7}$ MeV

(somewhat lower than the estimate of Bugajev, Gaździcki, and Gorenstein, who use higher T)

Geometry at various energies

Most central collisions (errors not estimated)

	NA44	PHENIX	PHENIX	PHENIX	BRAHMS
$\sqrt{s_{NN}}$ [GeV]	17	130	+STAR 130	200	200
c [%]	0-5*	0-5	0-5/0-6	0-5	10
τ [fm]	8.0	8.2	7.7	7.2	7.5
$\rho_{\rm max}$ [fm]	5.9	6.9	6.7	7.9	7.7
$\rho_{\rm max}/\tau$	0.73	0.84	0.87	0.90	0.97
$\beta_\perp^{\rm max}$	0.59	0.64	0.66	0.67	0.70
$\langle\beta_\perp\rangle$	0.43	0.47	0.48	0.50	0.52

week dependence of parameters, slight increase of the flow velocity on $\sqrt{s_{NN}}$

Successes

1. The thermal model works for the particle ratios

2. Supplied with expansion, it works for the $p_\perp$-spectra

3. Supplied with elliptic flow, describes identified v_2

4. Supplied with the excluded-volume corrections, works for the HBT radii

5. Description efficient, few parameters with clear interpretation

6. Works also very well for the hadrons containing strange quarks (ϕ, Λ, Ξ, Ω, ...)!

7. Universal freeze-out approximation supported by data (K^*'s, ϕ, ρ?)

8. Early freeze-out (HBT, $R_{\rm side}(\phi)$)

9. Model also works for the RHIC @ 200 GeV A as well as for SPS @ 17 GeV A

Questions to the model and beyond

1. Why should the simple $e^{-(E-\mu)/T}$ work? Kinetic arguments indicate there is no time to achieve thermal equilibrium in the gas of hadrons (early freeze-out)

2. Is this the property of hadronization ?

3. Questions to prehistoric (*i.e.* pre-freeze-out) times: *Was there quark-gluon plasma?* If yes, why the transverse size does not grow with the collision energy?

4. How to construct a (microscopic) model for early stages such that the conditions at freeze-out which we use are reached?