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# Clustering in heavy ion collisions. Why it could happen and how to observe it?

**Giorgio Torrieri**[*†]
[1]*Institut für Theoretische Physik, J.W. Goethe-Universität, Frankfurt, Germany*
*E-mail:* torrieri@th.physik.uni-frankfurt.de

**Igor Mishustin**
*FIAS, J.W. Goethe-Universität, Frankfurt, Germany and Kurchatov Institute, Russian Research Center, Moscow 123182, Russia*
*E-mail:* mishustin@fias.uni-frankfurt.de

**Boris Tomasik**
*Univerzita Mateja Bela, Banská Bystrica, Slovakia and Czech Technical University in Prague, Prague, Czech Republic E-mail:* tomasik@fpv.umb.sk

We argue that Clustering in heavy ion collisions could be the missing element in resolving the so-called HBT puzzle, and briefly discuss the different physical situations where clustering could be present. We then propose a method by which clustering in heavy ion collisions could be detected in a model-independent way

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[*]Speaker.
[†]A footnote may follow.



PoS(Confinement8)112

## 1. The HBT puzzle

One of the most unexpected, and as yet unexplained, experimental results found at the Relativistic Heavy Ion Collider (RHIC) concerns the description of particle interferometry observables [1]. It was originally expected that the deconfined matter would be a highly viscous, weakly interacting quark gluon plasma [2]. Thus, ideal hydrodynamics would not provide a good description of flow observables sensitive to the early stages of the collision, such as azimuthal anisotropy. The signature of choice of a phase transition from hydrodynamics models, one less sensitive to viscosity, was to be an increase of the "out" to "side" emission radius ratio due to longer lifetime of the system, caused by the softening of the equation of state in the transition/crossover region [3].

The data, however, exhibited an opposite behavior. Hydrodynamic simulations provided a good description of transverse momentum spectra and their azimuthal anisotropy. The same simulations, however, failed to describe HBT data [4]. Perhaps the most surprising aspect of the problem is the *way* in which the data does not fit: Measured parameters $R_o$ and $R_s$ are nearly identical [1]. Their (positive) difference $R_o^2 - R_s^2$ is thought to depend on the duration of particle emission. Hence, it looks like the fireball emits particles almost instantaneously and does not show any sign of phase transition or crossover. Hydrodynamics, with "reasonable" freeze-out condition (such as a freeze-out temperature of 100 MeV or so) can not describe this even qualitatively. This behavior, when compared to lower energy data, exhibits remarkably good scaling with multiplicity. The scaling's *existence*, however, is by itself surprising since the QCD equation of state, with it's critical density for a phase transition, should break it.

One physical effect missing in hydrodynamic calculations, which could explain this data (both the disagreement with hydrodynamics at a given energy and the scaling with energy and system size) is the hypothesis that at the phase transition the system breaks up into clusters, of size considerably smaller than, and independent of, the total system size.

Fragmentation of the bulk could help solving the problems associated with HBT. Firstly, fragment size, density and decay timescale, is approximately independent of either reaction energy or centrality. Hence, the near energy independence of the (comparatively short) emission timescale, and hence of $R_o/R_s$, should be recovered. Secondly, if the decay products do not interact (or do not interact much) after fragment decay, it can also be seen that $\langle \Delta x \Delta t \rangle$ can indeed be positive: outward fragments are moving faster, resulting in time dilation. This effect can be offset by time dilation of fragment decay by increasing the temperature at which fragments form, or by increasing fragment size. Recovering the linear scaling of the radii with $(dN/dy)^{1/3} (\sim N_{\text{fragments}})$ [1], while maintaining the correct $R_o/R_s$ is also possible if the fragments decay when their distance w.r.t. each other is still comparable to their intrinsic size.

## 2. Clustering in heavy ion collisions: How it could happen

Historically, the break-up of the system produced in heavy ion collisions into clusters has long been studied in the context of a first order phase transition [5]. As is widely known [6], a first order phase transition implies the existence of a mixed phase (whose extent in energy density corresponds to the latent heat) where the free energy has two coexisting minima,as well as a generally low (parametrically) *transition probability* between these minima.

The existence of the two minima introduces a rate of transition that can be macroscopic even if all the other microscopic scales of the system (mean free path, relaxation time) are small w.r.t. the macroscopic scale (the inverse of gradient of the collective flow. When this is large compared to the microscopic scales the system is, generally, a "good fluid" [7]).

If this characteristic timescale for transition between the coexisting minima is also parametrically small w.r.t. the flow gradient, the Navier-Stokes equations continue to be an effective description of the system, and the only effect of the phase transition will be a collapse of the speed of sound in the mixed phase (this is the approach assumed in [4]). If this scale is parametrically *large*, the system does not undergo a phase transition during the mixed phase, experiences supercooling, and eventually fragments due to a higher vacuum pressure [8]. If the transition scale and the flow gradient are comparable, the dynamics of the nucleation of the bubbles of "cold phase" will significantly distort the hydrodynamic flow. Hence, in two out of these scenarios the system will *not* evolve as a good fluid after the phase transition temperature, but will instead fragment into independent fragments, whose fragments (determined by causality, transition probability and flow gradient) are generally smaller and weakly dependent on the total system size.

The case most relevant to heavy ion collisions is, at the moment, not known. The flow gradient in the Heavy ion fluid is not precisely determined, due to our uncertainty in initial conditions. The transition probability between the two vacua, in the first order regime, is calculable from lattice QCD, through at present such an estimate is unknown. What is strongly believed [9], however, is that at low chemical potentials, relevant to RHIC and LHC energies, the phase transition is not first order, but in fact a smooth cross-over, with no double minima in the free energy. Hence, while clustering in the mixed phase might be relevant at lower energies (such as the RHIC and SPS energy scans, and the coming experimental program at FAIR [10]), it is unlikely to be relevant at top RHIC energies.

This, however, is *not* the only possible way for a system to cluster. As shown in [11, 12], a fluid could also break into clusters if the bulk viscosity of the system experiences a sharp peak. As shown in [13], this is indeed what happens in QCD; This rise in bulk viscosity can be understood from the fundamental symmetry features of QCD. Perturbatively, QCD is to a good approximation conformally invariant (the only conformally-breaking terms are the quark mass, parametrically small quark mass and the logarithmically slowly running coupling constant). Non perturbatively, however, QCD has the non-perturbative *conformal anomaly*, that manifests itself in the scale (usually called $\Lambda_{QCD}$) at which the QCD coupling constant stops being small enough for the perturbative expansion to make sense. This scale coincides with the scale at which confining forces hold hadrons together. Remembering that the shear ($\eta$) and bulk ($\zeta$) viscosities roughly scale as [14]

$$\eta \sim \tau_{\text{elastic}} T^4 \qquad \zeta \sim \left(\frac{1}{3} - v_s^2\right)^2 \tau_{\text{inelastic}} T^4 \tag{2.1}$$

where $\tau_{\text{(ine)elastic}}$ refers to the equilibration timescale of (ine)elastic collisions. The dependence of $\tau_{\text{inelastic}}$ on temperature can be guessed from the fact that, at $T_c$, the quark condensate $\langle q\overline{q}\rangle$ acquires a finite value, and the gluon condensate $\left\langle G_{\mu\nu}G^{\mu\nu}\right\rangle$ sharply increases at the phase transition. "Kinetically", therefore, timescales of processes that create extra $q\overline{q}$ and $GG$ pairs should diverge close to the phase transition temperature, by analogy with the divergence of the spin correlation length in the Ising model close to the phase transition.

These arguments give evidence to the conjecture that, close (from above) to $T_c$, bulk viscosity goes rapidly from a negligible value to a value capable of *dominating* the collective evolution of the system. As shown in [11, 12], in this regime, the N-dimensional Boost-invariant solution (thought to be relevant to ultra-relativistic hydrodynamics, both in heavy ion collisions [16] and the early universe) is *hydrodynamically* unstable against small perturbations. Recent numerical simulations, with Israel-Stewart hydrodynamics, provide evidence that this description is true, as cluster-like instabilities seem to be present (Fig. 11 of [17])

Thus, the *hydrodynamical evolution* of the system can break the system apart into small perturbations around the critical temperature, much like in the Spinoidal decomposition case, but without the need of a phase transition.

## 3. Phenomenology of clustering in heavy ion collisions

Several phenomena already point to clusters. The scaling of the $p_T$ fluctuations w.r.t. multiplicity [18]. Evidence for the existence of clusters, beyond the “trivial” clustering into hadrons, also exists in $p-p$ and $A-A$ data via angular correlations [19]. Event-by-event fluctuations of particle ratios are also *enhanced* w.r.t. the expectation from statistical mechanics [20], something cluster formation could explain. The incorporation of clustering dynamics with a realistic hydrodynamic solution has not yet been explored, through progress in this direction has been made [13].

A possible *direct* signature of clustering is provided by Kolomogorov-Smirnov testing (K-S) [22]: In a fluid evolving from the *same* initial conditions, and freezing out into particles from an approximately locally equilibrated Ansatz (such as the generally-used Cooper-Frye formula [23]), each event can look different because of thermodynamical fluctuations, but the *probability distribution function* for each event will be the *same* up to “trivial” auto-correlations. The auto-correlations due to resonances can be removed by triggering on particles non-correlated by resonances (e.g., only protons, since no resonance decays into two protons). These cuts, as well as limited acceptance in rapidity and azimuthal angle, will also remove correlations due to conservation laws [21].

As proven in [24], in the large event sample limit, the same underlying probability density functions will mean that $\sqrt{n}D$,( where $D$ is the maximum difference between the event-by-event cumulative distribution functions and $n$ is the multiplicity) is distributed according to the Kolomogorov-Smirnov distribution.

Deviations from this distribution can arise from Clusters. If events are frozen out from clusters (or any kind of inhomogeneites), each event will look different, and this difference will be *independent* to how carefully we have tuned our initial conditions to be similar via participant number and reaction plane cuts [21].

In conclusion, we have introduced the HBT puzzle, and explained how clustering at the critical temperature could help solve it. We have further given an overview of the physical processes capable of triggering clustering in the heavy ion system, and motivated the Kolomogorov-Smirnov analysis as a signature of clustering. GT would like to thank the LOEWE foundation and Frankfurt University for the support provided BT acknowledges support from VEGA 1/4012/07 (Slovakia) as well as MSM 6840770039 and LC 07048 (Czech Republic). IM acknowledges support provided by the DFG grant 436RUS 113/711/0-2 (Germany) and grants RFFR-05-02-04013 and NS-8756.2006.2 (Russia).

PoS(Confinement8)112

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PoS(Confinement8)112