

HORIZONS, CAUSALITY AND STRANGENESS PRODUCTION*

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Boost-invariant hadron production in high-energy collisions implies that the produced hadrons arise from causally disconnected fireballs. Discrete quantum numbers have thus to be conserved locally. For strangeness production, this defines a local conservation volume, which in an ideal resonance gas formulation leads to a suppression of strange particle rates. As a result, the strangeness suppression factor γ_s becomes a universal function of the initial energy density of the collision, for all collision configurations and energies. This prediction is found to be very well-satisfied for all pp , pA and AA data.

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Information transfer is limited by the speed of light, which, in turn, leads to the appearance of causality horizons. An observer at a spatial point $x = 0$ and time ct_0 can receive information only from points $|x| \leq c(t_0 - t)$. Events at points $|x| > c(t_0 - t)$ are causally disconnected, beyond the causal horizon of the observer (see Fig. 1).

In cosmology, this leads to the so-called horizon problem: why does cosmic background radiation from regions spatially separated and hence causally disconnected at the time of last scattering shows today the same temperature up to one part in ten thousand? This issue subsequently became one of the essential supports for inflation theory.

We want to show here that causality arguments similarly divide the space-time region for high-energy collisions of hadrons or nuclei into regions which cannot communicate with each other. This, in turn, has crucial consequences for the conservation of discrete quantum numbers.

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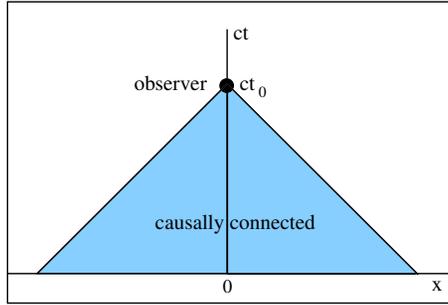


Fig. 1. Causal connectivity.

Consider boost-invariant hadron production in a high-energy collision [2] such that after a short equilibration time τ_0 , a strongly interacting but thermalized medium is formed. At a later time τ_h , this medium is assumed to freeze out into free-streaming hadrons. The world line for the formation of the thermal medium then is $(ct)^2 - x^2 = \tau_0^2$ that for the freeze out $(ct)^2 - x^2 = \tau_h^2$. The collision can thus be considered in terms of thermal “fireballs”, a central one produced at rest in the collision CMS, and others moving even faster along the collision axis (“inside–outside cascade”).

Evidently, fireballs at sufficiently large rapidity are causally disconnected from the more central fireballs, see Fig. 2. To consider this in more detail, the intrinsic size of the fireballs themselves has to be taken into account. We define this size d by requiring that the extreme points of the fireball at τ_0 are still in causal connection with the extreme points at τ_h , see Fig. 3.

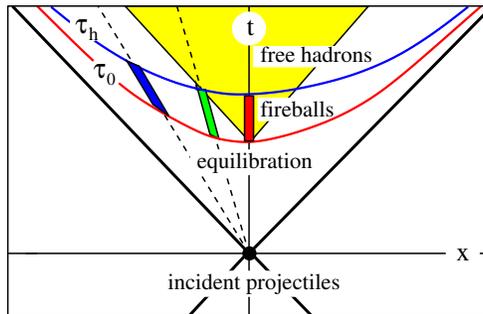


Fig. 2. Causality structure of boost-invariant hadron production.

In that case, the spatial extent d of the fireball is given by [3]

$$d = \sqrt{\frac{\tau_h}{\tau_0}} (\tau_h - \tau_0). \quad (1)$$

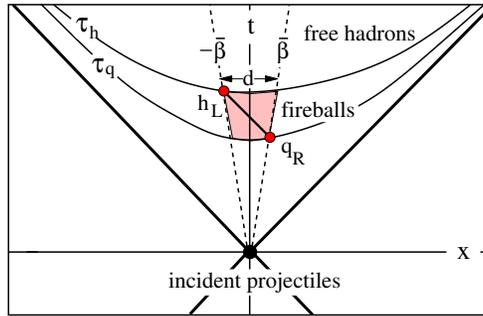


Fig. 3. Spatial fireball structure.

As a result, the space-time region available to the thermal medium is partitioned into causally disjoint fireball regions which cannot communicate with each other, see Fig. 4. Here, $\bar{\beta}_i$ denotes the average velocity of the i^{th} fireball. As already indicated, the causal disjointness, in turn, implies that discrete quantum numbers must be conserved within a given fireball. Such local conservation had been proposed previously as a mechanism to obtain an effective suppression of strangeness production in hadronic collisions [4,5].

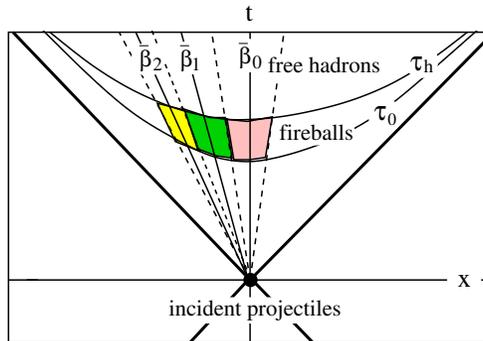


Fig. 4. Partitioning of the thermal space-time region.

The relative abundances of the different hadron species produced in such collisions are very well-specified in terms of an ideal resonance gas, with the only caveat that the production of strange particles fall below the predicted rates. This suppression is conventionally described in terms of a strangeness suppression factor γ_s , multiplying by γ_s^r , the predicted rate of a hadron containing r strange quarks or antiquarks. The resulting ideal resonance gas formalism, based on two parameters, the hadronization temperature T_H and the strangeness suppression γ_s , provides an excellent description of high-energy hadron production. While the hadronization temperature T_H becomes universal at high energies, with a value of about 160 MeV for

all collisions (pp , pA , AA), the suppression factor γ_s depends on both the collision configuration and the collision energy; see Fig. 5. The aim of this presentation is to explain this dependence [1].

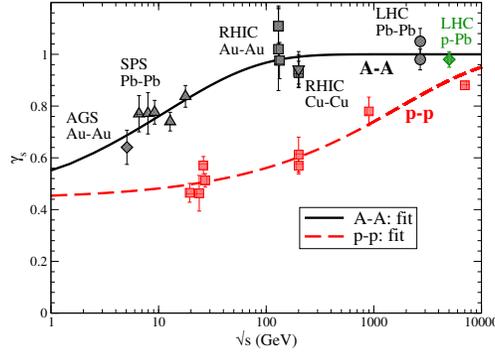


Fig. 5. Strangeness suppression γ_s for different collision configurations and energies [6, 7].

The basis of our approach is that strangeness suppression is due to local strangeness conservation, with a specific conservation volume V_c [5] and that this volume is defined by the above causality considerations [1], *i.e.* $V_c(d)$, with d given by Eq. (1) as a function of the equilibration time τ_0 and the freeze-out time τ_h . In a boost-invariant hadronisation scheme, these times are determined by the initial energy density ϵ_0 and the energy density at hadronisation, ϵ_h . For an ideal quark–gluon plasma, we have

$$\frac{\tau_h}{\tau_0} = \left(\frac{\epsilon_0}{\epsilon_h} \right)^{3/4}, \quad (2)$$

but the specific dependence of τ_0/τ_h on ϵ_0/ϵ_h is not important for our argumentation.

Lattice studies give $\epsilon_h \simeq 0.5 \text{ GeV}/\text{fm}^3$, and the equilibration time is conventionally taken to be about 1 fm. For the size of the causality region this implies $d(\tau_h) = d(\epsilon_0)$. In other words, the local conservation volume $V_c(d)$ and thus the strangeness suppression as such are uniquely specified by the initial energy density of the process, independent of all other collision parameters. We thus predict that γ_s is a universal function of the initial energy density: as a function of ϵ_0 , all data for γ_s , from pp , pA and AA collisions at all collision energies should lie on one universal curve.

To check this, we have to obtain from $\gamma_s(x, s)$ for collision configuration x (pp, pA, AA) and collision energy \sqrt{s} the corresponding $\gamma_s(\epsilon_0)$. The strangeness suppression factor γ_s has been parametrized in the forms [7,8] of

$$\gamma_s^A(s) = 1 - c_A \exp\left(-d_A \sqrt{A\sqrt{s}}\right), \tag{3}$$

$$\gamma_s^p(s) = 1 - c_p \exp\left(-d_p s^{1/4}\right), \tag{4}$$

for AA and pp collisions, respectively, with the constants $c_A = 0.606$, $d_A = 0.0209$; $c_p = 0.5595$; $d_p = 0.0242$. The corresponding energy densities are given by

$$\epsilon_q \tau_q \simeq \frac{1.5 m_T}{\pi R_x^2} \left(\frac{dN}{dy}\right)_{y=0}^x \quad \text{with } x \sim pp, pA, AA, \tag{5}$$

where the central multiplicities $(dN/dy)_{y=0}$ are given by

$$\left(\frac{dN}{dy}\right)_{y=0}^{AA} = a_A (\sqrt{s})^{0.3} + b_A, \tag{6}$$

$$\left(\frac{dN}{dy}\right)_{y=0}^{pp} = a_p (\sqrt{s})^{0.22} + b_p \tag{7}$$

with $a_A = 0.7613$, $b_A = 0.0534$; $a_p = 0.797$; $b_p = 0.04123$ [9]. Using these relations, we can now express γ_s as a function of $\epsilon_0 \tau_0$ for pp , pA and AA collisions, and then compare the result to data. The result is shown in Fig. 6.

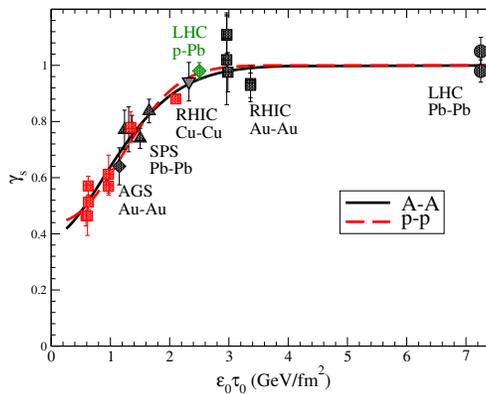


Fig. 6. Strangeness suppression γ_s as function of the initial energy density in pp , pPb and AA collisions [1].

First of all, we see in Fig. 6 that the resulting curves for γ_s in pp and AA collisions fully coincide, in contrast to the behavior found in Fig 5. In other words, strangeness suppression is a universal phenomenon as a function of the initial energy density; as a function of the collision energy, pp and AA collisions lead to different forms of behavior. Next, we note that all available data agree very well with the predicted universal form. This, moreover, also holds for the centrality dependence of γ_s for given collision configurations (Au–Au and Cu–Cu) at a fixed energy [1].

In closing, we recall that our causality considerations relate the size of the causal correlation region to the life-time of the thermal medium. Strangeness suppression provides an experimental measure of the correlation region, while the initial energy density determines the life-time of the thermal system. The observed scaling of γ_s with ϵ_0 is thus an observable consequence of our basic causality correspondence.

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