Analysis techniques for high-multiplicity collisions

David Seibert
Theory Division, CERN, CH-1211 Geneva 23, Switzerland

Abstract

I discuss methods for identifying and quantifying phase transitions in particle collisions, concentrating on two techniques for use in ultra-relativistic nuclear collisions. The first technique is to use rapidity correlation measurements to determine the correlation length, while the second is to use the transverse mass distribution of dileptons in the $\rho^0 - \omega$ peak to determine the transition temperature.

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*On leave until October 12, 1993 from: Physics Department, Kent State University, Kent, OH 44242 USA. Internet address: seibert@surya11.cern.ch.
1. Introduction

The goal of this talk is to present two techniques that can be used for quantifying phase transitions in ultra-relativistic nuclear collisions. I discuss these techniques in a general manner, to show how they might be used to study other collisions and other phase transitions. I first give a very general overview of an ultra-relativistic nuclear collision.

The basic physics of an ultra-relativistic nuclear collision is simple [1]. First, a lot of partons collide in a proper time less than about 1 fm/c, producing an enormous number of secondary particles. Then, in another 1 fm/c or so, the secondary particles (hopefully) equilibrate. I use proper time rather than time, because time varies with the reference frame, while the system looks approximately the same in all frames at equal proper time.

The period after equilibration is potentially the most interesting, as there is a chance to measure bulk properties of hot hadronic matter during this period. Many things might go on here. Typically, people hope that immediately after equilibration the hot secondaries will exist as a deconfined quark-gluon plasma or as chirally-symmetric hadronic matter. As the matter expands and cools, there should be some sort of transition, possibly an actual phase transition, from this exotic state back to normal hadrons. Finally, as the system expands further the matter will freeze out and flow to the detectors when the mean free path is long compared to the size of the system.

For now, I assume that this picture is correct, and that there is a phase transition to observe. I assume as little as possible about the nature of this transition; rather, I discuss ways to observe the physics of the transition. I discuss two proposed techniques in sections 2 and 3, and summarize in section 4.

2. Correlation length measurement

At a first-order phase transition the correlation length is usually different for the two coexisting phases, while at a second-order transition the correlation length diverges at the critical point. Thus, a change in the correlation length might indicate a phase transition. However, correlation lengths are not very easy to measure in particle collisions for two reasons: i) lengths are not directly measured but are inferred from velocity (rapidity) correlation measurements, and ii) the sample size typically changes from event to event. For brevity, I discuss only the first difficulty here.

The correlation length inference is simple in concept. If the phase transition is first-order, the transition occurs through a mixed-phase region, in which regions of the high- and low-temperature phases coexist. [In a second-order transition, there are instead very large correlated regions that form as the correlation length diverges at the critical temperature.] As interactions between particles with very different velocities are weak, the particles produced from these regions will be correlated in velocity.

The shape of the velocity (or rapidity) correlation function is fixed in the most likely case that the decays of the regions are isotropic in their rest frames, giving a scale of 1–2 units of rapidity (the same as for the correlations seen in pp collisions).
The magnitude of the correlation function is proportional to the number of particles emitted per region, so this number can be obtained directly. The scale of the regions (and hence the mean volume) is then determined by the correlation length, while the volume is also related to the number of particles, so the correlation length can be inferred from the velocity correlations with the help of some theory [2]. Useful methods for measuring the correlations and results from current experiments are given in Refs. [3] and [4].

One background for the fluctuations from a phase transition is the correlations due to hadronization. This background is most easily calculated by extrapolating correlation measurements from pp reactions, in which hadronization occurs but no bulk phase transition is expected. Current results indicate that the correlations seen in O+Em and S+Em collisions at $\sqrt{s} = 20$ GeV/nucleon are an order of magnitude larger than the signal extrapolated from pp data [5], so this background can largely be ignored.

It is easier to see large changes in the correlation length (signalling a phase transition) than to measure the correlation length, as knowledge of the density is not necessary. A large change in the correlation length follows directly from a large change in the number of particles per region. However, looking for a large change is not necessarily easy, and it gets more difficult as the rapidity density, $dN/dy$, increases [6]. The correlation signal is typically proportional to $(dN/dy)^{-1}$, while the statistical noise is proportional to $(dN/dy)^{-1/2}$, so the signal-to-noise ratio decreases as $(dN/dy)^{-1/2}$. Even worse, there is a non-statistical background from Bose-Einstein interference that is approximately independent of $dN/dy$, so the signal-to-background ratio can decrease as fast as $(dN/dy)^{-1}$! Thus, while this technique is simple in principle, it becomes infinitely difficult (and probably impossible) in the limit $dN/dy \to \infty$.

3. Transition temperature measurement

The proposal for measurement of the hadronic transition temperature is a more elaborate version of a proposal by Siemens and Chin for detecting the existence of the transition [7]. The technique is simple [8]: the experimenters measure the transverse mass, $m_T = (p_T^2 + m^2)^{1/2}$, distribution of lepton pairs in the $\rho^0 - \omega$ peak. This distribution is then fit to a thermal shape, and the temperature extracted from the fit is the transition temperature, $T_t$, with theoretical corrections of order 25%. Some of the theoretical corrections are discussed in Ref. [9].

Dileptons are used (rather than pions, that would allow separation of $\rho^0$ and $\omega$ mesons) because pions can only escape from the final state matter, as those formed earlier interact on the way out and their origin from resonances is lost. As leptons are not strongly-interacting, they can escape from the hot matter at much earlier times, so they are a better probe of the early stages of the collision.

Of course, once $T_t$ is extracted then there is the more difficult problem of its interpretation. Because of the generality of the method, this will not be very rigorous; essentially, $T_t$ is the temperature at which the $\rho$ mesons disappear. This could be due to dynamics, in which case $T_t$ should depend on collision energy and the sizes of the colliding nuclei, or it could be due to a bulk phase transition, in which case $T_t$ should be constant. Even in the case of a phase transition, there is the question of the nature
of the phase transition.

The technique works for many possible hadronic transitions (chiral symmetry restoration, deconfinement, etc.) because $\rho$ mesons are order parameters for all of these transitions. The $\rho$ exists in the low-temperature phase, but not in the high-temperature phase. The signal from $\rho$ mesons is thus an experimenter’s $\theta$-function, measuring properties of the system below $T_t$.

The $\rho$ mesons are also especially useful because they have a very short lifetime, $\tau_\rho = 1.3$ fm/c. Their main decay mode is into two pions, so by detailed balance their short lifetime guarantees a fast rate for the reaction $\pi\pi \to \rho$. Thus, the $\rho$ mesons remain near equilibrium (and in good thermal contact with the pions) whenever the expansion time is more than about one fm/c.

Because the $\rho$ mass is large ($m_\rho \gg T_t$), the number of $\rho$ mesons in the system (and thus the $\rho^0$-peak dilepton signal) decreases exponentially with $T^{-1}$ as the system cools below $T_t$. Most of the signal is produced when the temperature is near $T_t$, in a band with width of order $T_t^2/m_\rho$ below $T_t$. Thus, the theoretical corrections to $T_t$ are of order $T_t^2/m_\rho$. The rho mesons at freezeout are described fairly well by an equilibrium distribution at the freezeout temperature, remaining in the system for proper time $\tau_\rho$, so the freezeout signal is small if the system remains near equilibrium much longer than $\tau_\rho$.

Thus, the requirements for use of this technique are:
1. Some particle must vanish for $T > T_t$ (order parameter).
2. The lifetime of the particle must be short.
3. The mass should be much greater than $T_t$.
4. Observable decay products must escape the collision volume at early times.

It would appear at first glance that this technique should work well at all values of $dN/dy$. The technique is in principle possible even for $dN/dy \to \infty$, as the signal-to-background ratio is constant. However, the signal is difficult to measure, as the background (mainly statistical dileptons from $\pi^0$ decays) is large.

There is one further complication, that there should not be too many nearby resonances, so that the peak being used to identify the desired mesons can be extracted from the background. In the application to the hadronic phase transitions, this is not strictly true, as the $\omega$ is nearly degenerate with the $\rho$. This complicates the signal, but the background from $\omega$ mesons is much smaller than the signal from the $\rho^0$ mesons (because of the much faster $\rho$ decay rate) if the system spends enough time near equilibrium.
4. Summary

I have presented here the outlines of two techniques for identifying and characterizing phase transitions in particle collisions. The first technique, searching for a large change in the correlation length, is simple in concept but becomes impossible even in principle for large $dN/dy$. This technique provides a relatively theory-independent method to search for phase transitions. The second technique, obtaining the transition temperature from the $m_T$ spectrum of dileptons in the $\rho^0 - \omega$ peak, is more complicated in concept but is possible in principle even in the limit $dN/dy \to \infty$.

Both of these techniques should be possible to apply to other nuclear and high energy systems that might exhibit phase transitions. The second technique depends on having a fortuitous resonance that serves as an order parameter but has a short lifetime. This is probably not unlikely for strongly-interacting systems, due to the large number of resonances, but may make application to weakly-interacting systems difficult. The first technique should be applicable to the study of almost any transition that occurs at not too large values of $dN/dy$.

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