Temperature Fluctuations in Multiparticle Production

L. Stodolsky
Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 München, Germany
(Received 3 April 1995)

We explain how, in the thermodynamic interpretation of multiparticle reactions, it may be possible to experimentally determine a basic quantity characterizing the presumed thermodynamic system: the heat capacity. We exploit the fact that new heavy-ion experiments have such a high multiplicity that a "temperature" can be assigned on an event-by-event basis. This permits temperature *fluctuations* also to be defined. In a thermodynamic system, the latter are related to the heat capacity. The heat capacity may then be used to search for phase transitions and to study other thermodynamic aspects of the system.

PACS numbers: 25.75.+r, 12.40.Ee, 24.60.–k

Early in the study of many-particle production the notion of a "temperature" or a "transverse temperature" was introduced, motivated by the limited and well defined exponential dependence of secondaries with respect to transverse momentum. Since that time there have been many attempts to introduce thermodynamic ideas in multiproduction, perhaps the most dramatic being the idea of a phase transition at high energy density [1], something that might be observable in heavy-ion collisions. Since the number of particles produced, even at high energies, was never very large, this temperature had to be found as an average over many scattering events.

The situation changed recently with the advent of heavy-ion experiments involving large nuclei at very high energy. In such collisions the multiplicity in a single scattering may be so large (more than a thousand) [2] that we are tempted to examine the implications of the assumption that an approximately thermodynamic state is obtained in a single collision. In particular, a well defined exponential and thus a temperature may be found for a single event. If this is meaningful, then it should also be possible to speak of temperature fluctuations. That is, if a certain class of events or variables is believed to have a more or less definite temperature T, then by averaging over various events we may also obtain the dispersion in the temperature,

$$(\Delta T)^2 = \overline{(T - \bar{T})^2}\,.$$

According to a basic relation of thermodynamics [3], the temperature fluctuations of a system are related to its total heat capacity,

$$C^{-1} = \frac{(\Delta T)^2}{T^2}\,. \qquad (1)$$

Thus if certain degrees of freedom like the transverse energies or the gluon field are indeed to be identified with a thermodynamic system, we can then experimentally determine an important material parameter of this system: the heat capacity.

Knowing the heat capacity of a system implies considerable information about its thermodynamics. In particular, irregular behavior of the heat capacity is characteristic of phase transitions; in a first order transition there is a jump and in a second order transition a singularity, typically. Hence the study of C can shed light on the possible existence of a phase transition and its nature.

For example, if we wish to see if a class of events with some property, say, high strangeness content, is associated with a different phase than ordinary events, we could proceed as follows. Let a temperature be assigned to each event by a fit with the transverse energies, as is traditional. We then find the dispersion in the temperature for each class of events, being careful that the selection process does not introduce a bias that could influence the temperature fluctuations. If the C's found from Eq. (1) for the two classes differ significantly, this would be evidence for the formation of different phases.

Doubts are sometimes expressed as to the validity of the concept of temperature fluctuations [4]. We see no difficulty with this. Indeed, for the present problem it is important that we choose to deal with temperature fluctuations and not, say, with energy fluctuations. This is because of volume fluctuations. The latter are to be expected since the beam-target overlap will vary according to the impact parameter. Now Eq. (1) is valid even in the presence of volume fluctuations [3]. On the other hand, the energy fluctuations will have a component that is induced simply by the volume fluctuations, so they are not determined purely by the heat capacity.

The use of the thermodynamic picture and, in particular, Eq. (1) implies that the thermodynamic system in question is in contact with a large energy reservoir. This role is played by the longitudinal motion of the beam; that is, we suppose that energy can be exchanged freely between these degrees of freedom and those constituting the presumed thermodynamic system. Should the energies involved with the latter become significant compared with those in the beam, then energy conservation corrections, due to the finiteness of the reservoir, may have to be considered. Naturally, even if the thermodynamic assumptions, especially that of equilibrium in one collision, are justified, we must further assume that the effects in question, even if they exist, are not destroyed by the "freeze out" to the observable particles. It is perhaps not unrea-

 0031-9007/95/75(6)/1044(2)$06.00

sonable to assume that an initial fluctuation in transverse momentum or energy is not smoothed out in the transition to the final particles.

If the effects do show up in a clear way we might imagine going even further and trying to explore the full thermodynamics of the system by detailed measurements on an event-by-event basis. We would then need a continuously adjustable independent variable like the temperature in ordinary thermodynamics. If we do not wish to use the latter so as not to bias the fluctuations, we can use some appropriate definition for, say, the total transverse energy density [5].

The main questions, of course, that remain are can the system approximately thermalize in the short time available, and what imprints of this thermalization are visible in the final state?

I would like to thank P. Seyboth for useful comments and discussions of the data. I also would like to thank W. Ochs, S. Pokorksi, and J. Wosiek for valuable discussions.

[1] See, for example, *Quark Matter '90,* Proceedings of the Eighth International Conference on Ultrarelativistic Nucleus-Nucleus Collisions, Menton, France, 1990, edited by J.P. Blaizot; C. Gerschel, B. Pire, and A. Romana [Nucl. Phys. **A525** (1991)].

[2] In the NA49 experiment with lead-lead interactions at 160 GeV/nucleon there are about 2000 particles, of which 800 are measured. P. Seyboth (private communication).

[3] L. D. Landau and I. M. Lifschitz, *Course of Theoretical Physics,* Statistical Physics Vol. 5 (Pergamon Press, New York, 1958), Sect. 111. "Heat capacity" refers to C_v. To get a quantitative impression, a Planckian gas at $T = 200$ MeV occupying the volume of a lead nucleus has $C \approx 240N$, giving $\Delta T/T \approx (1/\sqrt{N})0.06$, where N is the number of degrees of freedom relative to the two for the photon. We stress that this is the total and not the specific heat capacity; thus it always contains an extensive factor like the volume. Although this is perfectly natural, it means that care must be taken in experimental tests involving absolute and not simply relative values of C. If acceptance effects, cuts, and so forth lead to viewing only some reduced fraction of the secondaries, the fluctuations will naturally be greater than with the full multiplicity.

[4] C. Kittel, Phys. Today **41**, No. 5, 93 (1988); T. C. P. Chui, D.R. Swanson, M.J. Adriaans, J.A. Nissen, and J.A. Lipa, Phys. Rev. Lett. **69**, 3005 (1992).

[5] See, for example, J. Bjorken, Phys. Rev. **27**, 140 (1983). For translation rules from temperature to energy density as the independent variable in critical behavior see L. Stodolsky and J. Wosiek, Nucl. Phys. **B413 [FS]**, 813 (1994), Eqs. (4).