Title
PION SOURCES IN RELATIVISTIC HEAVY-ION COLLISIONS

Author
Meng, Ta-Chung.

Publication Date
1978-10-01

To be submitted for publication

LBL-8358 c.2
Preprint

PION SOURCES IN RELATIVISTIC HEAVY-ION COLLISIONS

Meng Ta-chung

October 1978

Prepared for the U. S. Department of Energy
under Contract W-7405-ENG-48

DISCLAIMER

PION SOURCES IN RELATIVISTIC HEAVY-ION COLLISIONS

Meng Ta-chung

Lawrence Berkeley Laboratory, University of California
Berkeley, California 94720

and

Institut für Theoretische Physik der Freien Universität Berlin,
Berlin, Germany

ABSTRACT

Implications of the most recent pion production data are discussed. It is observed that they can be used to answer some of the crucial questions raised in understanding the basic reaction mechanism of relativistic heavy-ion collisions. As a by-product of this discussion, it is shown that the volume of the pion sources in violent collisions can be determined from single particle inclusive data. Further hadron-nucleus and nucleus-nucleus collision experiments are suggested.

In heavy-ion collisions at incident energies above a few hundred MeV per nucleon, production processes become important, and the overwhelming part of the emitted particles are pions. Hence, in order to understand the basic reaction mechanism of such collisions, it is necessary to know: "How are the pions produced at these energies?"

In this paper, we discuss the implications of the most recent pion production results.[1-3] After a brief discussion on some of the relevant general features of relativistic heavy-ion reactions, we focus our attention on the following problems:

(a) What do we know about the space-time evolution of the produced pions? For example, are the pions produced while the participating nucleons of the projectile-nucleus are still inside the target-nucleus? Hadron-nucleus collision experiments[4] at very high energies strongly suggest that the production time is so long that the nucleons inside the nucleus along the path of the incident hadron can be envisaged as acting collectively, and in first order approximation be considered as a single object -- an effective target (ET).[5] Do we see this kind of collective behavior[6] in relativistic heavy-ion reactions at the presently available energies[7]?

(b) What do we know about the pion sources in peripheral and central relativistic heavy-ion collisions? Is "temperature" a useful concept to describe such sources? What do we know about the spatial dimensions of such sources? In particular, how do they depend on the incident energy and the masses of the colliding nuclei?

We recall that one of the general features of relativistic heavy-ion collisions[8] is: The collision events can be classified into three categories according to their final state topologies. Events in the first category consist predominately of particles with relatively small transverse momenta, $p_\perp$, small emission-angles in the lab (θ_{lab}) or projectile (θ_{proj}) frame, and relatively small associated multiplicities. In a $p_\perp$-y contour plot[2] (y is the rapidity of the particle), such particles are concentrated in the neighborhood of $p_\perp/(mc) \ll 1$, $y = y_T, y_P$, where m is the mass of the particle, y_T and y_P are the rapidity of the target and that of the projectile-nucleus, respectively. Particles in the second category of events have relatively large $p_\perp$ and/or associated multiplicities. Such particles can be found at all angles. From the corresponding $p_\perp$-y plot, we see that they are emitted from a source with intermediate rapidity y_c: $y_T < y_c < y_P$. In events of the third category, particles of both types can be found.

Two conclusions can immediately be drawn from the general features mentioned above. Firstly, there seems to be two types of interactions in relativistic heavy-ion collisions. This means, in order to obtain an adequate description of such processes, it may be necessary to deal with two different kinds of reaction mechanisms. Secondly, both types of interactions have been observed in high-energy hadron-hadron and hadron-nucleus collisions. This strongly suggests that the basic reaction mechanisms of nucleus-nucleus collisions at the currently available heavy-ion accelerator energies[7] have much in common with those of high-energy hadron-hadron and hadron-nucleus processes.

A two-component picture has been proposed[5] some time ago to describe the gross features of hadron-nucleus collisions at high energies.[4] In this picture, a high energy hadron-nucleus process is considered as a hadron-effective target [see (a)] collision, which is either gentle or violent.

The characteristics of a gentle collision are: The energy- and momentum-transfer are relatively small. The colliding objects retain their identity after interacting with each other so that in such a collision it is possible to differentiate the fragments of the projectile from those of the target.

In violent processes the colliding objects lose their identity after the collision. The produced particles are emitted from a compound system formed by the two colliding objects. The relatively large energy- and momentum-transfer in such a reaction manifest themselves in producing particles with larger $p_\perp$ and/or in creating more particles in that collision event.

According to this picture, a high-energy nucleus-nucleus collision is nothing else but the collisions of all possible pairs of effective targets (ET's) and effective projectiles [EP's, EP: definition analogous to that of ET, see (a)], where the collision of every EP-ET pair can be either gentle or violent. Hence, a nucleus-nucleus collision event is, in general, a mixture of both types of EP-ET collisions, while there are also events in which such gentle or violent collisions dominate. This explains why the above-mentioned three categories are observed experimentally.

Pion production data[1] at angles near $\theta_{lab} = 0°$ and 180° as well as other empirical facts show[9,5] that the collective behavior mentioned in (a) indeed exists in gentle (peripheral) relativistic heavy-ion reactions in the present energy range.[7]

To study the reaction mechanism of violent (central) collisions[10] we look at the pions from sources with intermediate rapidities.[2] Since violent EP-ET collisions occur in more central nucleus-nucleus processes, the average masses of the EP's and ET's are $A_P^{1/3}M$ and $A_T^{1/3}M$ respectively. Here A_P and A_T are the mass numbers of the projectile and target nucleus, and M is the nucleon mass. Hence the rapidity y_c of the compound system formed by an EP-ET pair can be calculated provided that the incident kinetic energy per nucleon ε_{lab} is known:

$$y_{c(lab)} = \text{arc tanh}\left\{\frac{[\varepsilon_{lab}(\varepsilon_{lab}+2M)]^{1/2}}{\varepsilon_{lab}+M[1+(A_T/A_P)^{1/3}]}\right\} \qquad (1)$$

This is to be compared with the rapidity of the moving source in central heavy-ion collisions (see the $p_\perp$-y contour plots in Ref. 2).

As an illustrative example, we consider $Ne + NaF \rightarrow \pi^- + X$ and $Ne + Pb \rightarrow \pi^- + X$ at 0.8 GeV/N. The location of $y_{c(lab)}$ in the former (symmetrical) case is at 0.61. But, in the latter (asymmetrical) case: $y_{c(lab)}$ would remain at 0.61 if the pion source were the cms of the participating nucleon-nucleon system; $y_{c(lab)}$ would be shifted to 0.13 if the source were the cms of the two entire colliding nuclei; this model gives 0.41, which is also the experimental value.[2]

We have calculated y_c from Eq. (1) for all the beam, target, and incident energy combinations in the experiments of Nagamiya et al.[2] The agreement between experiment and theory is good. It would be useful also to have analyses[11] with multiplicity selections. If this picture is correct, we should see that the pions in high-multiplicity events are emitted from sources with rapidity y_c given by Eq. (1).

We now turn to the questions in (b). First, we recall the basic difference between a gentle and a violent EP-ET collision, and note in particular that there are two pion sources in the former[9] -- but only one in the latter case.[12] The "temperature problem" is of particular interest in the latter case. This is because, due to the relatively large energy-transfer in violent collisions, it is in such processes where one may see hadronic matter at extremely high temperatures and/or densities.[13]

Nagamiya et al[2] have observed that the points with maximum $p_\perp$ for each contour in the $p_\perp$-y plots have the following property: The single particle inclusive cross sections for pions and protons fall exponentially with increasing "transverse kinetic energy", $E_\perp - m$, where $E_\perp = (p_\perp^2 + m^2)^{1/2}$, and m is the mass of the observed particle.

It is tempting to interpret this phenomenon as that the source of the produced particles in a violent collision event is a system of gas in thermal equilibrium. But, such an interpretation is possible only if the following questions[14] can be answered: "Why does the "transverse energy" $E_\perp$ play a particular role?" "What is the reason to choose points with maximum $p_\perp$, especially when the colliding nuclei have unequal masses?"

In the proposed picture, the answer to these questions is obvious. Since all the emitting systems are moving along the incident axis, $E_\perp$ is the energy of the particle in the rest frame of the moving source, provided that the particle is observed at $\theta = 90°$ in this frame. But, the points with maximum $p_\perp$ on each of the above-mentioned contours <u>are</u> approximately the points at $\theta = 90°$! In fact, it is interesting to see that the observed[2] small deviation from a pure exponential dependence would have been eliminated if one had taken strictly the points at $\theta = 90°$.

Similar systematics in $E_\perp$-distribution has also been observed in hadron-hadron collisions at higher energies. Deutschmann et al[15] have, e.g., found that for $\pi^+ + p \rightarrow \pi^- + X$ at 16 GeV/c, $|y| < 0.1$ (y is the cms rapidity of the observed pion),

$$\frac{d\sigma}{d^3p}(E_\perp, y) \propto \left[e^{E_\perp/(kT)} - 1\right]^{-1} , \qquad (2)$$

where $kT = 117.5$ MeV.

Now, if we interpret[14] the result of Deutschmann et al[15] and that of Nagamiya et al[2] in terms of a statistical model: "The pion source is a system of bosons in thermal equilibrium, similar to the case of black-body radiation," then, the temperature, T, the volume, V, and the total energy, E_{total}, of this system are related to one another by an expression corresponding to the Stefen-Boltzmann law (all quantities are measured in the rest frame of the compound system which is the cms of the colliding objects). For example, in cases where the pions are isotropically distributed (in the above mentioned frame), we obtain

$$E_{total} = \frac{gV}{2\pi^2(\hbar c)^3}(kT)^4 \int_{x_0}^{x_1} dx \, \frac{x^2\sqrt{x^2 - x_0^2}}{e^x - 1} , \qquad (3)$$

where $x_0 \equiv mc^2/(kT)$, $x_1 \equiv E_{total}/(kT)$, m is the mass, and g is the statistical weight of the pion.

Equation (3) can, in particular, be applied to calculate V of the emitting system if T and E_{total} are known. Now T can be determined from the single-particle distribution or energy distribution,[16] and E_{total} can be calculated from the incident energy and the masses of the colliding objects. (To be more precise, one should take into account the measured ratio of pion to other types of emitted particles.) This means, the volume of the emitting system can be determined by single-particle inclusive data.

As an example, we consider the pions produced in the 16 GeV/c π^+p reactions.[15] The temperature, determined from $d\sigma/d^3p$ near $\theta = 90°$ is $kT = 117.5$ MeV. Since the overwhelming part of the produced particles are pions, it seems reasonable to set E_{total} in Eq. (3) to be the total energy of the colliding π^+p system ($E_{total} = 4.6$ GeV), which implies, however, that all of the pions are directly and independently produced. The value we obtain for the radius of the spherically symmetric pion source under this assumption is $R = 3.7$ fm. Now, it has been estimated experimentally[17] that only 10% to 30% of the pions are directly produced while the rest are due to resonance decay. This means only 10% to 30% of the above-mentioned energy is associated with the completely incoherent part of the pion gas. Taking this factor into account, we obtain $R = 1.7$ and $R = 2.5$ for 10% and 30% respectively. This is to be compared with $R = 1.85 \pm 0.15$ obtained in two-particle correlation experiments.[18]

We now apply this method to heavy-ion collisions: We first consider $Ne + NaF \rightarrow \pi^{\pm} + X$ at 0.8 GeV/N. Experimentally[2] it has been found that the (cms) angular distribution for $p_{\perp} \gtrsim m_{\pi}c$ is approximately isotropic and that kT determined from $d\sigma/d^3p$ at $\theta = 90°$ is 55 MeV. The value for the radius of the incoherent pion source, by assuming[19] 10% or 30% of the pions are directly produced, is found to be $R = 3.4$ and 4.9 fm respectively. The order of magnitude is consistent with the preliminary result of the first two-particle correlation data in relativistic heavy-ion collision of Fung et al.[3]

Furthermore, in order to study the dependence of source-size on incident energy and on the masses of the colliding nuclei, we also calculated the radii of the emitting systems from the data on $Ne + NaF \rightarrow \pi^- + X$ at

0.4 and 2.1 GeV per nucleon, as well as those on Ne + Pb $\rightarrow \pi^-$ + X and Ar + KCl $\rightarrow \pi^\pm$ + X at 0.8 GeV/N. The general features of the result[20] are: (i) R is rather insensitive to the masses of the colliding nuclei; (ii) R decreases with increasing incident energy. It would be very exciting to compare these results with those obtained in future two-particle correlation measurements. Furthermore, in order to study the spatial dimension in the transverse direction,[12] comparison between nucleus-nucleus and proton-nucleus collisions at the same incident energy (per nucleon) would be very helpful.

Acknowledgment

The author thanks his colleagues at LBL, especially Shoji Nagamiya and Phil Siemens for helpful discussions and valuable comments. He thanks Norman Glendenning and other members of the LBL Nuclear Theory Group for their hospitality.

This work was done under the auspices of the U.S. Department of Energy under Contract W-7405-ENG-48.

FOOTNOTES & REFERENCES

1. A.M.Baldin, JINR E1-11368 (1978); L.S.Schroeder, private communication.

2. S.Nagamiya et al., Proc. Int. Conference on Nuclear Structure Tokyo (1977), J. Phys. Soc. Japan 44 (1978) Suppl. p.378.; K.Nakai and J.O.Rasmussen, contribution to the above mentioned conference; S.Nagamiya et al., talk given at the 4th LBL Summer Conference on Relativistic Nuclear Collisions, Berkeley (1978), to be published.

3. S.Y.Fung, ibid.

4. See e.g., W.Busza, Proc. 6th Int. Conference on High-Energy Physics and Nuclear Structure, Santa Fe and Los Alamos, edited by D.E.Nagle et al. (AIP, 1975), p.211.

5. A summary of this simple physical picture can be found in: Meng Ta-chung and E.Moeller, Phys. Rev. Letters (in press).

6. The idea of such collective behavior has a long history. References can, e.g., be found in Refs. 4, 5, and 10.

7. from a few hundred MeV to several GeV per nucleon

8. H.H.Heckman et al., "An Atlas of Heavy-Ion Fragmentation Topology," LBL-report (unpublished).

9. H.B.Mathis and Meng Ta-chung, Phys. Rev. C18, 952 (1978).

10. The good agreement between the multiplicity distribution data and the collective tube model [see Y.Afek et al., Phys. Rev. Letters 41, 849 (1978) and the references given therein] also indicates that such collective behavior should exist in violent (central) heavy-ion collisions. This is because the average

multiplicity in violent collisions are much higher than that in gentle collisions, and hence it is the former that dominates when the overall average is taken. The existence of two different types of EP-ET (tube-tube) reaction mechanisms is essential in principle, and plays an important role in practice. For example, the difficulties discussed by S.A.Azimov et al. [Phys. Letters 73B, 339 (1978)] are due to the neglect of this fact [see also: L.Bergström et al., to appear in Phys. Letters; Y.Afek et al., ibid].

11. especially, analyses similar to that performed by the Pisa-Stony Brook group, see e.g., L.Foa in Proc. Int. Conference on Elementary Particles, Aix-en-Provence, 1973, J. de Phys. Suppl. 10 (1973) p.C1-317

12. In a nucleus-nucleus collision event, since the compound systems formed by different EP-ET pairs move approximately with the same velocity, the transverse dimension of the total compound system may be a few times that of a nucleon.

13. See, e.g., G.F.Chapline et al., Phys. Rev. D8, 4302 (1973).

14. The observed[2] difference in slope in $d\sigma/d^3p$ for pions and protons is not necessarily an evidence against the thermodynamical interpretation, since the compound system formed by the colliding objects has to expand (and probably go through a set of equilibrium stages) before it decays, several mechanisms are conceivable. Discussions on this and/or related problems can, e.g., be found in: A.Mekjian, Phys. Rev. Lett. 38, 640 (1978); N.K.Glendenning, LBL-7165 (1978); P.J.Siemens and J.O.Rasmussen, LBL-8383 (1978).

15. M.Deutschmann et al., Nucl. Phys. B70, 189 (1974).

16. In order to avoid the possible ambiguities at low $E_\perp$ (due to Coulomb corrections, etc.) and the less good statistics at higher $E_\perp$ in $d\sigma/d^3p$, one may use a formula similar to Wien's displacement law to determine T.

17. H.Kirk et al., Nucl. Phys. B128, 397 (1977).

18. M.Deutschmann et al., CERN/EP/Phys. 78-1 (1978).

19. An experimental estimate of the ratio at these energies would be very useful.

20. Here we assume that the ratio: (direct pions)/(all pions) does not strongly depend on the incident energy or on the masses of the colliding nuclei (see also Footnote 19).

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720