seen that the results of our analysis contain more high-momentum components in the 0.2- to 0.5-GeV/c region than any of the models, and disagree with one $(e,e'p)$ experiment, but agree with the other.

As with the $(e,e'p)$ experiments, a full study of all the processes that could complicate the interpretation of the inclusive electron measurements in terms of the plane-wave impulse approximation and nonrelativistic wave functions must be undertaken before any definite conclusions can be drawn. The result remains, however, that any theory must be able to explain the impressive experimental observation that nucleon scaling unifies inclusive electron-scattering data for the three lightest nuclei over a large kinematic region and for y values that imply very short distances within the nucleus.

This work was supported in part by the U. S. Department of Energy under Contract No. DE-AC03-76SF00515, and by the National Science Foundation under Grants No. PHY78-09378 and No. PHY81-08484.

[1]G. B. West, Phys. Rep. 18C, 263 (1975), and in *Proceedings of the International School on Electron and Pion Interactions with Nuclei at Intermediate Energies*, edited by W. Bertozzi, S. Costa, and C. Schaerf (Ariccia, Rome, Italy, 1979), p. 417.

[2]P. D. Zimmerman *et al.*, Phys. Rev. C 19, 279 (1979).

[3]I. Sick, D. Day, and J. S. McCarthy, Phys. Rev. Lett. 45, 871 (1980).

[4]W. Schütz *et al.*, Phys. Rev. Lett. 38, 259 (1977).

[5]S. Rock *et al.*, Phys. Rev. Lett. 49, 1139 (1982), with emphasis on the extraction of the neutron cross section.

[6]D. Day *et al.*, Phys. Rev. Lett. 43, 1143 (1979); S. Rock *et al.*, Phys. Rev. C, to be published. We have used a revised analysis of the data originally reported by D. Day *et al.*, to be published.

[7]M. Lacombe *et al.*, Phys. Rev. C 21, 861 (1980).

[8]E. Loman and H. Feshbach, Ann. Phys. (N.Y.) 48, 94 (1968).

[9]K. Holinde and R. Machleidt, Nucl. Phys. A256, 497 (1976).

[10]For the proton we used the fit dipole (Γ_ρ = 112 MeV) from F. Iachello, A. Jackson, and A. Lande, Phys. Lett. 43B, 191 (1973). For the neutron, we assumed that G_{En} = 0, and that G_{Mn} follows the empirical dipole law, reduced slightly at high Q^2 to agree with Ref. 5.

[11]A summary of, and references to, the work of I. J. McGee and L. Durand, III, are given in W. Bartel *et al.*, Nucl. Phys. B58, 429 (1973).

[12]E. Pace and G. Salme, Istituto Nazionale di Fisica Nucleare Report No. IPFN-ISS 82/1, to be published.

[13]M. Berheim *et al.*, Nucl. Phys. A365, 349 (1981).

[14]U. L. Agranovich *et al.*, Yad. Fiz. 25, 1123 (1977) [Sov. J. Nucl. Phys. 25, 595 (1977)].

Role of Mean Free Paths of Product Particles in High-Energy Nucleus-Nucleus Collisions

Shoji Nagamiya

Department of Physics, Faculty of Science, University of Tokyo, Hongo, Bunkyo-ku, Tokyo, Japan, and Nuclear Science Division, Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

(Received 20 August 1982)

The role of mean free paths of product particles in high-energy nuclear collisions has been studied. In inclusive energy spectra the observed slope difference among p, π, and K^+ can be interpreted as due to the difference in mean free paths of these particles, suggesting that particles with longer mean free paths probe most sensitively the early, highly excited, hot phase of the collision. With use of the data of pp and $\pi\pi$ interferometries further discussions on the space-time evolution of the system are developed.

PACS numbers: 25.70.Bc, 25.70.Fg

One of the main goals in the research of high-energy nucleus-nucleus collisions is to probe experimentally the highly excited, compressed, hot phase of nuclear matter. Obviously, a nuclear collision is time dependent, and, as demonstrated in cascade calculations,[1] the time interval during which the system is at this hot phase would be of the order of $(2-3)\times 10^{-23}$ s. Unfortunately, particles detected by actual experiments, such as p, π, K^+, etc., will record the entire (time-integrated) history of the collision. Thus, an important question to ask here is whether a particular type of these particles can most sensitively probe this hot phase. In this Letter I first discuss this question using the data of inclusive energy spectra of p, π, and K^+.

Once we have obtained an answer to the above question, the next important question to ask is if we can study the space-time evolution of the system, and, in particular, how the system is going to expand after the collision and how the hot baryonic system dissipates into final observed particles. I discuss this question using the data of two-particle correlations.

In single-particle inclusive spectra for p and π the observed invariant cross sections at 90° c.m. (from nearly equal-mass collisions) are approximately expressed as[2]

$$E(d^3\sigma/dp^3) \propto \exp(-E^{\text{c.m.}}/E_0). \quad (1)$$

where $E^{\text{c.m.}}$ is the kinetic energy of the observed particle in the c.m. frame and E_0 is a parameter. As shown in Ref. 2, the value of E_0 increases monotonically as the beam energy increases, and, in addition, E_0 is consistently smaller for π than for p.

In the thermal model this E_0 is approximately equal to the temperature T. Therefore, within the framework of this model the value of E_0 must be the same for p and π, since they are emitted from a common thermal bath.[3-5] This is inconsistent with the data. In order to overcome this difficulty Siemans and Rasmussen[6] have proposed a model of a radially expanding flow. At a fixed kinetic energy of emitted particles, the velocity of protons is much smaller than that of pions, because $m_p > m_\pi$. Therefore, if a radially expanding flow is superposed on the thermal spectra, the slower particles (p) are influenced more by this flow than are the faster particles (π). In other words, there will be a greater enhancement in kinetic energy for protons than for pions. This idea explains reasonably well the observed difference in E_0 between p and π.

From the point of view of the phase space of individual NN collisions, the observed slope difference also seems reasonable. In order to produce pions the 140-MeV rest-mass energy has to be supplied. Then, if the total energy were fixed, less kinetic energy would be available for the emission of π than for the emission of p. This mechanism would, thus, result in $E_0(\pi) < E_0(p)$. In fact, on the basis of this idea the available data have been explained reasonably well.[7,8]

Although the above two mechanisms seem to be successful in explaining the observed slope difference, I point out here that neither model has considered carefully the final-state interactions among particles produced in a collision, especially interactions between the emitted particles and the hot baryonic system created in a collision. A macroscopic quantity which describes these interactions is the mean free path, λ. Since $\sigma(\pi N) \approx 100-200$ mb is larger than $\sigma(NN) \approx 40$ mb, $\lambda(p)$ is larger than $\lambda(\pi)$ in nuclear matter. Therefore, pions would be rescattered more frequently than protons. Since the system would eventually be cooled down as time proceeds, pions would sample a later, and thus colder, stage of the system more sensitively than would protons, because of these frequent rescatterings. This mechanism induces again $E_0(\pi) < E_0(p)$. Therefore, all three possibilities above support the experimental fact that E_0 for π is smaller than E_0 for p.

In order to clarify this point we discuss next the K^+ spectra which have been measured recently by Schnetzer *et al.*[9] The observed spectrum shape is again exponential. In addition, as pointed out in Ref. 9, the value of E_0 for K^+ is larger than that for p and π. For example, in Ne + NaF collisions at 2.1 GeV/nucleon, $E_0 \approx 142$ MeV for K^+,[10] ≈ 122 MeV for p,[2] and ≈ 102 MeV for π. [Note that E_0 defined in the present paper is slightly different from T_0 defined in Ref. 9, and the value of E_0 is generally larger than that of T_0.]

If a radially expanding flow determines the slope difference, we then expect

$$E_0(\pi) < E_0(K^+) < E_0(p), \quad (2)$$

since $m_\pi < m_{K^+} < m_p$, and thus at a given kinetic energy the velocity of K^+ should lie just in between the velocities of p and π. On the other hand, if the phase space of the individual NN collisions determines the slope difference, we expect

$$E_0(K^+) < E_0(\pi) < E_0(p), \quad (3)$$

since the threshold energy for K^+ production is much higher than that for π production, so that the least kinetic energy is available for K^+. Finally, if the mean free paths of product particles determine the slope difference, then we expect

$$E_0(\pi) < E_0(p) < E_0(K^+), \quad (4)$$

since $\sigma(K^+N) \approx 10$ mb, and thus $\lambda(\pi) < \lambda(p) < \lambda(K^+)$. According to this idea, K^+ samples an earlier, and thus highly excited, hot stage of the system more sensitively than π and p. Only this last relation (4) agrees with the experimental data. Therefore, it is likely that the slope difference between π, p, and K^+ is primarily due to the difference in λ among these particles and not due to the radial expansion nor to the phase space.

The above situation is schematically illustrated in Fig. 1. At the initial stage of the collision the energy density of the system would increase as a result of multiple NN collisions. Then the system would be cooled down, again through multiple NN collisions. For final particles that are emitted, particles with longer mean free paths tend to sample a phase of higher energy density of the system, and thus tend to carry higher kinetic energies (namely, larger values of E_0). If this argument is correct, then each type of product particles records a different time of nuclear collision and serves as a nuclear clock. In this regard, future measurements of photons or lepton pairs would be very interesting because of their extremely long mean free paths in nuclear matter.

Extending the preceding argument, let us discuss the space-time evolution of the system. Recently, small-angle two-particle correlations for an Ar + KCl system have been reported from $\pi\pi$ (Ref. 11) and pp (Ref. 12) measurements (Hanbury Brown–Twiss effect[13]), to determine the source radius, R. Although several corrections due to mutual final-state interactions have to be applied to the raw data to evaluate R, the best values reported thus far, for the participant region, are as follows: $R = 3.2 \pm 0.3$ fm for $\pi^-\pi^-$, $R = 3.9 \pm 0.4$ fm for $\pi^+\pi^+$, and $R \approx 2.4$ fm for pp. The pn correlations that eventually create deuterons can be used also to estimate the value of R, as proposed by Mekjian.[14] Recently, Sato and Yazaki[15] modified the formula of Mekjian in order to eliminate the effect of the intrinsic radius of a deuteron. An empirical analysis based on this idea was reported in Ref. 10 from which we have $R \approx 2.4$ fm for the Ar + KCl system. Summarizing these data, it seems that R determined from $\pi\pi$ (3.2– 3.9 fm) is consistently larger than that determined from pp or pn (≈ 2.4 fm).

According to several cascade calculations,[1,16] most of the NN collisions would be completed when both the projectile and target reach a maximum overlap. Then the system starts to expand and to be cooled down. Therefore, we can naively expect that, at the stage when the system reaches the highest energy density, it receives the highest compression and reaches the highest particle density. If p, π, and K^+ observe different stages of the collision, as shown in Fig. 1, it is then not too surprising that the source radius, R, determined from the pion degree of freedom is larger than that determined from the nucleon degree of freedom, since (a) $R \propto \rho^{-1/3}$ and (b) nucleons tend to probe an earlier, compressed, high-density stage than pions. This situation is schematically illustrated in Fig. 2. With use of a naive participant-spectator model,[17] the above results of two-particle correlations lead to $\rho \approx 2\rho_0$ when the system is probed by nucleons and $\rho \approx 0.6\rho_0$ when it is probed by pions. Here, according to this model, $R \approx 3$ fm at $\rho = \rho_0$. Of course, it is too early to conclude anything definite at the present stage from these data alone. However, these data suggest that the space-time evolution of the system might be able to be studied from extensive studies of small-angle two-particle correlations. Especially, future measurements of two-K^+ or two-γ interferometry are extremely interesting to probe the highest energy- and particle-density phase of the system created in high-energy nuclear collisions.

The above two arguments on E_0 and R may further provide information on the dynamical path of the collision. Inclusive spectra tell us the *effective* temperature, T, for each particle. Two-

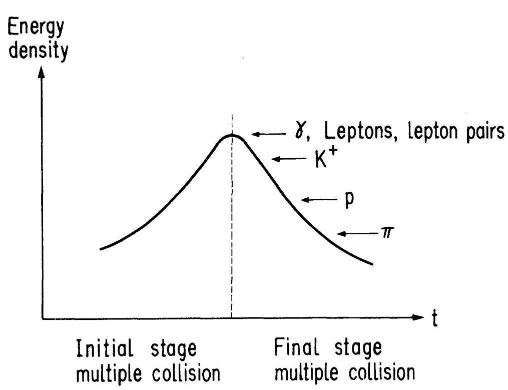

FIG. 1. A schematic illustration of an expected time dependence of high-energy nuclear collision, and the proposed particle probes at various stages.

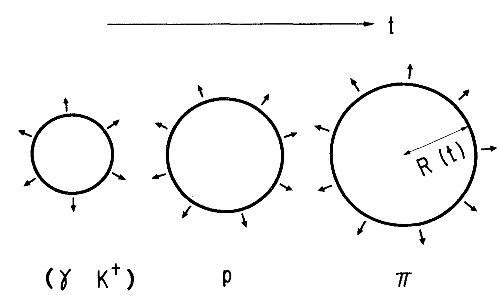

FIG. 2. A schematic illustration of the space-time evolution of the system as suggested from the data of small-angle two-particle correlations.

particle correlation data tell us the *effective* density, ρ, for it. If we plot these observed values in the (ρ, T) plane, we would then obtain the dynamical path of the collision in this plane.

In conclusion, the cross-section slope difference among p, π, and K^+ in inclusive energy spectra suggests that mean free paths of these product particles seem to play the major role in determining such a difference. It also implies that K^+ probes most sensitively the highest energy-density phase of the collision. The data of small-angle two-particle correlations further suggest that particles with longer mean free paths tend to probe the compressed higher particle-density phase of the system. Since the present arguments are based mostly on an intuitive idea, it would be interesting in the future to theoretically establish the relationship among E_0, R, and λ.

Finally I comment that the present argument obtained at the Bevalac cannot be applied immediately to the higher beam energies expected at the CERN super proton synchrotron or the intersecting storage rings. At these energies all the values of mean free paths for π, p, and K^+ converge to a value close to a nuclear radius. Therefore, only photons or lepton pairs would sample a phase of high energy density. Since the energy density might reach up to 2 $\mathrm{GeV/fm^3}$ at these high beam energies,[18, 19] it will be interesting to measure photons and lepton pairs at the CERN super proton synchrotron to probe such a high-energy-density phase.

This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U. S. Department of Energy under Contract No. DE-AC03-76SF00098. It was also supported by the Institute for Nuclear Studies–Lawrence Berkeley Laboratory Collaboration Program.

[1]K. K. Gudima and V. D. Toneev, Joint Institute for Nuclear Research Report No. E2-12644, 1979 (unpublished).
[2]S. Nagamiya, M.-C. Lemaire, E. Moeller, S. Schnetzer, G. Shapiro, H. Steiner, and I. Tanihata, Phys. Rev. C 24, 971 (1981).
[3]J. Gosset, J. I. Kapusta, and G. D. Westfall, Phys. Rev. C 18, 844 (1978).
[4]S. Das Gupta, Phys. Rev. Lett. 41, 1450 (1978).
[5]A review of the thermal model is given in S. Das Gupta and A. Z. Mekjian, Phys. Rep. 72, 131 (1981).
[6]P. J. Siemens and J. O. Rasmussen, Phys. Rev. Lett. 42, 844 (1979).
[7]J. Knoll, Phys. Rev. C 20, 773 (1979).
[8]R. L. Hatch and S. E. Koonin, Phys. Lett. 81B, 1 (1978).
[9]S. Schnetzer *et al.*, Phys. Rev. Lett. 49, 989 (1982).
[10]S. Nagamiya, in Proceedings of the Fifth High Energy Summer Study, Berkeley, May 1981, Lawrence Berkeley Laboratory Report No. 12652, 1981 (unpublished), p. 141.
[11]W. A. Zajc *et al.*, in Proceedings of the Fifth Energy Summer Study, Berkeley, May, 1981, Lawrence Berkeley Laboratory Report No. 12652, 1981 (unpublished), p. 350.
[12]Z. Zarbakhsh *et al.*, Phys. Rev. Lett. 46, 1268 (1981).
[13]R. Hanbury Brown and R. Q. Twiss, Nature (London) 178, 1046 (1956).
[14]A. Z. Mekjian, Phys. Rev. C 17, 1051 (1978).
[15]H. Sato and K. Yazaki, Phys. Lett. 98B, 153 (1981).
[16]J. Cugnon, Phys. Rev. C 22, 1885 (1980); Y. Yariv and Z. Fraenkel, Phys. Rev. C 20, 2227 (1979), and 24, 488 (1981); G. Bertsch and J. Cugnon, Phys. Rev. C 24, 2514 (1981).
[17]J. Hüfner and J. Knoll, Nucl. Phys. A290, 460 (1977).
[18]R. Anishetty, P. Koehler, and L. McLerran, Phys. Rev. D 22, 2793 (1981).
[19]H. Satz, to be published.