Average Transverse Momentum and Energy Density in High-Energy Nucleus-Nucleus Collisions

T. H. Burnett, S. Dake, M. Fuki, J. C. Gregory, T. Hayashi, R. Holynski, J. Iwai, W. V. Jones, A. Jurak, J. J. Lord, O. Miyamura,[a] T. Ogata, T. A. Parnell, T. Saito, S. Strausz, T. Tabuki, Y. Takahashi,[b] T. Tominaga, B. Wilczynska, R. J. Wilkes, W. Wolter, and B. Wosiek

Institute for Cosmic Ray Research, University of Tokyo, Tanashi, Tokyo 188, Japan
Department of Physics, Kobe University, Kobe 657, Japan
Okayama University of Science, Okayama 700, Japan,
Department of Applied Mathematics, Osaka University, Osaka 560, Japan
Science and Engineering Research Laboratory, Waseda University, Tokyo 162, Japan
Department of Physics and Astronomy, Louisiana State University, Baton Rouge, Louisiana 70803
Space Science Laboratory, Marshall Space Flight Center, National Aeronautics and Space Administration, Huntsville, Alabama 35812
School of Science, University of Alabama in Huntsville, Huntsville, Alabama 35899
Department of Physics, University of Washington, Seattle, Washington 98105
Institute for Nuclear Physics, PL-30-055 Krakow, Poland.

(Received 30 May 1986; revised manuscript received August 27, 1986)

Emulsion chambers were used to measure the transverse momenta of photons or π^0 mesons produced in high-energy (≥ 1 TeV/amu) cosmic-ray nucleus-nucleus collisions. A group of events having large average transverse momenta has been found which apparently exceeds the expected limiting values. Analysis of the events at early interaction times, of the order of 1 fm/c, indicates that the observed transverse momentum increases with both rapidity density and energy density.

PACS numbers: 25.70.Np, 13.85.Tp, 96.40.Mn

The currently accepted theory of strong interactions, quantum chromodynamics (QCD), predicts the formation of new phases of hadronic or nuclear matter at high temperatures and/or high baryon densities.[1] In particular, quark-gluon–plasma (QGP) and chiral-symmetry phase transitions are expected to take place in high-energy heavy-ion collisions in which the particle density can be significantly higher than that in elementary particle collisions.[2] The Japanese-American Cooperative Emulsion Experiment (JACEE) has been observing high-energy collisions of cosmic-ray nuclei in balloon-borne emulsion chambers.[3-5] In this paper, we present an analysis of the measured average transverse momentum ($\langle P_T \rangle$) of photons (or π^0 mesons) correlated with the observed particle density and the energy density (ε) in high-energy (>1 TeV/amu) nucleus-nucleus interactions. The results indicate a breakdown of the limiting behavior of $\langle P_T \rangle$.

Several emulsion chambers [each having four blocks of dimension $40\times 50\times(25-30)$ cm^3] were exposed at altitudes of 3.5–5.0 g/cm^2 for about 30 h. A typical chamber consisted of more than 100 emulsion plates (50–450-μm-thick emulsion coated on both sides of 800-μm thick acrylic plates), plastic detectors (CR-39), acrylic target plates, x-ray films, and lead sheets. The primary charge (Z_A), vertex position, pseudorapidity distribution ($\eta \equiv -\ln\tan\theta/2$, θ=emission polar angle), charged-particle and photon multiplicities ($N_{\rm ch}, N_\gamma$), individual photon energies ($E_\gamma \geq 30$ GeV) and transverse momenta ($P_{T\gamma}$), and the total cascade energy ($\sum E_\gamma$) were measured by post-flight microscope analysis.[3,4] Typical accuracies of the measurements were $\Delta Z_A \leq (0.2-2.0)e$, $\Delta\eta \leq 0.1$, $\Delta E_\gamma / E_\gamma \leq 0.22$, and $\Delta P_{T\gamma}/P_{T\gamma} \leq 0.25$. Details of the detector and the methods have been reported elsewhere.[4]

The average P_T for individual interactions is obtained by two independent methods (methods I and II). Method I examines the $P_{T\gamma}$ distribution of individual photon-initiated showers in an event. This allows an estimate of $\langle P_{T\gamma} \rangle$ and that of the presumed parent π^0 mesons, $\langle P_{T\pi^0} \rangle$, from the relationship[6] $dn/dP_{T\pi^0} = q_T d^2n/dq_{T\gamma}^2$, where q_T and $q_{T\gamma}$ denote $\frac{1}{2}\{P_{T\pi^0} + (m_\pi^2 + P_{T\pi^0}^2)^{1/2}\}$ and $\frac{1}{2}\{P_{T\gamma} + (m_\pi^2 + P_{T\gamma}^2)^{1/2}\}$, respectively. The uncertainty in the measurements of $\langle P_{T\pi^0} \rangle$ by this method is typically 15% to 20%. The sources of uncertainty involve, among other things, the gamma-ray detection threshold ($E_\gamma^{\rm th} \geq 30$ GeV), the finite number of detected photons (20–300),[7-9] and one's capability to identify photons with a specific event. The uncertainty is larger for the extremely high-multiplicity events ($N_{\rm ch} \geq 400$). For these events we estimate that $\langle P_{T\pi^0} \rangle$ by method I could be overestimated as much as 30%. This results from electron contamination due to bulk spreading from neighboring cascades.

Method II is a Monte Carlo analysis[3] of an event and is free from above-mentioned effects. Here we compare the three-dimensional shower in differentially segmented pseudorapidity regions with Monte Carlo–generated cascades, leaving the average P_T values of all mesons ($\langle P_{T\pi} \rangle$) as a free parameter. This analysis is feasible only in the large-rapidity region of very high-multiplicity events ($N \geq 400$). The Monte Carlo program uses the exact pseudorapidities of the detected charged particles, and assumes isospin symmetry of the pions, and an in-

TABLE I. Summary of the highest-multiplicity heavy-nucleus events. The $[\eta_L]$'s following the $\langle P_T \rangle$ values indicate the laboratory pseudorapidity ($\eta_L \equiv -\ln \tan(\theta/2)_{\rm lab}$) region of the measured $\langle P_T \rangle$ data.

Event type (TeV/amu)	$N_{\rm ch}$	$\langle P_{T\pi^0} \rangle$ (GeV/c)	$[\eta_L]$	$\langle P_{T\pi} \rangle$ (GeV/c)	$[\eta_L]$	$dN/d\eta\,(\lvert\eta\rvert \le 1)$	$\varepsilon_{\rm min}$ (GeV/fm^3)
V(1.5)+Pb	1050^{+300}_{-30}	0.95 ± 0.31	3.7–6.4	0.55 ± 0.05	≥ 6.4	258 ± 12	2.4
Si(4.1)+Ag/Br	1010 ± 30			$0.55^{+0.12}_{-0.05}$	≥ 6.1	183 ± 10	2.7
Si(4.0)+Pb	790^{+40}_{-25}	1.30 ± 0.30	4.6–5.5	$1.00^{+0.2}_{-0.15}$	≥ 5.5	147 ± 8	3.8
Ca(100)+CHO	760 ± 30	0.53 ± 0.04	6.5–8.3			81 ± 8	2.0
Ca(0.5)+Pb	670 ± 40	1.03 ± 0.18	4.2–5.1	1.1 ± 0.5	≥ 5.1	142 ± 8	3.2
Ca(1.8)+Pb	> 452	$1.6^{+0.1}_{-0.3}$	3.5–6.0	$1.1^{+1.0}_{-0.35}$	5.3–6.0	100 ± 16	2.2
Ti(1.0)+Pb	> 416	1.0 ± 0.2	3.8–6.6			134 ± 8	2.9
C(> 1.5)+Pb	400^{+15}_{-30}	$1.6^{+0.4}_{-0.6}$	4.0–7.0	≥ 1.2	≥ 6.0	81 ± 7	4.5

variant exponential distribution for P_T. The uncertainties in $\langle P_T \rangle$ with this method are larger than the statistical errors ($\sim 10\%$), and depend mainly on one's ability to remove the fragmentation proton component accurately from the produced particles. We bounded the uncertainty by considering the two extreme cases of all particles in the largest-rapidity region being protons and being pions.

The data from both methods of analyses are summarized and compared in Table I. Although different rapidity regions are considered in applying the two methods, the results are reasonably consistent considering the measurement uncertainties.

We have estimated the energy density (ε) at the typical soft QCD interaction time ($\tau_0 \simeq 1$ fm/c), using results on $\langle P_T \rangle$ and a simple formula proposed by Bjorken.[10] This formula, based upon an inside-outside cascade picture for the space-time development of the hadrons created in ultrarelativistic nucleus-nucleus collisions, is

$$\varepsilon_{\rm min} \equiv (\langle P_T \rangle^2 + m_\pi^2)^{1/2} \times \tfrac{3}{2}(dN/d\eta_c)/2\pi\tau_0 A_{\rm min}^{2/3},$$

where $dN/d\eta_c$ denotes the central pseudorapidity density of the charged particles in the nucleon center-of-mass system (c.m.s.). To calculate $dN/d\eta_c$ we used the data for $\lvert \eta_c \rvert < 1$. $A_{\rm min}$ is the atomic mass number of the smaller nucleus in a collision. For events that have nuclear fragments, $A_{\rm min}$ was reduced by the mass number of the fragment. Alternative estimation formulas have been proposed for ε which take into account the hydrodynamical development,[11–14] and all of them give larger values than $\varepsilon_{\rm min}$.

About one hundred interactions of primary nuclei have been identified above a detection threshold energy of $\sum E_\gamma \ge 1$ TeV. Their corresponding primary energies are greater than about 1 TeV/u. Events with $\sum E_\gamma \ge 2$ TeV were fully analyzed, of which 12 and 25 events had the projectile charges $2 \le Z_A \le 5$ and $Z_a \ge 6$, respectively. The measured $\langle P_{T\pi^0} \rangle$ (or $\langle P_{T\pi} \rangle$) and the total visible cascade energy ($\sum E_\gamma \ge 2$ TeV) are shown in Fig. 1. Most of the proton-Lucite interactions previously analyzed[5] showed $\langle P_{T\pi^0} \rangle \le 0.7$ GeV/c. Twenty-three of these are also displayed in Fig. 1. Comparing these we see that some heavy-nucleus interactions exhibit noticeably larger $\langle P_T \rangle$ values, in a similar $\sum E_\gamma$ range, than proton events.

The high-$\langle P_T \rangle$ event rate in an emulsion chamber cannot be estimated in a straightforward manner because of the complicated detection conditions associated with the $\sum E_\gamma$ threshold. (The $\sum E_\gamma$ trigger, in conjunction with the energy spectrum of the primary particles, generally favors detection of high inelasticity events and central collisions.[3,4]) If we consider undetected high-energy collisions (that released too small $\sum E_\gamma$ for detection), and use known cosmic-ray fluxes,[4,5,15] we estimate that approximately 5%–10% of the heavy-ion collisions ($Z_A \ge 6$), and less than 1% of the light-ion collisions ($Z_A \le 5$), would yield values of $\langle P_T \rangle$ greater than 700 MeV/c. These rates are comparable with the fraction of central-collision cross sections ($\sim 10\%$).

The dependence of $\langle P_T \rangle$ on the central rapidity density is examined in Fig. 2. An approximately constant behavior[16] of $\langle P_T \rangle$ (~ 400 MeV/c) has been established in hadron-hadron collisions at energies up to 1.8 TeV.[17] A gradual increase of $\langle P_T \rangle$ with increasing pseudo-rapidity density has been indicated by the antiproton-proton collision ($\bar{p}$-p) data (Arnison *et al.*[18]) at a laboratory ener-

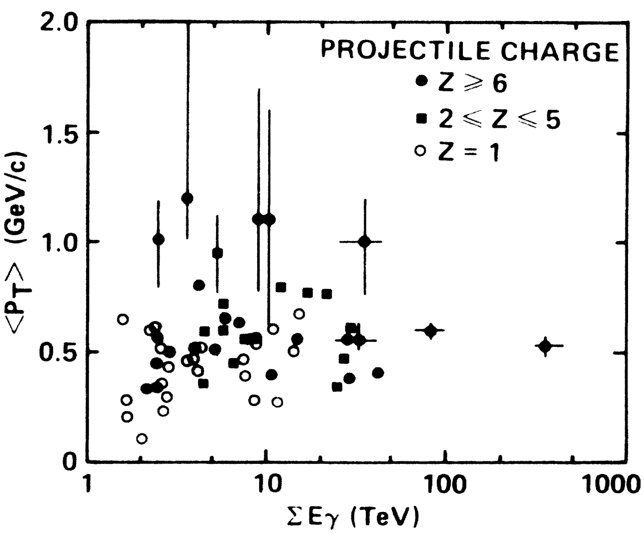

FIG. 1. A scatter plot of $\langle P_T \rangle$ data in terms of $\sum E_\gamma$.

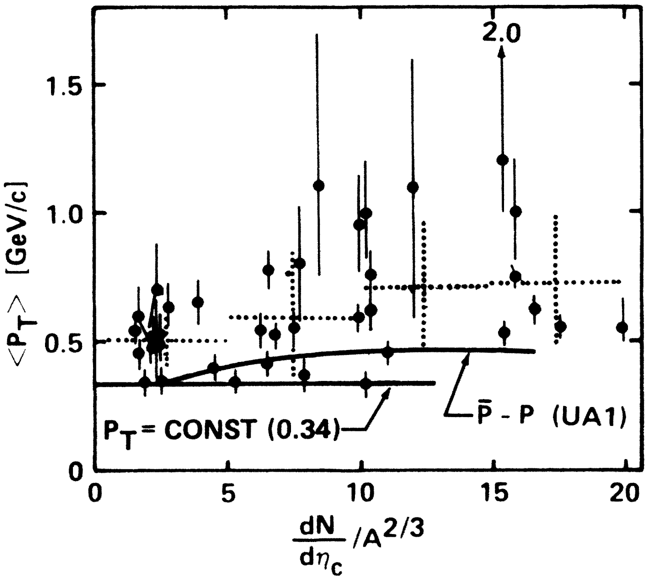

FIG. 2. Dependence of $\langle P_T\rangle$ on the central rapidity density per unit colliding volume of nucleus-nucleus interactions $[(dN/d\eta)/A_{\rm min}^{2/3}]$. Dotted crosses indicate average dependences.

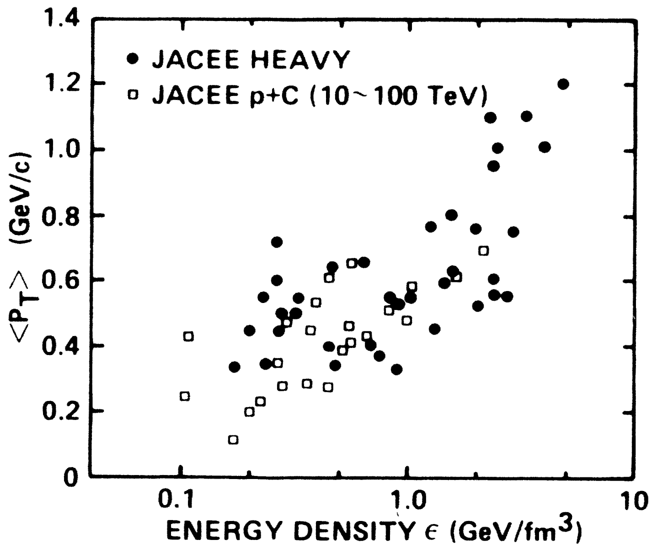

FIG. 3. Correlation of $\langle P_T\rangle$ with the energy density ε. Full circles are for individual nucleus events $(2\le Z\le 26)$ and open squares are for proton-lucite events.

gy of 150 TeV. The present data are at energies of several TeV/u, and therefore, one would expect a scatter about a constant value of $\langle P_T\rangle$ if heavy-ion collisions are nothing more than a simple superposition of elementary-particle collisions. Although the statistics are limited and the fluctuations from event to event are very large in Fig. 2, the data suggest systematically higher $\langle P_T\rangle$ values and their gradual increase at high-rapidity densities.

To examine these high-$\langle P_T\rangle$ events further, we show the correlation of $\langle P_T\rangle$ with $\varepsilon_{\rm min}$ in Fig. 3. The median values (and dispersions, σ) of $\langle P_T\rangle$ for the events with $\varepsilon<1$ GeV/fm^3 and with $\varepsilon>2$ GeV/fm^3 are 490 ($\sigma=130$) MeV/c and 850 ($\sigma=240$) MeV/c, respectively. Almost all high-multiplicity heavy-nucleus events (Table I) indicated high energy densities (≥ 2 GeV/fm^3) with significantly higher $\langle P_T\rangle$ values than the average of the highest-energy nucleon-nucleon collision data (0.4–0.5 GeV/c).

It is interesting to note that the high $\langle P_T\rangle$ values (>700 MeV/c) in Fig. 3 begin around 1–2 GeV/fm^3, which would be in the range 3–6 GeV/fm^3 if the other formulas[11-14] were used for estimating the energy density. These values are comparable with, or even greater than, the predicted critical values (1–2 GeV/ fm^3) for QGP phase transitions.[1,2,19] At these high energy densities a growth of P_T with increasing energy, or rapidity, density has been expected in thermodynamical and hydrodynamical studies of the QGP phase transition.[2,20,21]

Although interpretation of the data in terms of the formation of new states of matter is stimulating, it should be noted that there have been other proposed effects that would predict the growth of $\langle P_T\rangle$ in nucleus-nucleus collisions.[22,23] These include multiple scattering,[24] impact-parameter effects,[25] and the influence of QCD minijets.[26] While not studied quantitatively, these could partially explain an increase of $\langle P_T\rangle$ with increasing incident energy and mass number.

In summary, high average transverse momenta are indicated in high-energy (≥ 1 TeV/u) nucleus-nucleus interactions. They are observed in correlation with high rapidity, and high energy, density. Further experimental studies of $\langle P_T\rangle$ values with better statistics at various energies are required to allow clear discrimination of theoretical models. In particular, direct measurements of the $\langle P_T\rangle$ of charged mesons $(\pi^\pm, K^\pm)$ in very high-energy heavy-ion collisions are necessary to confirm the present results.

This work is supported in part by the Institute for Cosmic Ray Research, Japan Society for Promotion of Science, Kashima Foundation, U. S. Department of Energy, National Aeronautics and Space Administration, and National Science Foundation.

---

[a]Corresponding author, at Osaka.
[b]Corresponding author, at Alabama and NASA.

[1]J. I. Kapusta, Nucl. Phys. **B148**, 461 (1979); H. Satz, Nucl. Phys. **A400**, 541 (1983).

[2]E. V. Shuryak, Phys. Rep. **61C**, 71 (1980); M. Jacob and J. Tran Thanh Van, Phys. Rep. **88C**, 1 (1982); T. W. Ludlam and H. E. Wegner, Nucl. Phys. **A418**, 375c (1984).

[3]T. H. Burnett *et al.*, Phys. Rev. Lett. **50**, 2062 (1983). The definition of the energy density in this paper is different by a

factor of 2.

[4]T. H. Burnett *et al.*, Phys. Rev. Lett. **51**, 1010 (1983), and Nucl. Instrum. Methods Phys. Res. Sect. A **251**, 583 (1986).

[5]T. H. Burnett *et al.*, in *Proceedings of the Nineteenth International Cosmic Ray Conference, La Jolla, California, 1985,* edited by F. C. Jones, J. Adams, and G. M. Mason, NASA Conference Publication No. 2376 (Goddard Space Flight Center, Greenbelt, MD, 1985), Vol. 2, pp. 32 and 48, Vol. 6, p. 164, and Nucl. Phys. **A447**, 189 (1985).

[6]G. I. Kopylov, Phys. Lett. **41B**, 371 (1972).

[7]The relationship $\langle P_{T\pi^0}\rangle \simeq 2\langle P_{T\gamma}\rangle$ holds only for $dn/dP_{T\gamma} \propto \exp(-P_{T\gamma}/P_0)$ with a slope parameter $P_0 > m_\pi$. A previously reported event (Ca+C in Ref. 3) showed $\langle P_{T\gamma}\rangle = 350$ MeV/c with $dn/dP_{T\gamma}^2 \propto \exp(-P_{T\gamma}/P_0)$, whose $\langle P_{T\pi^0}\rangle$ should be 525 MeV/c, instead of 700 MeV/c.

[8]The low-P_T region ($P_{T\gamma} < 100-200$ MeV/c) is biased by E_γ^{th} and causes uncertainties (typically, 10%–15%) in $\langle P_{T\gamma}\rangle$ values, which is estimated for each event in terms of $dn/dP_{T\gamma} \propto P_{T\gamma}^\alpha \exp(-P_{T\gamma}/P_0)$, with α ($-1 < \alpha < +1$; mostly $\alpha \simeq 0$) depending on the intercept values at $P_T = 0$ for adjusting $N_\gamma \simeq N_{\text{ch}}$. The errors in $P_{T\gamma}$ measurements ($\Delta P_{T\gamma}/P_{T\gamma} < 25\%$) and overlapping probabilities of π^0 mesons cause overestimation in $\langle P_{T\gamma}\rangle$ values up to 4%–7% and 3%–5%, respectively.

[9]Individual cascade analyses of photons in events with Pb target was only feasible for those with large $\langle P_{T\pi^0}\rangle$ values (≥ 0.6 GeV/c). In those events, individually detected high-energy cascades gave $P_{T\pi^0}$ ($\simeq P_{T\gamma}$) when subjected to kinematical limitations in satisfying the criteria for separation (> 15 μm) of two photons from a π^0 decay before cascades develop substantially in the calorimeter.

[10]J. D. Bjorken, Phys. Rev. D **27**, 140 (1983).

[11]M. Gyulassy and T. Matsui, Phys. Rev. D **9**, 419 (1984).

[12]A. Hosoya and K. Kajantie, Nucl. Phys. **B250**, 66 (1985).

[13]P. Danielowicz and M. Gyulassy, Phys. Rev. D **31**, 53 (1985).

[14]H. Sumiyoshi *et al.*, Z. Phys. C **23**, 391 (1984).

[15]M. Simon *et al.*, Astrophys. J. **239**, 712 (1980).

[16]I. Pomeranchuk, Dokl. Akad. Nauk SSSR **78**, 889 (1951); R. Hagedorn, Nuovo Cimento Suppl. **3**, 147 (1965).

[17]A. Breakstone *et al.*, Phys. Lett. **132B**, 463 (1983).

[18]G. Arnison *et al.*, Phys. Lett. **118B**, 167 (1982).

[19]M. A. Shifman, A. I. Veinshtein, and V. I. Zakharov, Nucl. Phys. **B147**, 385, 448, 519 (1979).

[20]L. van Hove, Phys. Lett. **118B**, 138 (1982); Z. Phys. C **21**, 93 (1983), and Nucl. Phys. **A447**, 443 (1985). This latest paper suggests for QGP formation a possible requirement of higher rapidity densities than those observed in the present experiment, based on a simplified interpretation of previously reported $\langle P_T\rangle$ data (Ref. 5) and its dispersion as being independent of rapidity density. The details of the data reported here (see Fig. 2) are not consistent with that interpretation.

[21]M. Gyulassy, K. Kajantie, H. Kurki-Suonio, and L. McLerran, Nucl. Phys. **B237**, 477 (1984).

[22]A. Dar and A. Margolis, to be published.

[23]T. Ochiai, S. Date, and H. Sumiyoshi, Rikkyo University Report No. RUP-85-4, 1985 (to be published).

[24]A. Capella, C. Pajares, and A. V. Ramallo, Nucl. Phys. **B241**, 75 (1985).

[25]S. Barshay, Phys. Rev. D **29**, 1010 (1984).

[26]M. Jacob, CERN Report No. TH-3515, (to be published).