Extremely High Multiplicities 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, H. Oda, T. Ogata, T. A. Parnell, T. Saito, T. Tabuki, Y. Takahashi,[a] T. Tominaga, B. Wilczynska, R. J. Wilkes, W. Wolter, and B. Wosiek

Institute for Cosmic Ray Research, University of Tokyo, Tanashi, Tokyo 188, Japan, and Department of Physics, Kobe University, Kobe 657, Japan, and Department of Applied Mathematics, Osaka University, Osaka 560, Japan, and Science and Engineering Laboratory, Waseda University, Tokyo 162, Japan, and Department of Physics and Astronomy, Louisiana State University, Baton Rouge, Louisiana 70803, and Space Science Laboratory, Marshall Space Flight Center, National Aeronautics and Space Science Administration, Huntsville, Alabama 35807, and Department of Chemistry, University of Alabama in Huntsville, Huntsville, Alabama 35807, and Department of Physics, University of Washington, Seattle, Washington 98195, and Institute for Nuclear Physics, PL-30-055 Krakow, Poland

(Received 18 April 1983)

Two unusually-high-multiplicity interactions of high-energy heavy nuclei are observed in a balloon-borne emulsion chamber: A Si + AgBr event (4 TeV/nucleon) and a Ca + C event (100 TeV/nucleon), with 1015 and 760 charged particles, respectively. The multiplicities and rapidity distributions favor the multichain model but not the wounded-nucleon superposition model. The high average p_T (550–700 MeV/c) and the rapidity fluctuations of the events are not readily understood in terms of any superposition models.

PACS numbers: 13.85.Tp, 25.70.Np, 94.40.Rc

Since Landau's hydrodynamical ideas[1] of multiple meson production by colliding nuclei, there have been few frameworks that treat dense hadronic particles as a collective, mutually interacting system, but independent collision models have been developed.[2,3] Recently, new theoretical developments on dense hadronic matter have been made from such viewpoints as the bag model[4] and quantum chromodynamics (QCD),[5] which predict that nuclear matter at some sufficiently high energy density undergoes a phase transition into unconfined quark-gluon plasma. Furthermore, the realization of high energy density in nucleus-nucleus interactions is predicted from considerations of multiple scattering in the fragmentation region[6] and the space-time evolution of created mesons in the central region.[7] So far, however, there have been too few experimental studies to evaluate any of these models.

The Japanese-American cooperative emulsion experiment (JACEE) is investigating the high-energy interactions of cosmic-ray nuclei with balloon-borne emulsion chambers.[8] Three flights at an atmospheric depth of 3.5–5 g/cm^2 and a total exposure of about 100 m^2 sr h have yielded about 100 events at energies exceeding 1 TeV/nucleon. Among the forty analyzed interactions with primary charge $Z \geqslant 6$, two events have been found with charged multiplicities far exceeding those of any other directly observed interaction, and these events provide an experimental test of some of the features predicted by existing collision models.

The emulsion chambers employed in JACEE are fine-grain, multilayered track detectors that serve simultaneously as both targets and coordinate/ionization recorders. More than 100 plastic-based emulsion plates (50–200-μm-thick nuclear emulsion on both sides of an 800-μm acrylic plate) are interleaved in the target with inert acrylic plates (2 mm thick) and CR-39 track detectors (1.6 mm thick), as well as in the calorimeter with x-ray films and lead absorber (1–2.5 mm thick). The emulsions provide submicrometer accuracy for coordinates of charged tracks and 22% energy resolution for photons having energies in the range 50–1000 GeV.[8] The primary energy is estimated by the mean Castagnoli method,[9] i.e., use of the angular distribution of secondary particles to estimate the Lorentz factor (γ_c) of the center-of-mass system (CMS). The total electromagnetic cascade energy ($\sum E_\gamma$) observable in the calorimeter is also used to estimate the primary energy via the partial inelasticity (k_γ).[10] For a given event, these two independent methods generally agree within a factor of 2.

The highest-multiplicity event observed is of

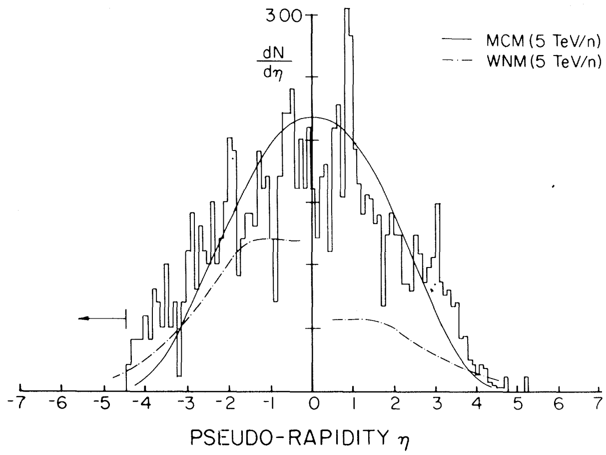

FIG. 1. The CMS pseudorapidity distribution of charged particles in the Si + AgBr event. Solid curve, multichain-model calculation; dashed curve, wounded-nucleon-model calculation; both for $\langle P_{T\pi}\rangle = 0.4$ GeV/c. The arrow indicates the unobserved region.

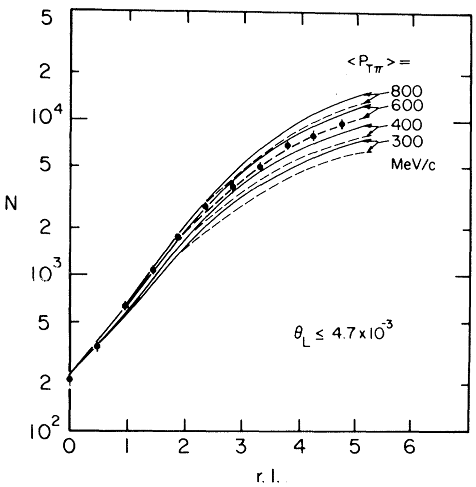

FIG. 2. Cascade development of the Si + AgBr event. The number N includes charged hadrons as well as electrons; r.l. means radiation length. The curves are from Monte Carlo simulations assuming the observed rapidity distribution (solid curve) and the multichain model (dotted curve), to which the assumed average $P_{T\pi}$ is indicated.

the form

$$\mathrm{Si}(4\ \mathrm{TeV/nucleon}) + \mathrm{AgBr} \rightarrow 5N_\mathrm{h} + (1010 \pm 30)N_\mathrm{ch} + > 170\ \mathrm{photons}, \quad (1)$$

where N_h and N_ch stand for heavily ionizing tracks and singly charged relativistic tracks, respectively. The pseudorapidity ($\eta \equiv -\ln\tan\theta/2$) distribution of N_ch in the CMS is shown in Fig. 1 for $\gamma_c = 45$. The energy of individual photons is not measurable in this Si event, since the interaction vertex is located in a nuclear emulsion inside the calorimeter and the cascades have overlapping cores. However, the three-dimensional development of overlapping cascades within the laboratory angle of 4.7 mrad ($\eta > 1.5$) was consistent with a Monte Carlo simulation (Fig. 2) assuming charge symmetry and 550 ± 100 MeV/c[11] for the average transverse momentum of π^0 mesons ($\langle P_{T\pi^0}\rangle$). From the centroid of the pseudorapidities the γ_c is estimated to be 45 ± 5, which gives 4.1 ± 0.7 TeV/nucleon primary energy.[12]

The second-highest-multiplicity event is simultaneously the most energetic nucleus ever directly observed:

$$\mathrm{Ca}(100\ \mathrm{TeV/nucleon}) + \mathrm{C}(\mathrm{or\ O}) \rightarrow \mathrm{He} + (760 \pm 30)N_\mathrm{ch} + > 300\ \mathrm{photons}. \quad (2)$$

From the rapidity distribution of N_ch shown in Fig. 3 we obtain $\gamma_c = 225 \pm 50$, which is equivalent to the primary energy $E_0 = 100^{+50}_{-40}$ TeV/nucleon.[13] The transverse momentum (P_T) was individually measured for photons with energy exceeding 50 GeV and the CMS rapidity between 0.11 and 2.18. Some photons from secondary vertices downstream contaminate the data in the very-small-P_T region, but this background has been eliminated statistically by requiring the measured photon transverse momentum ($P_{T\gamma}$) to be larger than 200 MeV/c. After these corrections, the photon/charged-particle ratio is estimated to be 0.95 ± 0.24. A maximum-likelihood analysis assuming an exponential P_T distribution gives $\langle P_{T\gamma}\rangle = 315 \pm 25 + 35$ MeV/c for the observed

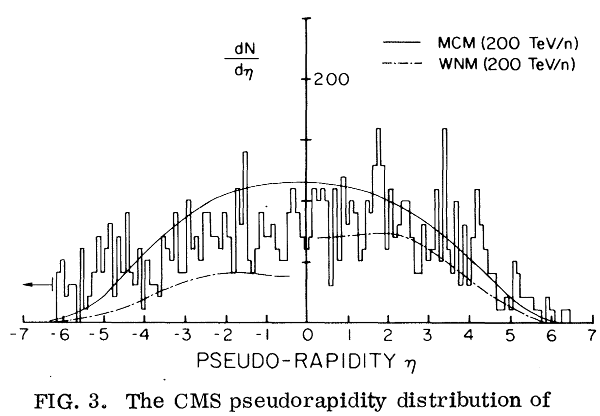

FIG. 3. The CMS pseudorapidity distribution of charged particles in the Ca + C event. Curves are the same as in Fig. 1 except for the energy.

photons shown in Fig. 4. Thus, $\langle P_{T\pi^0}\rangle$ is obtained to be 799 ± 50 MeV/c, which is about 70% higher than those obtained by proton events at the CERN intersecting storage ring energies[14] and, in the 10–100-TeV region, observed by JACEE.[8] Recent antiproton-proton ($\bar{p}p$) data at 150 TeV by the UA-1 group have confirmed that the inclusive average $P_{T\pi}$ in nucleon interactions does not exceed 420 MeV/c.[15] Most of the other nucleus-nucleus events in the JACEE experiment have $\langle P_{T\pi^0}\rangle$ around 400 MeV/c.[8] No experimental biases responsible for a high average P_T have been found.

The observed multiplicities and pseudorapidity distributions have been compared with superposition models of nucleon interactions, without consideration of any subsequent phase transition. The wounded-nucleon model (WNM) of Bialas, Bleszynski, and Czyz[2] uses a linear superposition of meson production from wounded nucleons. The multichain model (MCM) of Kinoshita, Minaka, and Sumiyoshi[3] incorporates cumulative superposition of each elementary collision in the interacting nuclei. These model calculations require the rapidity density function for nucleon collisions, which we have determined by an empirical formula using 1.8-TeV proton-proton data[16] and 150-TeV $\bar{p}p$ data.[17] The results are shown in Table I (multiplicities) and in Figs. 1 and 3 (pseudorapidity distributions). The observed multiplicities differ by more than four standard deviations from the values calculated by the WNM. The MCM, on the other hand, exhibits reasonably good agreement with the observed multiplicities and rapidity distributions, except in the fragmentation region.[18] However, if we assume $\langle P_{T\pi}\rangle = 600$ MeV/c, the MCM predictions are reduced to 80% of the values shown in Table I and Figs. 1 and 3.

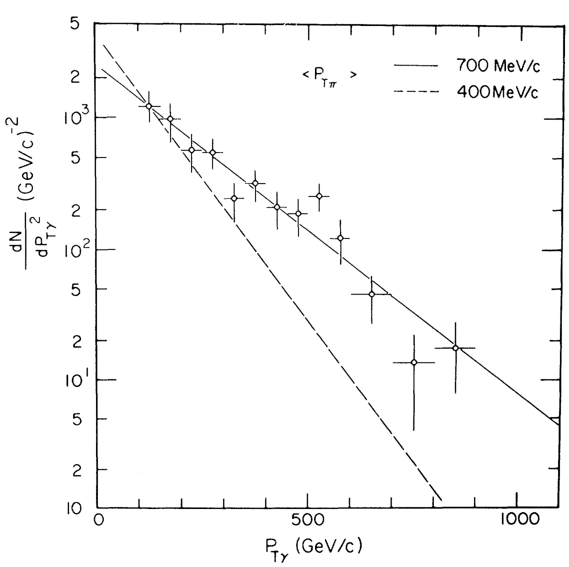

FIG. 4. Differential transverse momentum distribution of photons in the Ca+C event.

The local abundances in the fragmentation region of both the Si and Ca events may not be negligible if one considers the possibility of fragmentation fireballs, as predicted by Anishetty, Koeler, and McLerran for quark matter formation among the fragment nucleons.[6] The combination of fragmentation fireballs and the reduced MCM with $\langle P_{T\pi}\rangle = 600$ MeV/c can, in fact, improve the fit to the observed rapidity distributions.

Finally, we estimate the energy densities of the events in the central region by

$$\epsilon \geqslant (\langle P_{T\pi}\rangle^2 + m_\pi^2)^{1/2}\tfrac{3}{2}(dn/d\eta)/\pi R_A^2 t, \qquad (3)$$

where m_π and R_A represent the pion mass and the radius of the colliding volume. At the expansion time of $t = (1\text{ fm})/c$, Eq. (3) gives 4.0 ± 1.0 GeV/fm^3 and 4.5 ± 1.1 GeV/fm^3 for the Si and Ca events, respectively. Even if we use 0.4 GeV for the energy factor in Eq. (3), the energy densities are 2.85 and 2.5 GeV/fm^3, respectively, which obviously exceed the predicted critical value of 0.6–1.5 GeV/fm^3 for quark-gluon deconfinement.[4–7]

In summary, the two high-multiplicity events favor the multichain model, but not the wounded-nucleon model. Neither model explains such features associated with the observed events as high average transverse momentum and the particle abundances in the fragmentation region. As the energy densities of the events far exceed the critical density, these features may be related

TABLE I. Calculated multiplicities by WNM and MCM models. The symbols N and D denote the average and the dispersion of the charged multiplicity at the impact parameter smaller than 2 fm.

Event type	Energy (TeV/nucleon)	WNM N	WNM D	MCM N	MCM D
Si+Ag	2	482	56	759	100
	5	589	68	1020	110
Ca+C	100	399	70	779	166
	200	449	77	923	194

to the postulated quark matter formation. Further study is needed to clarify whether there is a real relationship between them.

This work is supported by the Japan Institute for Cosmic Ray Research, the Japan Society for Promotion of Science, and the Kashima Foundation, and in part by the U. S. Department of Energy, the National Aeronautics and Space Administration, and the National Science Foundation. We acknowledge the support of personnel at the National Scientific Balloon Facility, Palestine, Texas, in successful balloon flights.

[a]Address correspondence to Y. Takahashi, Department of Physics and Astronomy, Louisiana State University, Baton Rouge, La. 70803.

[1]L. D. Landau, Izv. Akad. Nauk SSSR, Ser. Fiz. 17, 51 (1953).

[2]A. Bialas, M. Bleszynski, and W. Czyz, Nucl. Phys. B111, 461 (1976).

[3]K. Kinoshita, A. Minaka, and H. Sumiyoshi, Z. Phys. C 8, 205 (1981).

[4]S. A. Chin, Phys. Lett. 78B, 552 (1978).

[5]T. D. Lee, Columbia University Report No. CU-TP-170, 1981 (unpublished); E. V. Shuryak, Phys. Rep. 61, 71 (1980), and references therein; J. Engels, F. Karsch, I. Montvay, and H. Satz, Phys. Lett. 101B, 89 (1981), and 102B, 332 (1981).

[6]R. Anishetty, P. Koeler, and L. McLerran, Phys. Rev. D 22, 2793 (1980).

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

[8]T. H. Burnett *et al.*, in *Proton-Antiproton Collider Physics—1981*, edited by V. Barger, D. Cline, and F. Halzen, AIP Conference Proceedings No. 85 (American Institute of Physics, New York, 1982), p. 552, and in *Elementary Particles and Future Facilities*, edited by R. Donaldson, R. Gustafson, and F. Paige (Fermilab, Batavia, Ill., 1982), p. 641.

[9]C. Castagnoli *et al.*, Nuovo Cimento 10, 1539 (1953).

[10]The k_γ has a standard deviation exceeding 50% in the inclusive cross section, but is on the order of 10% for central-collision events.

[11]A Monte Carlo simulation by the MCM rapidity distribution (Fig. 1) gives better fit to the data when $\langle P_{T\pi}\rangle$ is 620 ± 50 MeV/c, as is shown in Fig. 2.

[12]The shower gives $\Sigma E_\gamma = 35\pm 10$ TeV, from which, by the assumption of $k_\gamma = 0.19\pm 0.03$ for the Si event, the primary energy is estimated to be 180 ± 60 TeV (6.5 ± 2.2 TeV/nucleon).

[13]The cascades of the Ca event give $\Sigma E_\gamma = 340\pm 100$ TeV, and the calculation of k_γ taking into account the secondary interactions downstream gives 0.13 ± 0.02, from which we get the primary energy of 2600 ± 900 TeV (65 ± 20 TeV/nucleon).

[14]B. Alper *et al.*, Nucl. Phys. B100, 237 (1975).

[15]G. Arnison *et al.*, Phys. Lett. 118B, 167 (1982). K. Alpgard *et al.*, Phys. Lett. 115B, 71 (1982), give a 50% higher value.

[16]W. Thome *et al.*, Nucl. Phys. B129, 365 (1977).

[17]K. Alpgard *et al.*, Phys. Lett. 107B, 310, 315 (1981).

[18]The hydrodynamical models in Refs. 1 and 7 do not explain the region $|\eta| > 2$ of the Ca event.