# Meson Multiplicity versus Energy in Relativistic Nucleus-Nucleus Collisions

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A systematic study of meson multiplicity as a function of energy at energies up to 100 GeV/u in nucleus-nucleus collisions has been made, using cosmic-ray data in nuclear emulsion. The data are consistent with simple nucleon-nucleon superposition models. Multiplicity per interacting nucleon in *AA* collisions does not appear to differ significantly from *pp* collisions.

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It will soon become possible to study ultrarelativistic heavy-ion collisions at terrestrial accelerators, at energies orders of magnitude above those presently achievable. Currently, the only source of such collisions above 4 GeV/u is the cosmic-ray beam. Although the fluxes attainable are very low by machine standards, a systematic study of many interactions should at least point the way for future study. This paper reports on such a study, specifically measuring the variation of meson multiplicity with energy.

The data consist of interactions of galactic cosmic rays ($Z=6$ to 26, $\bar{Z}=13.7$) in nuclear emulsions (primarily Ag, Br, C, N, O, and H) flown on three balloon flights, two over Texas and one over India. The different geomagnetic cutoffs at these locations allow a natural subdivision of the data into two distinct data sets. The energy range of the data is 1.7 to about 100 GeV/u. With definition of an inelastic interaction as one in which the projectile charge is changed, 1849 inelastic interactions were found, of which 1460 were completely analyzed, including angle measurements of secondary mesons, protons, alphas, and heavier projectile fragments. Angle data, which are used to calculate the primary energy of the 1460 events, are measured to an accuracy of 0.1°. The number of charged mesons (pions plus kaons) is given by $\langle n_\pi\rangle = n_s - (Z_p - \sum Z_i)$, where $n_s$ is the number of singly charged relativistic secondaries, i.e., those particles with ionization less than 1.4 times minimum ionization in emulsion (equivalent to pion energy $>70$ MeV and proton energy $>400$ MeV); $Z_p$ is the charge of the projectile, measured to within one charge unit; and $Z_i$ represents projectile fragments with charge $\geqslant 2$. The error in $\langle n_\pi\rangle$ is 1–2 per event. We emphasize that the "along-the-track" method of scanning for interactions used means that essentially all of the inelastic interactions were found.

First we present results integrated over the two data sets. The 1275 events of the Texas data (minimum energy $E_0=1.7$ GeV/u) had $\langle n_\pi\rangle = 6.8\pm0.3$ with median energy $E_m=3.2$ GeV/u and mean energy $\bar{E}=6.2$ GeV/u, while the 571 India events ($E_0=7.5$ GeV/u) had $\langle n_\pi\rangle = 16.0\pm1.1$ with $E_m=12.2$ and $\bar{E}=20.4$ GeV/u. $\bar{E}$ and $E_m$ are calculated from the known cosmic-ray energy spectrum

$$dJ/dE = kE^{-\alpha}, \tag{1}$$

where $J$ is the intensity [flux/(unit area) · (unit time)], $k$ is a constant, and $\alpha$ is the spectral index, which is $\alpha \simeq 2.5$ for $E<20$ GeV/u and $\alpha\simeq 2.7$ for $E>20$ GeV/u.[1]

For a more detailed look at $\langle n_\pi\rangle$ versus energy, the energy of the primary nucleus is determined for those events with secondary angles measured, since these are necessary for the measurement. A correction factor was added to account for those few events without meson production which were not analyzed for angles, making the total number of events represented as a function of energy 1694.

Briefly, the energy-measurement method used here is the following.[2-4] Assuming constant transverse momentum $\langle p_t\rangle$ of secondaries, the momentum in the mesons and interacting protons (of number $N_P$) is summed using the measured angles of secondaries, and then divided by $N_P$. $N_P$ is determined by observation of patterns in the angular distributions, which are more pronounced the higher in energy that one goes. A similar method of measuring energy is used for spectator protons and alphas,[3] and then averaged with the participant energy described above. Table I shows the $\langle p_t\rangle$ values used for the initial calculation (input $\langle p_t\rangle$), which are derived from various sources.[3,5-8] [For the input $\langle p_t\rangle$ of spectator protons and alphas, the peak (most probable) $p_t$ is used instead of the mean $p_t$, as explained in Ref. 3.] Note that the accuracy of these values does not have a large effect on the results, as explained below.

In comparing to the known energy spectrum of Eq. (1), it was apparent that far too many events have measured energies below the known cutoffs. We partially correct for this by adjusting $\langle p_t\rangle$ in each of the energy measurements (meson plus interacting proton, spectator proton, alpha) so that the measured values of $(\bar{E}+E_m)/2$ were equal to the known values in the two data sets in each case. We call the resulting transverse momentum $\langle p_t\rangle_{\text{eff}}$ in Table I.

We pause in our explanation of the energy measurement to comment on the rise of $\langle p_t\rangle$ with energy in

 

TABLE I. $\langle p_t \rangle$ values used to calculate energy. Input $\langle p_t \rangle$ is obtained from various data (Refs. 3,5–8); $\langle p_t \rangle_{\rm eff}$ is determined by forcing the resulting spectrum to fit the known one.

| Secondary particle | Input $\langle p_t \rangle$ (MeV/$c$ u) Texas | India | $\langle p_t \rangle_{\rm eff}$ (MeV/$c$ u) Texas | India |
|---|---|---|---|---|
| Meson | 242 | 296 | 223 | 385 |
| Interacting proton | 575 | 575 | 529 | 748 |
| Spectator proton | 99 | 99 | 126 | 252 |
| Alpha | 48 | 50 | 71 | 164 |

Table I. The effective $\langle p_t \rangle$ required for the spectator methods in the India data set are seen to be 2 to 3 times larger than the input values, whereas the Texas values are consistent with accelerator data.[3,5–8] The participant (meson plus interacting proton) method shows a somewhat less dramatic enhancement. Although we do not fully understand the reason for this effect, we make some observations: (1) For spectators, the large tail observed in secondary-$\alpha$-particle $p_t$ distributions[3,8] seems to increase with energy, even though the peak value of the distribution does not.[3] Thus the effective $p_t$ must rise with energy. This is possibly related to ideas involving collective flow of nuclear matter.[9] (2) A sharp rise of $\langle p_t \rangle$ with energy density may be a signal of a phase transition to a quark-gluon plasma (QGP).[10] We do not think that our data demonstrate this, for two reasons: (a) Our data sample all impact parameters, whereas QGP is likely to form only in central collisions with high energy density; (b) the $\langle p_t \rangle$ enhancement is higher for spectators than participants, contrary to expectations. These ideas will be further investigated in a forthcoming paper.

Returning to the energy determination, we found that some of the events still have measured energies below the known cutoffs. We assume at this point that the events are ordered correctly in energy. Each event is then assigned a new energy strictly in accordance with the cosmic-ray energy spectrum. Since in this work we only use bins with large numbers of events, this should not cause too great an error. A simulation performed using as input the energy distribution measured in a 1.7-GeV/u $^{55}$Mn beam produced errors of $< 7\%$ in the bin median energy over 100 simulations. This method of ordering events also means that the precise values of $\langle p_t \rangle$ used are not too important.

One simple model for predicting meson multiplicity in nucleus-nucleus collisions is the multichain model (MCM).[11,12] This model is essentially a superposition of nucleon-nucleon collisions which utilizes Glauber-theory concepts. Input to the model is the inelastic proton-proton cross section[13] $\sigma_{pp}^{\rm inel}$ and the charged-particle multiplicity for $pp$ collisions $\langle n_{\rm ch} \rangle_{pp}$.[14] An even simpler Glauber-type model is the wounded-nucleon model (WNM).[15] The expression for multiplicity here is $\langle n_\pi \rangle = \frac{1}{2} \langle N_{PT} \rangle \langle n_\pi \rangle_{pp}$, where $\langle N_{PT} \rangle$ is the number of inelastically interacting (projectile plus target) nucleons and $\langle n_\pi \rangle_{pp}$ is the number of produced mesons.[16] The difference between the models is that while WNM uses a simple constant $\langle n_\pi \rangle_{pp}$ at a given energy, MCM calculates the multiplicity per chain including energy-momentum conservation and an energy-degradation distribution function as well as using a fudge factor to account for cascading.[12] Integrating the model results over the cosmic-ray energy spectrum for the India data set gives $\langle n_\pi \rangle = 15.0$ for MCM and $\langle n_\pi \rangle = 19.1$ for WNM, while the data give $\langle n_\pi \rangle = 16.0 \pm 1.1$; agreement is reasonable. No comparison is given for the Texas data since the models are not valid below 10 GeV/u.

The meson multiplicity as a function of energy is shown in Fig. 1. Each point represents some 200 events, plotted at its median bin energy $E_m$, which is close to its mean energy $\bar{E}$. The exception is the

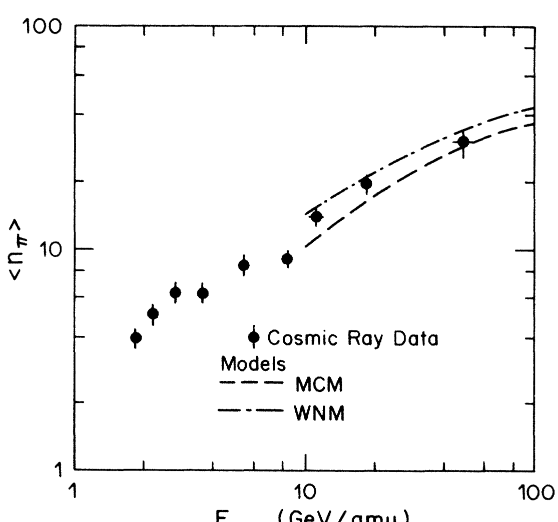


FIG. 1. Mean meson multiplicity vs energy in cosmic-ray-nucleus–emulsion-nucleus collisions. Also shown are predictions of the multichain model (MCM) (Ref. 12) and the wounded-nucleon model (WNM) (Ref. 15), valid above 10 GeV/u.

highest-energy point (65 events, $\bar{E}=78.2$, $E_m=48.2$ GeV/u). The error in $\langle n_\pi \rangle$ given is statistical only. $\langle n_\pi \rangle$ is seen to vary with energy approximately as $E^{0.7}$. The data lie between the two models considered.

To compare the present work to data with different targets and projectiles, we divide $\langle n_\pi \rangle$ by $\langle N_{PT} \rangle$, the mean number of participant nucleons in the target and projectile. In individual events $N_P$ was previously determined from the data for use in the energy measurement. However, this value exhibited an unexpected energy dependence.[4] Even though the mean value of $N_P$ over both the Texas and India data sets agreed with the model values, the value of $N_P$ near the India cutoff (7.5 GeV/u) was not consistent with the Texas value at the same energy. Moreover, the models predict a very weak dependence of $N_P$ on energy, whereas the data show a definite decrease from cutoff to higher energies in both data sets. The reason for this must be related to the rise of $\langle p_t \rangle$ discussed above: Protons at large angles are invariably identified as interacting protons (contributing to meson production), which they may not be, if, for example, they are exhibiting collective nuclear flow. Thus, in *each* data set separately, $N_P$ would be overestimated preferentially for events with relatively large secondary angles, i.e., events with low measured energies.

An attempt to use the experimental target particle multiplicity as a measure of $\langle N_T \rangle$ was also not successful. Thus we use calculated values of $\langle N_{PT} \rangle$. Glauber theory gives[15]

$$\langle N_{PT} \rangle = (A_T \sigma_{pA_P} + A_P \sigma_{pA_T})/\sigma_{A_P A_T}, \tag{2}$$

where $\sigma_{A_P A_T}$ is the total nucleus-nucleus cross section, and $\sigma_{pA}$ is the total inelastic proton-nucleus cross section. Glauber calculations, for example, in $pA$ collisions give values for $\sigma_{pA}$ about 10% different from measured cross sections.[17] We choose to use empirical formulas for $\sigma_{pA}$ [18] and $\sigma_{AA}$ [19] to achieve maximum accuracy. Specifically

$$\sigma_{pA} = 44.9 A^{0.7} \text{ mb}, \tag{3a}$$

$$\sigma_{A_P A_T} = 10\pi (1.29)^2 (A_P^{1/3} + A_T^{1/3} - b)^2 \text{ mb}, \quad b = 1.189 \exp[-0.054\,47 \min(A_P, A_T)]. \tag{3b}$$

The value of $N_{PT}$ is calculated for each energy bin, since $A_P$ varies slightly among the bins ($\langle A_T \rangle$ is assumed to be the same in all bins).

The result is shown in Fig. 2. The cosmic-ray data are compared to low-energy nucleus-nucleus data from the Bevalac[20] and the Dubna Synchrophasotron.[21] CERN intersecting-storage-ring (ISR) $\alpha$-$\alpha$ data at high energy[22] are also shown. For the ISR and Bevalac data $\langle N_{PT} \rangle$ was measured; for the Dubna data $\langle N_{PT} \rangle$ was calculated in the same manner as for the cosmic rays. Also shown in Fig. 2 is the charged-meson multiplicity

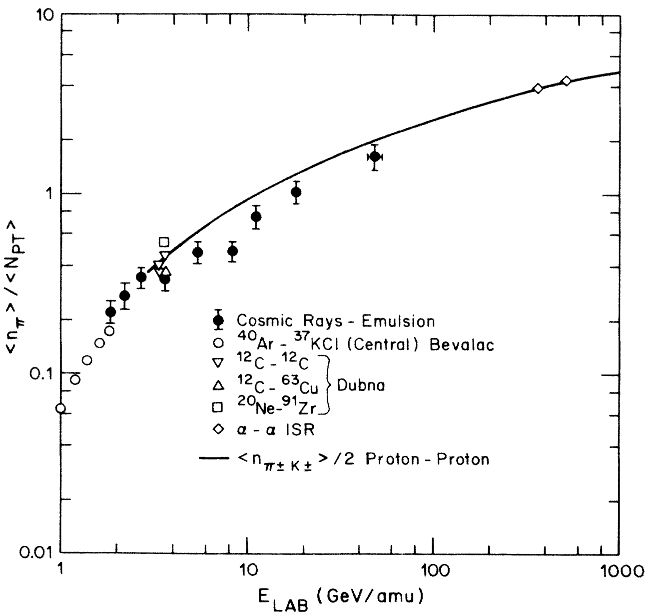


FIG. 2. Meson multiplicity per interacting projectile or target nucleon vs median bin energy. Nucleus-nucleus data: cosmic rays, this work; accelerators, Bevalac (Ref. 20), Dubna (Ref. 21), and ISR (Ref. 22). A fit to proton-proton data is also shown (Ref. 16). For explanation of how $\langle N_{PT} \rangle$ was determined in $AA$ collisions, see text.

in proton-proton collisions.[16] We account for the fact that the accelerator data measure only negative produced particles by extrapolating from measured values.[16,23] For $AA$ collisions[23] we use $\pi^\pm/\pi^- = 1.72$–$1.80$ for $E=1$–$1.8$ GeV/u and $\pi^\pm/\pi^- = 1.89$ to 1.95 for $E=3.4$–$3.6$ GeV/u. For the $\alpha\alpha$ data we use $\pi^\pm K^\pm/\pi^- K^- \simeq 2.15$ from $pp$ data.[16] The cosmic-ray data are seen to agree with the accelerator nucleus-nucleus data at $E < 4$ GeV/u.

To check consistency among the values of $\langle N_{PT} \rangle$ used, a Glauber calculation[12] was performed for the central collisions of the Ar-KCl data. The result was only 11% below the values measured by Sandoval *et al.*[20] A further justification of the calculation of $\langle N_{PT} \rangle$ used in the cosmic-ray data is the fact that the multiplicity per interacting nucleon shows no dependence on projectile charge $Z_p$; see Fig. 3. The total multiplicity per interacting nucleon over all energies is $0.56 \pm 0.07$ for low $Z_p$, $0.54 \pm 0.07$ for medium $Z_p$, and $0.55 \pm 0.07$ for high $Z_p$. This is strong support both for the idea of combining different $Z_p$ and for using this particular variable to describe the multiplicity.

To try to determine whether the difference between the cosmic-ray nucleus-nucleus data and the proton-proton data in Fig. 2 is significant, we consider a different way of assigning $\langle N_{PT} \rangle$, namely using the Glauber-theory calculations[12] to calculate the cross sections of Eq. (2) rather than using the empirical

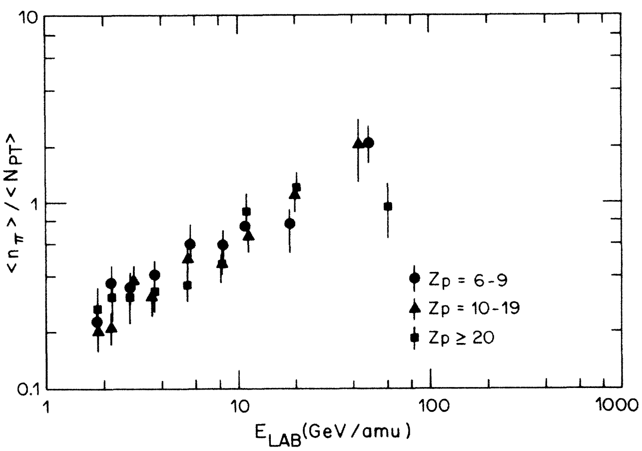


FIG. 3. Multiplicity per interacting nucleon vs energy as a function of projectile charge $Z_p$.

values of Eqs. (3). These values of $\langle N_{PT} \rangle$ are $\sim 20\%$ lower than the values obtained using the empirical expressions at the mean cosmic-ray projectile $\bar{A}_p = 28.4$. The resulting values for $\langle n_\pi \rangle / \langle N_{PT} \rangle$ agree within error with the $\langle n_\pi \rangle_{pp}/2$ in Fig. 2 for all but one bin. Thus the difference in meson multiplicity between $AA$ and $pp$ collisions may be attributed only to one's determination of $\langle N_{PT} \rangle$.

In conclusion, the first systematic study of meson multiplicity versus energy in nucleus-nucleus collisions above 4 GeV/u has been completed. The data show general agreement with the multichain model and the wounded-nucleon model, but do not distinguish between these simple nucleon-nucleon superposition models. Multiplicity per interacting nucleon in the cosmic rays is in accord with previous nucleus-nucleus accelerator results at $E < 4$ GeV/u. No dependence on projectile charge is seen in this variable. When account is taken of the ambiguity in assigning values to the number of interacting nucleons, differences between the meson multiplicity measured in cosmic-ray nucleus-nucleus interactions and accelerator $pp$ data seem to be insignificant. The overall conclusion is that meson production in nucleus-nucleus collisions on the average is not inconsistent with a superposition of nucleon-nucleon collisions in this energy range.

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