Session B11: Nuclear Effects in High Energy Collisions and Related Topics

Chairman: G. A. EKSPONG
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1. Multibaryon Interactions at Relativistic Energies
   A. M. BALDIN
2. Comments
   E. SKRYPCZAK
3. Experiments on High Energy Nuclear Collisions
   T. FERBEL
4. Total Cross Sections on Nuclei and K_s^0 Regeneration on Nuclei
   B. WINSTEIN
5. Big Hadron Model—A Unified Description of Multiple Production off Hadrons and Nuclei—
   F. TAKAGI
6. Comments on Collective Tube Model
   A. WROBLEWSKI
7. "Fluctons" and High Momentum Transfer in Nuclear Processes
   D. I. BLOKHINTSEV

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B 11 Multibaryon Interactions at Relativistic Energies

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Great success of the quark models in describing both the static properties of hadrons and the reactions involving them makes it possible to apply to the study of more complicated and perhaps more critical phenomena for the test of the theory. In this connection, the study of the reactions involving multibaryon configurations have recently become still more popular in high energy physics. At the XVIII International Conference on High Energy Physics in Tbilisi several talks[1-5] were devoted to effects for which small internucleon spacings in the interaction of high energy particles with nuclei are essential. It is obvious that if these spacings are of the order of the confinement radius or less then the quark degrees of freedom must play a definite role. There exist estimates of the order of magnitude of the density of nuclear matter at which it transforms to a state of "quark plasma" and even possibly to a crystalline state.

The collisions of high energy particles and relativistic nuclei with nuclei are presently interpreted on the basis of the idea of asymptotic freedom and quark-parton models. The problem of confinement and quark interaction at large distances is also of great importance for their interpretation. Information on multibaryon resonances appears, in turn, to contribute greatly to clarifying the problem of confinement. The (ΛP) and possibly $(\Lambda\Lambda)$ and $(\Lambda\Lambda P)$ resonances discovered by Shakhbasian[7] have recently been interpreted[8,9] as multi-quark formations in a single "bag." The confirmation of the existence[*1] of such large "quark plasmons" would be very important, in particular, it would mean that we have already discovered a metastable state of superdense nuclear matter, *i. e.*, multibaryon states possessing elementary particle density.

Among a very large number of papers on interactions of high energy particles with nuclei and on the physics of relativistic nuclei submitted to the present Conference we have chosen only the results which deal in some way or other with the problems mentioned above and which are most adequate to the programme of the present Conference. Our attention is focussed on the one-particle distributions of particles produced in particle–nucleus and nucleus–nucleus collisions. Of most interest in the particle production is the region of limiting fragmentation of nuclei which is kinematically forbidden for one-nucleon collisions.

The particle production in this region is given the name of cumulative effect and the first data on cumulative production of mesons by relativistic deuterons on nuclei was reported as early as in 1972 at the XVI International Conference on High Energy Physics in Batavia.[10] Since that time a great deal of information on this effect relative to the class of hard collisions was accumulated. The kinematic limits are defined by the cumulative number N, that is by the effective number of the nucleons of a fragmenting nucleus involved in the reaction. For one-particle distributions the minimal value of N is determined by the kinematic limits imposed on the mass of the object taking part in the collision

$$\mathrm{I}+\mathrm{II}\to 1+\cdots \tag{1}$$

When $\exp|y_{\mathrm{I}}-y_{\mathrm{II}}|\gg 1$ in the region of the limiting fragmentation of nucleus I the relativistically invariant quantity $N^{\min}$ assumes the following values

$$N^{\min}=\begin{cases}\dfrac{E_1-P_{1\mathrm{L}}}{m_{\mathrm{p}}} & \text{in the rest system of nucleus I}\\[2ex] \dfrac{P_{1\mathrm{L}}}{P_{\mathrm{I}}^{0}} & \text{in the rest system of a particle or nucleus II}\end{cases} \tag{2}$$

where P_{I}^{0} is the momentum per nucleon, m_{p} the proton mass, $y_{\mathrm{I,II}}$ the rapidities, $P_{1\mathrm{L}}$ the longitudinal momentum. The cumulative effect corresponds to the region defined as $N^{\min}>1$. The scaling with the variable $N^{\min}$ is valid much better than with x_{F}.

The cumulative effect was predicted[12] on the

[*1] See also H. Ikeda *et al.* contribution No. 625, session A5 of this Conference.

basis of the following assumptions. In the spirit of the parton models the one-particle distribution $\rho_{\mathrm{I}}^{\mathrm{II}}=(1/\sigma_{\mathrm{in}})E_1(d\sigma/d\boldsymbol{p}_1)$ in the region of the limiting fragmentation of nucleus I is taken in the form of a superposition of the one-particle distributions which are due to the limiting fragmentation of the objects of mass Nm_{p} inside nucleus I

$$\rho_{\mathrm{I}}^{\mathrm{II}}=\sum_N P_N \rho_N^{\mathrm{II}} \tag{3}$$

Without further assumptions on the probability P_N for finding a constituent with mass Nm_{p} inside the nucleus and on an explicit form of ρ_N the following properties of the cumulative effect can be indicated:

1. The dependence of ρ on the properties of the target (particle II) must practically be absent due to limiting fragmentation. Thus, it is clear that to study the spectra of secondary particle beams which are due to the collisions of relativistic heavy ions the latter need not be accelerated. It is enough to study particle production on these nuclei at angles close to 180° under the action of e. g. protons. It was just in such experiments that the basic data on the cumulative effect had been obtained.[11]

2. The most important characteristic of the cumulative effect is the dependence of $\rho_{\mathrm{I}}^{\mathrm{II}}$ on the atomic weight of the fragmenting nucleus A_{I} since it enables us to make definite conclusions on P_N. The ρ_N values are expected to be identical for various nuclei.

3. The kinematic boundary enters ρ_N and defines in eq. (3) the lower limit of summation or integration over N if it is supposed in the spirit of parton models that N assumes continuous values. This means that the A_{I} dependence of ρ must be variable with changing kinematic boundary. The selection of the events containing cumulative particles (or group of particles) is the selection of the configurations in the wave function of a nucleus which contains N nucleons at so small distances at which their parton quark constituents are collectivized. The quark collectivization must strongly be affected by the increase of the quark interaction potential providing quark confinement. The order of magnitude of the cross section of the cumulative effect and the A_{I} dependence of ρ were predicted on the basis of the following assumptions:

a) The constituents move in the nucleus in an uncorrelated manner, that is, P_N is described by a binomial distribution

$$\frac{A!}{N!(A-N)!}\,q^N(1-q)^{A-N} \tag{4}$$

where q is the probability for a constituent to fall into the region occupied by a multinucleon cluster. The distance at which the nucleons lose their individuality was assumed to be $r\sim 0.6-0.7$ fm. This estimate is well confirmed by experiment.

b) The multinucleon cluster, or the large parton, possesses the properties of a usual hadron and to get estimates ρ can be taken from the data on particle production in p–p collisions.

The above assumptions enabled us to predict the following properties of the cumulative effect: If we insert in (4) $q=(\tau/\tau_0A^{1/3})^2\sim 1/A^{2/3}$ then a fast increase of the A dependence with increasing cumulative number is obtained (approximately an additional factor $A^{1/3}$ with increasing N by unity). The P_N probability must decrease rapidly with increasing N independently of our specific assumptions. Therefore it is natural to consider only the first term in (3), coresponding to $N=N^{\min}$. It follows from this consideration that in the region of cumulative particle production by relativistic nuclei $\sigma_{\mathrm{in}}\rho$ must depend on the atomic weight in an exponential manner A^m, where m increases monotonously with secondary particle momentum $m\simeq(2/3)+(1/3)(P_1/P_{\mathrm{I}}^0)$. At $P_1>P_{\mathrm{I}}^0$ the power exponent must exceed unity. The dependence of the cross sections on the atomic weight of target-nucleus II in the fragmentation region of nucleus I must vanish due to the property 1. As a result, the dependence of the cross section on the atomic weight A_{I} with changing y_1 from the values near y_{I} to the values in the vicinity of y_{II} changes very strongly: the exponent m changes by more than a factor of 10!.

The predicted properties of the cumulative effect have well been confirmed experimentally. The discovered dependences on the cumulative particle energy are described by simple exponentials. It is interesting to note that the simplest dependence

$$\sigma_{\mathrm{in}}\rho=\mathrm{const}\cdot A_{\mathrm{II}}^{n}A_{\mathrm{I}}^{m}\exp\left[-aN^{\min}\right] \tag{5}$$

where a is constant and $n\approx 1/3$, describes satisfactorily all the main regularities of the cumu-

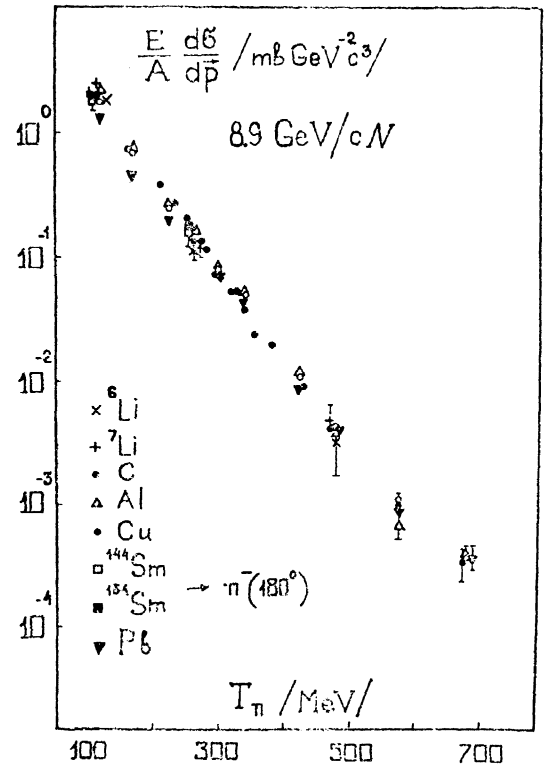

Fig. 1.

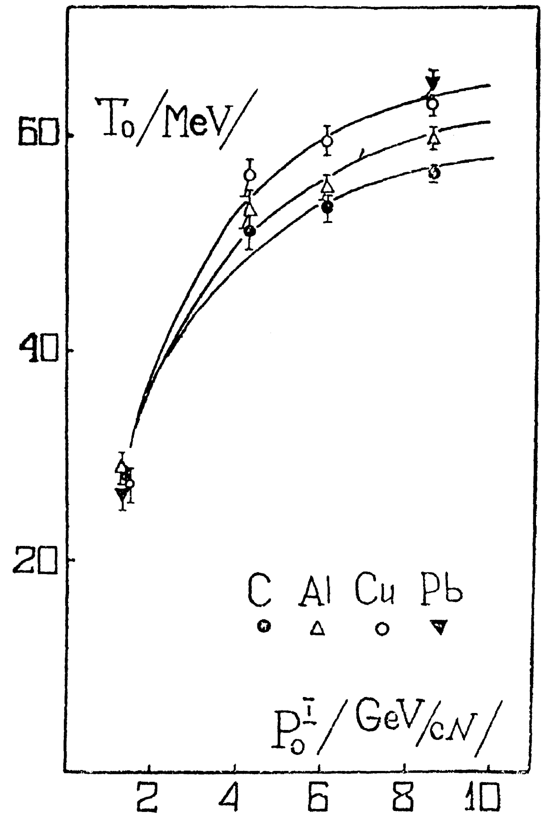

Fig. 2.

lative particle production including the angular distributions.

The main properties of the cumulative meson production were discovered in 1971 and studied by Stavinsky and his co-workers at Dubna.[1,10] The limiting fragmentation of nuclei from deuterium to uranium in the range of the cumulative numbers up to 4 had been investigated by this team. Pions, protons and nuclear fragments played the role of the cumulative particles.

Figure 1 shows[13] new data on the one-particle distributions in the reaction $P+A\rightarrow \pi(180^\circ)$ in the region of fragmentation of nuclei at a proton momentum 8.9 GeV/c. The cumulative number $N^{\min}=1$ corresponds to $T_\pi=$ 270 MeV and $N^{\min}=2$ to $T_\pi=629$ MeV. The cross sections are normalized to the atomic weight. Similar data are obtained for other proton energies. A large amount of experimental data for the cumulative numbers from 1 to 2 is described by the simple formula

$$E_\pi \frac{d\sigma}{dp_\pi} = C\cdot A\cdot \exp\left[-\frac{T_\pi}{T_0}\right] \qquad (6)$$

where T_π is the pion kinetic energy, C and T_0 are constants. Figure 2 gives the dependence of T_0 on the momentum per nucleon P_I^0 of the nucleus in the anti-lab. system for different nuclei. As is seen from the figure, T_0 weakly increases with A, the limiting fragmentation of nuclei into pions (independence of the cross section of P_I^0) begins in the region $P_\mathrm{I}^0\approx 4$ GeV/c which is in accordance with the condition $|y_\mathrm{I}-y_\mathrm{II}|>L$, where $L\approx 2$ is the correlation length in the rapidity space.*[2] Figure 3 presents the data on fragmentation of nuclei into deuterons in the reaction $pA\rightarrow d(180^\circ)$. The cross sections are in this case normalized to $A^{5/3}$ which shows the existence of A^m dependences with m larger than unity. Figure 4 gives new data on the limiting fragmentation of the lightest nuclei. The extreme points correspond to an almost absolute kinematic limit. Figure 5 shows the dependence of the inclusive meson production cross sections for different nuclei (H, D, He, Pb) on the emission angle for fixed meson momenta.

Protons and pions emitted in the backward direction in high energy hadron-nucleus interactions are studied by Fujioka *et al.*[14] The energy range is measured to be for protons and pions from ~80 to 300 MeV, the energy

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*[2] It follows from this consideration that for the case when particle II is a pion, gamma quantum or a neutrino the limiting fragmentation of nuclei must begin at an energy lower than 1 GeV.

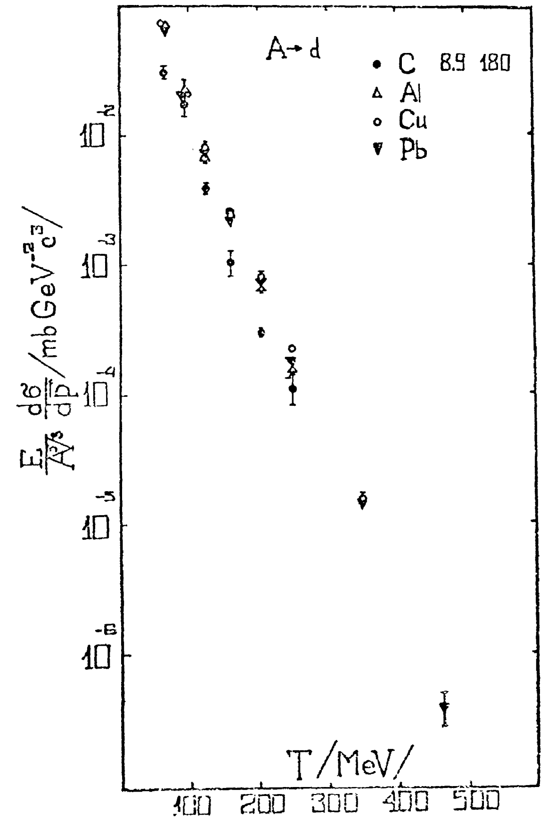

Fig. 3.

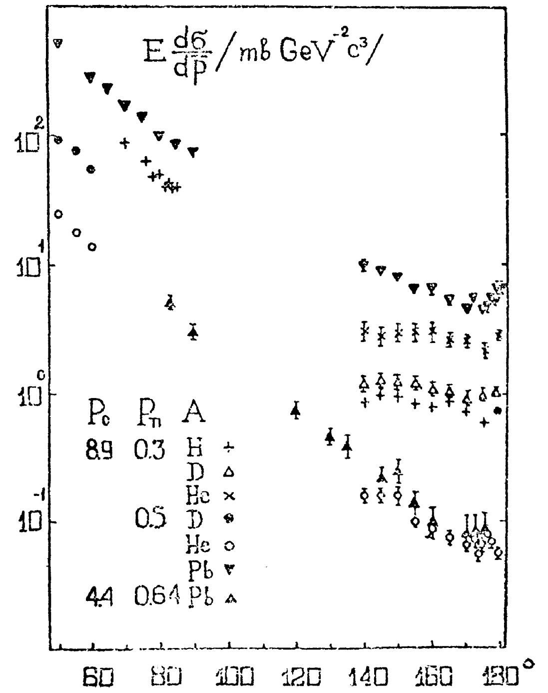

Fig. 5.

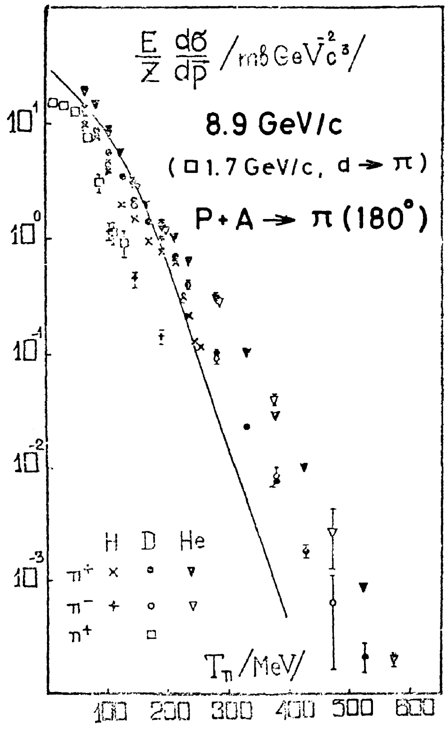

Fig. 4.

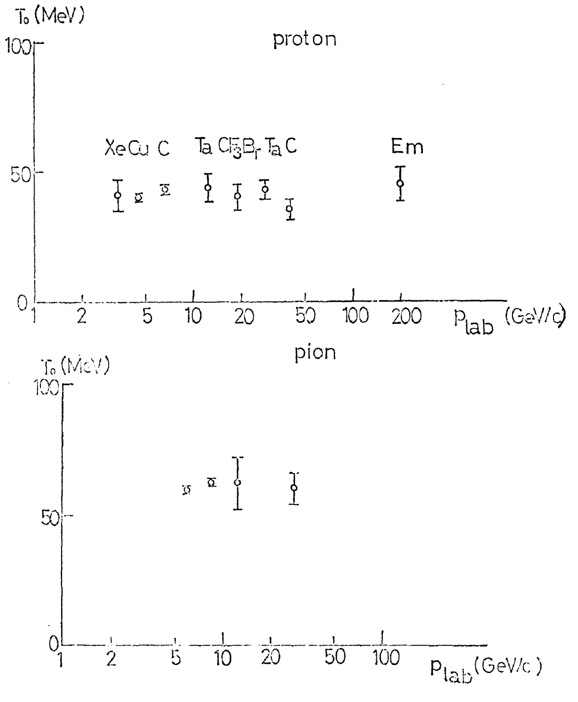

Fig. 6.

spectra are expressed by exp $[-T/T_0]$. T_0 for protons is 40–45 MeV within the range of primary momenta from 4 to 205 GeV/c. T_0 for pions is 60–65 MeV within the range of primary momenta from 12.6 to 28.5 GeV/c (see Fig. 6). The data obtained in such a wide energy range well supplement the data for low energies and demonstrate that the limiting fragmentation of nuclei begins at rather low energies (cf. Figs. 2, 8 and 6). A good illustration of this assertion is Fig. 7 from ref. 15 which shows the distributions of mainly pions in the (πA) and (pA) reactions up to an energy of 400 GeV over the pseudo-rapidities of secondary particles. The region of limiting fragmentation corresponds to $-2<\eta<1$.

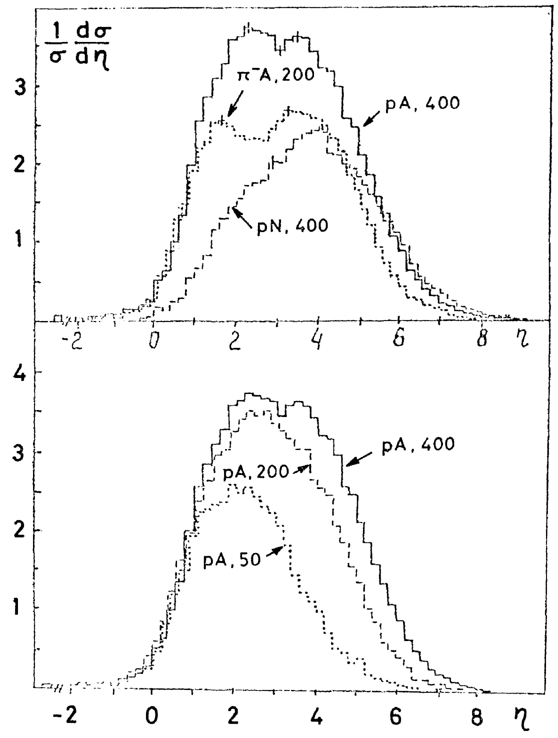

Fig. 7.

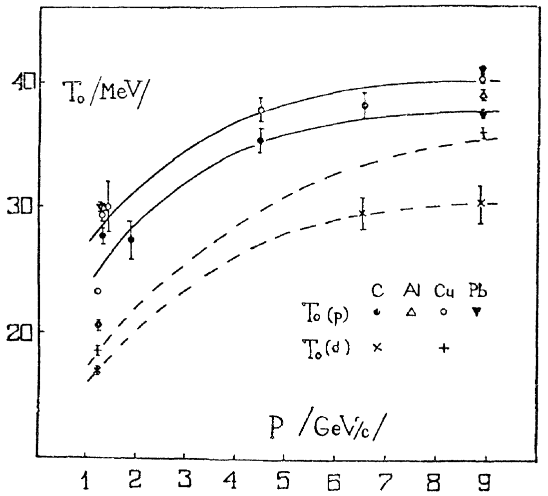

Fig. 8.

The yield of cumulative protons exceeds by about two orders of magnitude that of cumulative pions and the study of the cumulative protons had begun long before the notions of scale invariance and limiting fragmentation of nuclei became of current use. Figure 8 shows the T_0 values for different fragmenting nuclei as functions of the momentum of primaly protons: 1.22 GeV/*c* (180°); 1.28 GeV/*c* (140°)[17]; 1.39 GeV/*c* (150°)[18]; 1.86; 4.50; 6.57 GeV/*c* (137°)[19]; 8.9 GeV/*c* (180°)[20]. The dependences are seen to be regular and the agreement with the data of Fig. 6 gives evidence for the validity of limiting fragmentation. A special emphasis should be placed on the investigations on proton production from nuclei at large angles performed by Leksin and his co-workers[19] and discussed in Tbilisi.[2]

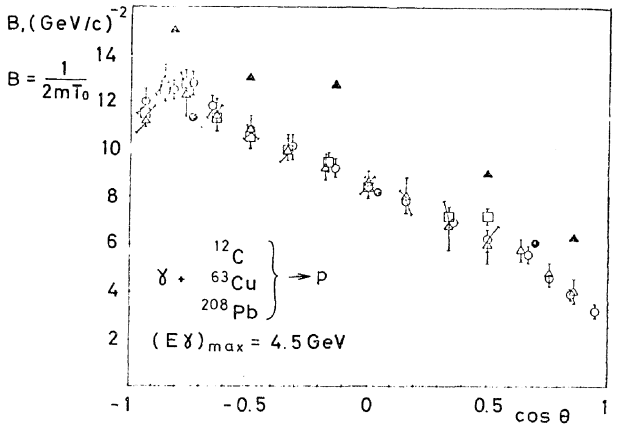

Fig. 9.

A very interesting confirmation of the universal dependences such as exp $[-T/T_0]$ was obtained in Batavia where the cross section for proton production in the backward hemisphere in the antineutrino-neon interactions was studied (see the review by Nezrick[21]) and on the Erevan accelerator[22] where gamma quanta were used as particles II. Figure 9 gives the angular dependence of the parameter $B=1/2\, m_p T_0$, where m_p is the proton mass obtained in reactions of limiting fragmentation of nuclei C^{12} (ϕ), Cu^{63} ( ) and Pb^{208} (▯) induced by gamma quanta with an energy $(E_\gamma)_{\max}=4.5$ GeV from ref. 22. The data marked by (▲) are taken from ref. 23 and are relative to an energy $(E_\gamma)_{\max}=1.2$ GeV. It is worth noting that the T_0 value obtained in this case for angles close to 180° is in satisfactory agreement with the discussed above ($T_0 \sim 40-50$ MeV). New data on cumulative production of protons and Λ hyperons in the fragmentation of ^{12}C nuclei are reported in ref. 24. Pions with a 4 GeV/*c* momentum and neutrons with an average momentum $\langle P_n \rangle = 7$ GeV/*c* were used as particle II. A large statistics enables us to see deviations from the simple exponential of the type exp $[-T/T_0]$. In Fig. 10, where the kinetic energy distribution of protons is given, attention is drawn to an irregularity in the region of $T\sim 60$ MeV which is similar to that observed in the reaction $d+p\rightarrow p(pn)$. For the latter reaction the nature of this irregularity is quite clear: it is due to the interaction of

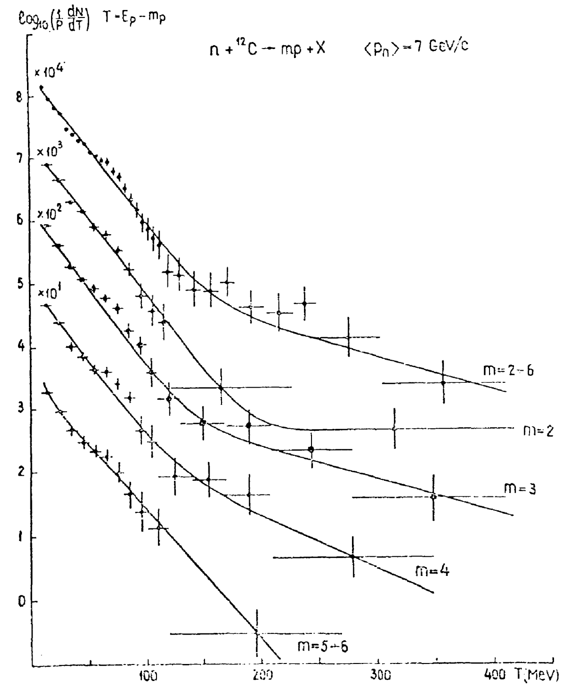

Fig. 10.

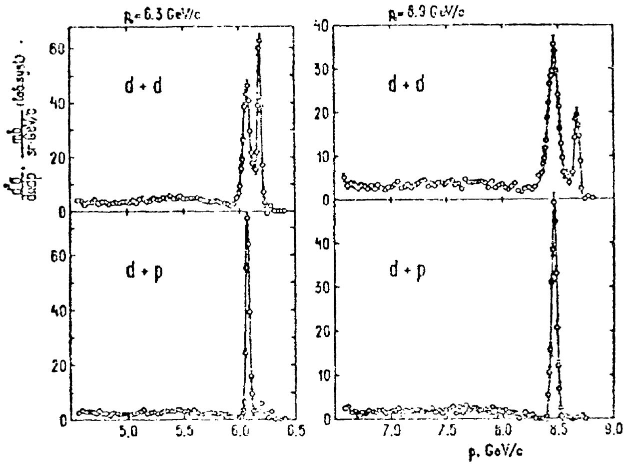

Fig. 11.

the two remaining nucleons in the final state.[20] This fact may indicate that a considerable fraction of the cumulative effect for baryon systems is due to the interaction in the final state which is disregarded in the theories based on the idea about hard scattering processes.

The importance of the effects of multiple interaction of nucleons in the relativistic collision of nuclei with relatively large momentum transfers is shown in ref. 26, where the interactions of 6.3 and 8.9 GeV/c deuterons with protons and deuterons for four-momenta transfers $|t|=0.41$ and 0.80 (GeV/c)^2 resp. were studied (see Fig. 11).

Of a particular interest for the theory is the cumulative Λ particle polarization measured in ref.24. In accordance with an earlier paper,[27] where the cumulative Λ particle polarization was also measured, it reaches its maximum possible value for an angle $\theta=90°$ and is independent according to limiting fragmentation of the nature of a bombarding particle. In the paper[24] there is a confirmation of the important fact established in the work of the Institute of Theoretical and Experimental Physics[28] that the parameter T_0 is independent of the multiplicity of the protons produced.

The studies of particle production on nuclei with high $P_\perp$ bear a direct relation to the limiting fragmentation problems. In experiments of the Cronin team[29] the same strong A dependences[59] as those found in the cumulative effect studies were discovered. Recently a similar A dependence was detected[30] in the hadron jet production in π^- and p beams on nuclei at high energies. If it is parameterized as A^m then m (π^- incident)$\simeq 1.3$ and m (p incident)$\simeq 1.45$ and roughtly constant with $P_\perp$(3—6 GeV/c). The large values of such exponents are a strong evidence for new dynamics.

A development of the cumulative effect model (eq. (3)) on the basis of the quark-parton approach has been made by Efremov.[3] The model links the cross sections for particle production on nuclei with large $P_\perp$ with the cross sections for cumulative particle production and explains qualitatively the hadron polarization in these processes. The calculations[31] based on the assumption that the cumulative process is defined by the hard binary collision of a "fluctuons" 's parton with the parton of an incident particle give

$$d\sigma \approx \sum_{q}^{A} P_q^A d\sigma_N\left(x_2, \frac{x_1}{q}\right)\left(1-\frac{x_1}{q}\right)^{a(q-1)} \tag{7}$$

The "fluctuons" are multibaryon configurations of mass $N^{\min} m$ at small relative distances, P_q^A is the same as P_N in eq. (3)

$$x_1 = -\frac{u}{s} \approx N^{\min}, \quad x_2 = -\frac{t}{s} = \frac{E_1}{E_{11}}$$

The hypothesis about nuclear density fluctuations was suggested by Blokhintsev[32] for expalining the knocking out of light nuclei by protons[33] from heavier nuclei when the momentum transferred to a light nucleus is much larger than the binding energy of this nucleus. As the estimates based on the quark bag model show,[31,34] the probabilities for the existence of multiquark fluctuons in nuclei are enough to account for the order of magnitude of P_N. A parton recombination model of cumulative hadron production which is similar to the one of ref. 31 was developed by Takagi.[35]

A very interesting rough version of the model specified by eq. (3) was proposed in ref. 36. The simplification of eq. (3) consists in the following (let particle II be a proton)

$$\rho_{\mathrm{p}}^{\mathrm{I}}(s, y, p_\perp) \approx \rho_{\mathrm{p}}^{\mathrm{p}}(\langle N_{\mathrm{I}}\rangle s, y+\log \langle N_{\mathrm{I}}\rangle, p_\perp) \quad (8)$$

where $\langle N_{\mathrm{I}}\rangle \simeq A_{\mathrm{I}}^{1/3}$ is the effective number of the nucleons involved in the collision. Dar and some other authors showed that eq. (8) is a very ecomonic way for describing a large amount of experimental material. In ref. 15 it is indicated that this version encounters some difficulties which seem to some of its authors[37] to be only a restriction on the range of applicability. There is also a certain development of the Strikman and Frankfurt suggestion[4] about the predominance of the pairing correlations in the wave function of nuclei for explaining the cumulative particle production.[38] In ref. 39 it is pointed to the importance of experimental study of the vector meson cumulative production and to a possibility of observing in these processes manifestation of the dynamic properties of the conserved quantum numbers (isospin, hypercharge and baryon number) suggested by the Yang–Mills theory.

In refs. 40, 41 the cumulative effect regularities are accounted for on the basis of the cluster model. In the rest system of the nucleus the pion decay spectrum of a moving cluster has, contrary to eq. (6), the form

$$f = \mathrm{const} \cdot \exp\left[-\frac{P_\mu u^\mu}{T_0}\right]$$

where u^μ is the four-velocity of the cluster and P_μ the four-momentum of the detected pion. The pion production outside the kinematic limits for nucleon-nucleon collision is in this model due to the large mass of a cluster produced in the process of successive collisions.

At the Tbilisi Conference much attention was also paid to the opposite (with respect to the cumulative) part of single-particle spectra in the longitudinal rapidity space, that is, the region of fast particles produced on nuclei, and especially, to the problem of attenuation of fast particles with increasing atomic number. The papers[15,42,45–49,61] submitted to the persent Conference are just devoted to this problem. The importance of the study of hadron–nucleus collisions in this region is due to the unique possibility of obtaining information about the space–time evolution of the collision process and the interaction of pre-hadronic matter.

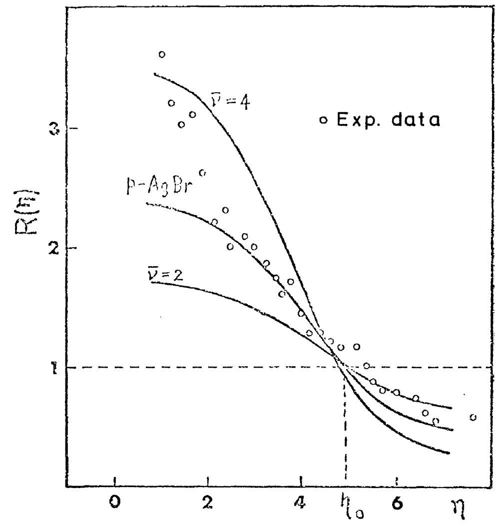

Fig. 12.

Figure 12 from the paper by Suzuki[42] presents the comparison of the theoretical calculations by the fireball cascade model with the experimental data[15] for the ratio

$$R(\eta) = \frac{1}{\sigma_{\mathrm{pA}}} \cdot \frac{\mathrm{d}\sigma_{\mathrm{pA}}}{\mathrm{d}\eta} \Big/ \frac{1}{\sigma_{\mathrm{pN}}} \frac{\mathrm{d}\sigma_{\mathrm{pN}}}{\mathrm{d}\eta}$$

where $\eta = -\ln tg\, \theta/2$ is the pseudorapidity. In the range $\eta > 5$ R becomes smaller than unity and strongly decreases with increasing A. This manifestation of the many-nucleon effects has for the past two years been an object of many theoretical investigations including those on the basis of quark–parton models. In ref. 15 attention is paid to the position of the point η_0 where $R(\eta_0) = 1$ as a function of energy which is especially important in connection with the new data on $R(\eta)$ at an energy 400 GeV.[15] The available experimental data indicate that $Y_{\max} - \eta_0 \approx \mathrm{const}$. Figure 13 gives the comparison of the dependence $(Y_{\max} - \eta)$ as a function of energy with the existing theories. The curves 1 and 2 are the results of calculations by the parton–cascade model.[43] Alternatively in the eikonal type models[44] this quantity should be constant and equal to ≈ 2.6 (the dotted line) which is in excellent agreement with experiment.

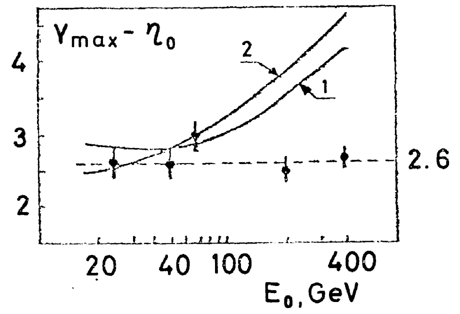

Fig. 13.

Experiments suggest that the interaction of newly produced systems with nucleons inside the nucleus is suppressed to a large extent. In order to understand these effects there have been various attempts to incorporate the space–time evolution in the model of multiple production on nuclei. However, up to the present we have at our disposal no theory of a sufficiently predictive power, the available theories can mainly give a partial explanation of the existing experimental data.

The radio of the multiplicities $R_c = \langle n \rangle_A / \langle n \rangle_p$ for pion production on nuclei and protons in the central region ($1.10 \leq \eta \leq 3.34$) was measured by Bellini *et al.*[50] The experimental data can be approximated by the power function A^α with $\alpha = 0.011 \pm 0.02$ which is in agreement with the predictions of the coherent tube model and the quark model in the impulse approximation[51] and is in disagreement with the version of the parton model developed in ref. 52.

The above considerations show that in the study of the processes of interaction of high energy particles with nuclei it is of particular interest to single out multiple production events which involve a few nucleons of the nucleus (multinucleon interactions). There are the following methods of such an extraction:

1. Extraction of cumulative particles in the region of limiting fragmentation (see above),

2. Extraction by the charge (hypercharge) of produced particles. In the papers submitted to the present Conference the multinucleon interactions are singled out on the basis of the followint criteria:

a) the charge $Q = n_+ - n_-$, where n_+ is the number of π^+ mesons and fast protons, and n^- is the number of negative particles. For the reactions $\pi^- + {}^{12}C$ the events with $Q > 0$ are attributed to the interactions with several (ν) protons ($\nu \geq Q+1$). The data on $\pi^-(\nu p)$ interactions[53] are compared with those on ($\pi^- p$) at the same energy (40 GeV). The quantity

$$R = \frac{1}{\sigma_{in}} \frac{d\sigma_{\pi(\nu p)}}{dP_L} \Bigg/ \frac{1}{\sigma_{in}} \cdot \frac{d\sigma_{\pi p}}{dP_L}$$

as a function of the longitudinal momentum P_L in the lab. frame passes unity for $P_L = 5-7$ GeV/c and $R < 1$ for large P_L in agreement with the data discussed above.[15] A detailed comparison of the data[53] on inclusive reaction $\pi^- + C^{12} \to \pi^+(\pi^-)$ with the presently available theories of multiparticle production on nuclei is given in ref. 54.

b) double charge exchange $\pi^- + A \to \pi^+$. As the study[55] of this reaction shows at an incident momentum 4.7 GeV/c the main part of the cross section is described by a two-step mechanism using the well-known data on πN interaction. In the high energy tail of the positive particle spectrum we should apparently take into account the few-nucleon mechanism.

3. Large possibilities of extracting multinucleon interactions come from the investigations with relativistic nuclei.[11] In addition to the cumulative effect studies with relativistic nuclei started as early as in 1971,[10] the determination of ν by the number of the proton spectators Z_s: $\langle \nu \rangle = 2(Z - \langle Z_s \rangle)$ (Z is the incident nucleus charge, $\langle Z_s \rangle$ the average charge of stripped particles) was also found to be a good method.[58] The latter was used to establish[56] that the π^- meson and fast proton multiplicities increase in proportion to $\langle \nu \rangle$ while the change in the g-particle multiplicity is slower with increasing $\langle \nu \rangle$.

In earliest discussions of perspectives of the relativistic nuclear physics sceptics asserted that the nucleus–nucleus collisions would be very complicated and would give little information. The invalidity of this scepticism is shown in Fig. 14 which gives a photograph obtained from the Dubna propane bubble chamber.[56] The event is a peripheral interaction of a relativistic carbon nucleus of an energy of 50 GeV with a carbon nucleus of propane with a subsequent central interaction of the nucleus fragment with the carbon nucleus. The multiparticle production of this type is found to be simpler from the topological viewpoint than those in p–p collisions at an energy of hundreds of GeV. The experimental data show that

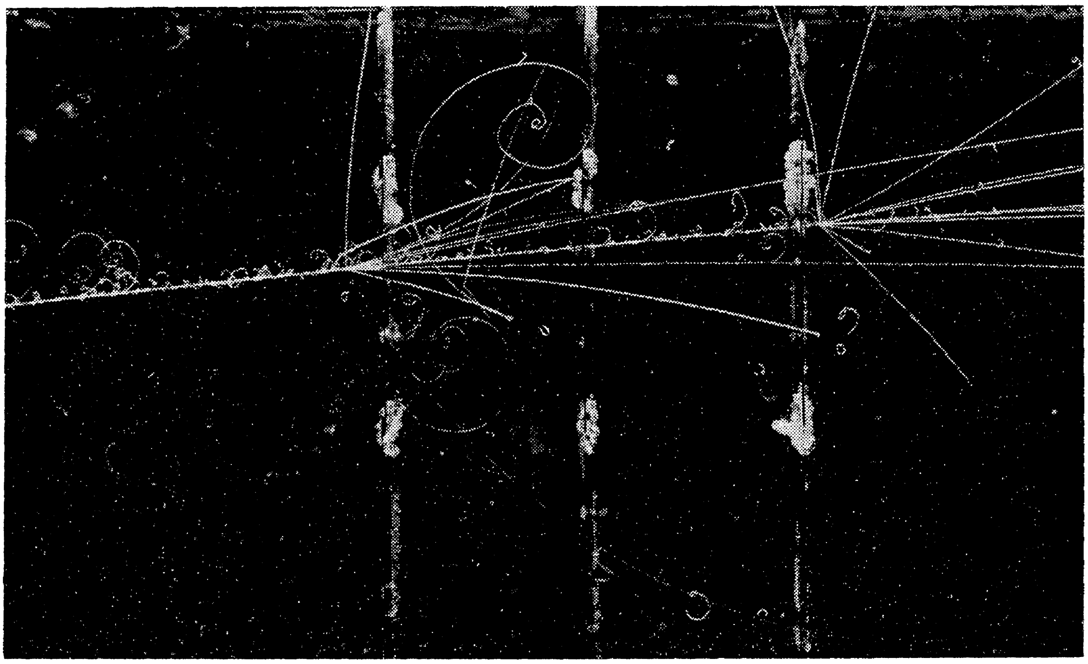

Fig. 14.

the average number of the nucleons of the bombarding nucleus interacting with a target-nucleus $\langle\nu\rangle$ is rather large. For example, it reaches $\langle\nu\rangle=6.00\pm0.60$ for the collision of the carbon nucleus with the tantalum nucleus. The tantalum plates were placed inside the working volume of the propane chamber.

The similarity of multiparticle processes occuring in nucleus–nucleus and p–p collisions has clearly been proved on a streamer chamber.[57,25] The inelastic nucleus-nucleus cross sections are large and agree well with a simple geometric picture.[56–58,60]

Conclusions

1. Since the XVIII International Conference in Tbilisi a large amount of experimental information on multinucleon interactions has been obtained.

(a) The range of an approximate validity of the limiting fragmentation of nuclei has been clarified.

(b) The universal energy dependences of the cross sections in the cumulative region have been clarified and improved.

(c) Data on the angular distributions and polarization of the cumulative particles have been obtained.

(d) Strong A dependences have been observed not only in the cumulative effect and production of particle with large $P_\perp$, but also in the production on nuclei of hadron jets.

(e) Some dependences of the cumulative particles on the quantum numbers have been established.

2. The study of different manifestations of quark plasmons (fluctuons) in nuclei and multibaryon resonances predicted by quark models is an important and extensively developed trend of the high energy physics.

3. The attempts to construct a theory of phenomena related to large momentum transfers to multinucleon systems must cover all the balk of experimental data from (a) to (e). The most promising candidate for such a theory—the quark–parton theory of hard collisions—needs further development.

4. The possibility of studying the space–time picture of development of the strong interaction process by means of hadron–nucleus interaction and the particle formation length concept need further theoretical and experimental grounds.

References

1. V. S. Stavinsky: *Proc. XVIII Int. Conf. High Energy Physics*, Tbilisi (1976) A6–1.
2. G. A. Leksin: *ibid.*, A6–3.
3. A. V. Efremov: *ibid.*, A6–12.
4. L. L. Frankfurt and M. I. Strikman: *ibid.*, A6–16.
5. B. T. Chertok: *ibid.*, A7–1.
6. V. I. Zakharov: *ibid.*, B–69.
7. B. A. Shakhbazian, *et al.*: in *Proc. XVIII Int. Conf. High Energy Physics*, Tbilisi (1976) C–35, and contribution No. 143 Sect. A5.
8. R. L. Jaffe: Phys. Rev. Letters **38** (1977) 195.

9. A. Th. M. Aerts, P. J. G. Mulders and J. J. de Swart: Phys. Rev. **D17** (1978) 260.
10. A. M. Baldin: *Proc. XVI Int. Conf. High Energy Physics*, v. I (1972) p. 277, FNAL
11. A. M. Baldin: *Particles and Nuclei* **8**, (1977) p. 429, see also 1, 2.
12. A. M. Baldin: Preprint JINR P7–5808 (1971). The talk submitted to the IV Int. Conf. Elementary Particles and Nuclear Phys. Dubna (1971).
13. A. M. Baldin, *et al.*: contribution No. 151, section B11 of the present Conference.
14. G. Fujioka, *et al.*: contribution No. 522, section B11 of the present Conference.
15. Alma-Ata–Gatchina–Moscow–Tashkent Collaboration: contribution No. 307, section B1 of the present Conference.
16. S. Frankel, *et al.*, Phys. Rev. Letters **36**, (1976) 642.
17. V. I. Komarov, *et al.*: Dubna Preprint E–10573 (1977).
18. D. R. F. Cochran, *et al.*: Phys. Rev., **D6** (1972) 3085.
19. Yu. D. Bajukov, *et al.*: Izv. Akad. Nauk, ser. fiz. XXX (1966) 521.
20. A. M. Baldin, *et al.*: Communications of JINR, PI–11302 (1978).
21. F. A. Nezrick.: Preprint Fermilab Conf. 77/112 Exp (1977).
22. K. V. Alanakyan, *et al.*: Yad. Fiz, **25** (1977) 545 and Preprint Yerevan Phys. Inst. 221 (13)–77.
23. V. S. Kuzmenko, *et al.*: Pis'ma Zhurn. Exp. Theor. Fiz, **23** (1978) 174.
24. B. A. Shakhbazian, P. P. Temnikov and A. A. Timonina, Contribution No. 171, Section B11 of the present Conference.
25. A. M. Baldin: JINR communications EI–11368 (1978).
26. L. S. Azhgirey, *et al.*, contribution No. 170, section B11 of the present Conference.
27. I. I. Vorobiew, *et al.*: Pis'ms to JETP **22** (1975) 390.
28. A. V. Arefiev, *et al.*: Yad. Fiz. **27** (1978) 16.
29. J. W. Cronin, *et al.*: Phys. Rev. **B11** (1975) 3105.
30. C. Bromberg, *et al.*: Preprint Fermilab-Conf. 77/62 Exp (1977).
31. D. I. Blokhintsev, *et al.*: contribution No. 178, section B11 of the present Conference.
32. D. I. Blokhintsev: JETP **33** (1957) 1295.
33. L. S. Azhgirey, *et al.*: JETP **33** (1957) 1185.
34. V. A. Matveev and P. Sorba: Fermilab-Publ. 77/36 Thy (1977).
35. F. Takagi: contribution No. 84, section B11 of the present Conference.
36. Y. Afek, *et al.*: *Proc Topical Meeting Multiparticle Production from Nuclei at Very High Energies*, Trieste, June 1976; Meng-Ta-Chung: *ibid.*, p. 435 and Phys. Rev. **D15** (1977) 197; F. Tagaki: Lett. Nuovo Cimento **14** (1975) 559 and contribution No. 86 Section B11 of the present Conference; A. Z. Patashinskii: JETP Letters **19** (1974) 338.
37. L. Bergström and S. Fredriksson: CERN Preprint TH 2505 (1978).
38. L. L. Frankfurt and M. I. Strikman: Preprint 415 LINP (1978).
39. A. M. Baldin and S. B. Gerasimov: JINR Communication E2–11804 (1978) and contribution No. 146, section B11 of the present Conference.
40. M. I. Gorenstein and G. M. Zinoviev: contribution No. 978, Section B11 of the present Conference.
41. I. G. Bogatskaja, M. I. Gorenstein and G. M. Zinoview: contribution No. 927, Section. BII of the present Conference.
42. S. Suzuki: contribution No. 362, Section B11 of the present Conference.
43. N. N. Nikolaev and A. V. Ostapchuk: Nucl. Phys., **B134** (1978) 729.
44. A. Capella and A. Kaidalov: Nucl. Phys. **B111** (1976) 477.
45. V. G. Ableev, *et al.*: contribution No. 155, Section BII of the present Conference.
46. A. Minaka and H. Sumiyoshi: contribution No. 532, Section B11 of the present Conference.
47. S. Date, *et al.*: contribution No. 360, Section B11 of the present Conference.
48. K. Kinoshita, A. Minaka and H. Sumiyoshi: contribution No. 533 of the present Conference.
49. S. Hirabayashi, K. Kobayakawa and T. Morii, contribution No. 294, Section B11 of the present Conference.
50. G. Bellini, *et al.*: contribution No. 129, Section B11 of the present Conference.
51. V. V. Anisovich, *et al.*: Preprint LNPL–352 (1977).
52. S. J. Brodsky, *et al.*: Phys. Rev. Letters **39** (1977) 1120.
53. Buchurest–Dubna–Sofia–Tashkent Collaboration: contribution No. 207, Section B11 of the present Conference.
54. F. K. Aliev, *et al.*: CERN Preprint TH 2511 (1978), contribution No. 1090, Section B11 of the present conference .
55. O. B. Abdinov, *et al.*: contribution No. 942 and N152 Section B11 of the present Conference.
56. Alma-Ata–Budapest, Crakow–Dubna–Moscow–Prague–Sofia–Tashkent–Tbilisi–Ulan–Batior–Varna–Warsaw–Yerevan Collaboration: contribution No. 145, Section B11 of the present Conference.
57. A. Abdurakhmanov, *et al.*: contribution No. 156, Section B11 of the present Conference.
58. Buchurest–Dubna–Koshice–Leningrad–Moscow–Tashkent–Warsaw Collaboration: contribution No. 996, Section B11 of the present Conference.
59. In the paper by J. Kishiro, *et al.* (contribution No. 409, Section B11 of the present Conference) similar strong A dependences have been observed for inclusive π^+ production for $0.3 \leq P_\perp \leq 1.0$GeV/$c$ in p nucleus and π^+ nucleus collisions at $P_{\mathrm{Lab.}} =$ 4.3 GeV/c, that is in the region of relatively low energies.
60. J. Dias de Deus and P. Kroll: contribution No. 300, Section B11 of the present Conference.
61. N. Masuda: contribution No. 277, Section B11 of the present Conference.

PROC. 19th INT. CONF. HIGH ENERGY PHYSICS
TOKYO, 1978

B 11

A Comment to Prof. A. M. Baldin's Talk

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I have a comment, concerning one of the problems, covered by Professor Baldin's talk, namely the statement, that the multiplicity of secondaries, emitted from the nucleus–nucleus collisions is proportional to the number of nucleons which have interacted with the target nucleus. In our experiment (paper 996, contributed to this Conference), performed by use of a rather old-fashioned nuclear emulsion techniques, we studied inelastic interactions of ^{12}C nuclei (50 GeV/*c*) with emulsion nuclei. The emulsion techniques with all its well known drawbacks is, however, a useful tool for exclusive analysis of individual events. For each event the total charge of projectile fragments could be reliably determined, thus yielding a reasonable estimate of the number of incident nucleons, which have interacted with the target nucleus, N_{int}. The multiplicities of secondaries (shower and heavily ionizing particles, -s, g and 6 tracks-, separately) and their emission angles were also determined for each event. The results (Figs. 3 and 4 of the paper) are not consistent with the hypothesis of a) proportionality of secondary multiplicities to N_{int}, and b) identicity of angular distributions of shower particles (mainly pions) for various values of N_{int}.

These results seem to indicate that considering a nucleus–nucleus interaction as a simple superposition of collisions between incident nucleons and the target nucleus would be an oversimplification of the mechanisms involved in nucleus–nucleus collisions.

PROC. 19th INT. CONF. HIGH ENERGY PHYSICS
TOKYO, 1978

B 11

Hadron–Nucleus Inclusive Data from Fermilab

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We summarize the results from papers submitted to this Conference pertaining to the inclusive production of particles in hadron–nucleus collisions as studied at Fermilab.

There were many interesting papers submitted to this session. Luckily for me Professor Baldin has taken upon himself the task of reporting on the majority of these papers and has left me only with the review of the experiments performed at Fermilab.

The specific manuscripts I have considered are the following:

1) Paper No. 8 by Y. K. Lim (Singapore) and J. E. Laby (Melbourne) on the interactions of 400 GeV protons in emulsion.

2) Paper No. 630 by D. Chaney *et al.* (Rochester–Northwestern–Fermilab Collaboration) on hadron production in neutron–nucleus collisions at ~300 GeV.

3) Paper No. 676 by D. Burke *et al.* (Michigan) on hadron production in neutron–nucleus collisions at ~200 GeV.

4) Paper No. 673 by M. R. Whalley *et al.* (Michigan) on production of neutrons in

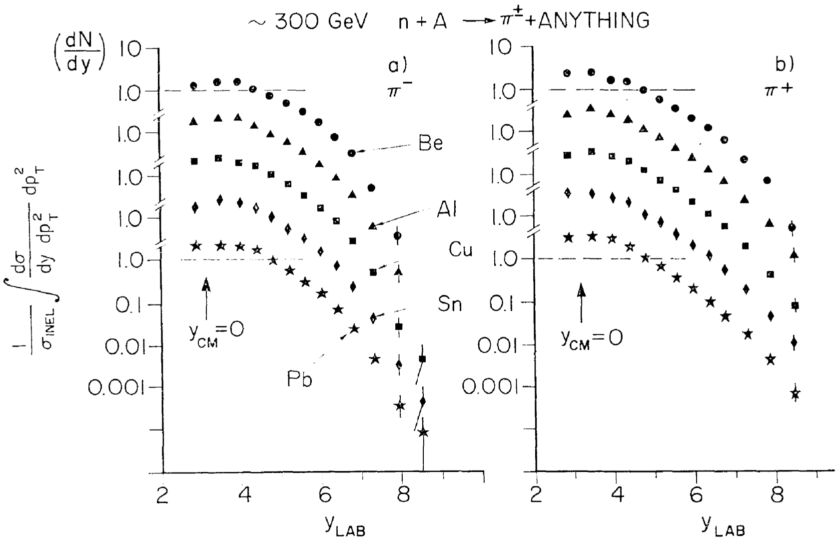

Fig. 1.

proton–nucleus collisions at 400 GeV.

5) Paper No. 652 by H. Band *et al.* (Duke–SUNY, Albany Collaboration) on π–Ne interactions at 10.5 and 200 GeV.

6) Paper No. 669 by C. O. Kim *et al.* (Korea–Paris–Ottawa–Lyons–Lund–Belgrade–Stantander Collaboration) on proton interactions in emulsion between 30 and 400 GeV.

7) Papers No. 328 and No. 329 by J. Gaidos *et al.* (Purdue–Fermilab Collaboration) on the production of nuclear fragments in collisions of protons with nuclei of noble gases.

Lim and Laby present evidence for a lack of energy dependence in the target fragmentation regime for the production of minimum-ionizing (shower) as well as more heavily ionizing (gray and dark) particles. Their data (possibly because of relatively poor statistics) do not display the small scaling violations which have been noted by H. Band *et al.* The authors also report evidence for KNO scaling in the production of shower particles.

Chaney *et al.* have measured inclusive particle production using specially designed spark chambers in a magnet spectrometer; Burke *et al.* have made their measurements, without the benefit of a magnet, using wide gap optical chambers; it is comforting, therefore, that in regions of overlap the two experiments using disparate techniques agree very nicely on the A-dependence of particle production. These experiments also agree with the recently reported measurements from the Fermilab–MIT group (again, using a totally different experimental technique).[1] The essential features of the data on neutron–nucleus collisions gleened from these new results will be detailed below.

Just as was the case for older measurements on the interactions of cosmic-rays, the newest experiments display a rather weak dependence of the produced-particle multiplicity on atomic number A. Figure 1 displays the data of Chaney *et al.* for differential multiplicity (integrated over p_T) as a function of laboratory rapidity for production off Be, Al, Cu, Sn, Pb nuclei (top to bottom); for the sake of clarity results for successive nuclei have been translated by a decade in multiplicity. Data for the production of negative particles is given in (a) and positive particles in (b). (The experiment does not have mass identification and consequently all produced particles have been interpreted as pions. The neutron beam is a broad-band beam with a mean value of momentum of about 300 GeV/c; thus a pion at rest in the center of mass has a typical rapidity of 3.2.) The fact that the multiplicity is only weakly dependent on A indicates that there is very little classical cascading within nuclear matter. That is, the time scale for the completion of a hadronic reaction is such that the individual particles produced in the initial collision do not develop into their asymptotic states rapidly enough to allow them to behave as independent objects that can interact multiply within the struck nucleus.

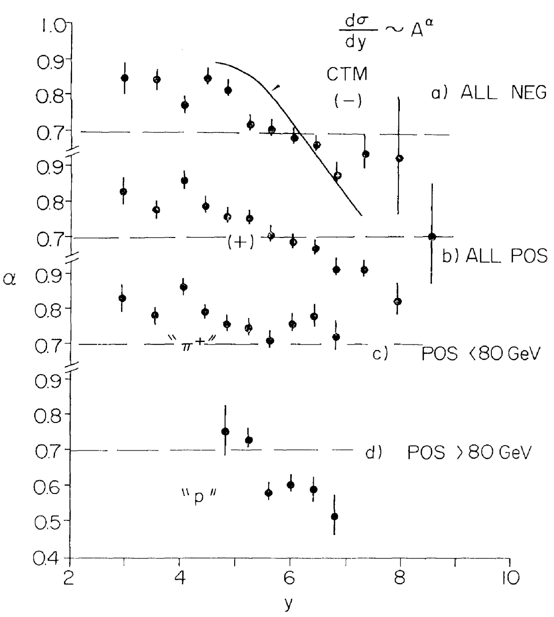

Fig. 2.

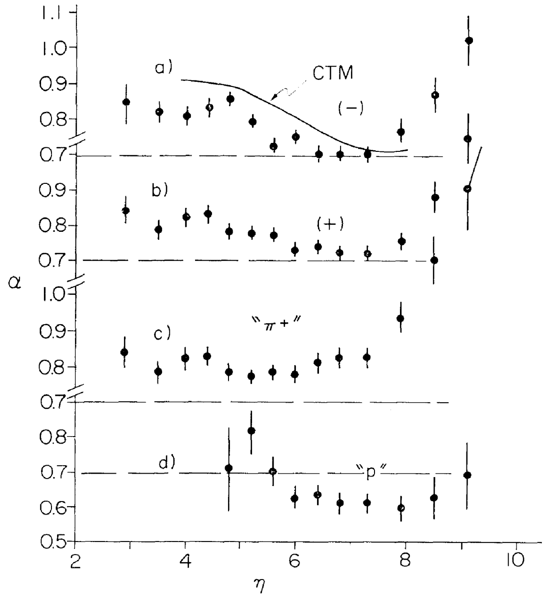

Fig. 3.

To establish the A-dependence of inclusive production, data of the kind displayed in Fig. 1 have been fitted to the simple form

$$\frac{d\sigma}{dy} \sim A^{\alpha}.$$

The results of such fits by Chaney *et al.* are shown in Fig. 2. The parameter α is displayed as a functon of rapidity for all negative particles (a), all positive particles (b), (c) positive particles with laboratory momenta below 80 GeV/c (mainly π^+), and (d) positive particles with momenta in excess of 80 GeV/c (mainly protons). The value of α for both positive and for negative particles appears to fall monotonically from $\alpha \sim 0.85$ at $y_{\rm cm} \simeq 0$ to $\alpha \sim 0.55$ at largest y. The fact that the multiplicity decreases with increasing A for $y \gtrsim 6$ speaks for multi-Regge pole or cut contributions to inclusive production on nuclei.

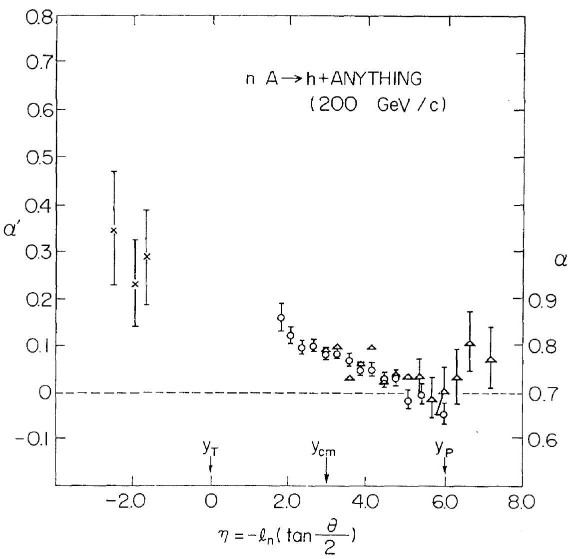

Fig. 4.

If instead of y, Chaney *et al.* parameterize their data in terms of pseudo-rapidity ($\eta = -\ln \tan \theta/2$), they reach a somewhat different conclusion regarding the behavior of α at large η. These results are given in Fig. 3 for the same categories of events as described in Fig. 2. The value of α at small pseudo-rapidities is still ~ 0.85, but at larger η the value of α does not appear to fall below 0.7 (except for the "proton" data). In fact, for $\eta \gtrsim 7$ the value of α rises beyond $\alpha = 1$. Figure 4 displays similar data of Burke *et al.* obtained for neutrons of ~ 200 GeV/c incident momentum. Consequently, it appears that the previously reported[2] lack of dependence of multiplicity on A at large η (*i.e.*, a constant value of $\alpha \simeq 0.7$) is consistent with the observations of Chaney *et al.* when the momentum information available in this experiment is ignored. (The Fermilab–MIT group did not have reliable measurements in the largest-η region where $\alpha \gtrsim 1$.) The dramatic increase observed in α at large values of η may originate, at least, partially from electromagnetic contributions to pion production (these go as $\sim A^2$). The cross section for the Coulomb dissociation of neutrons is substantial at high energies[3] and it is reasonable to expect largest effects from such sources at small production angles or large η. However, the fact that

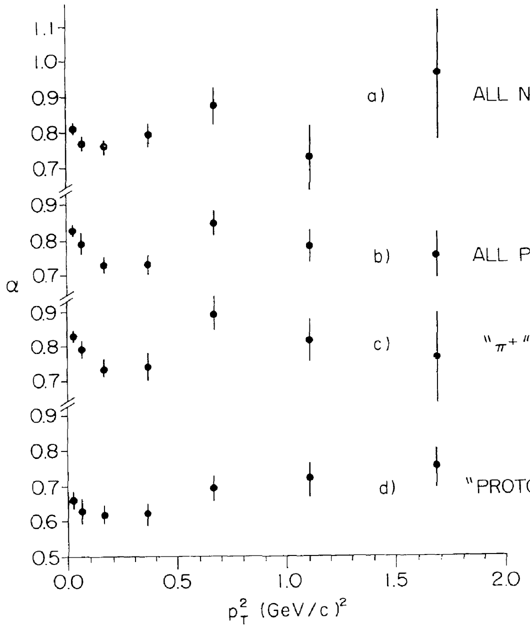

Fig. 5.

positive as well as negative particles display similar increases in α, leads me to suspect that the observation may not be entirely due to electromagnetic production but that it may rather indicate the presence of some new (and hopefully interesting) cumulative effect in the data.

An apparently general feature of inclusive production from nuclear targets, observed previously by Cronin *et al.*[4] and by Garbutt *et al.*,[5] is the increase of α with increasing p_T. This effect has been attributed to hard parton scattering contributions in inclusive particle production.[6] Figure 5 displays the presence of this feature in the data of Chaney *et al.* Multihadron production, as measured in the CIT, FNAL, Chicago Circle, Indiana and UCLA "Jet" Experiment 260,[7] also indicates an increase in α at arge p_T. These results are shown in Fig. 6. The values of α are smaller for π–A than for p–A data, again consistent with observations on single-particle production (see later).

The data of Chaney *et al.* also appear to show an increase of α at smallest p_T, reminiscent of the results presented previously by Garbutt *et al.*

It has been found at Fermilab that minority particles display essentially the same features as the majority particles, with the exception that the values of α tend to be smaller for objects produced with small cross sections.[8]

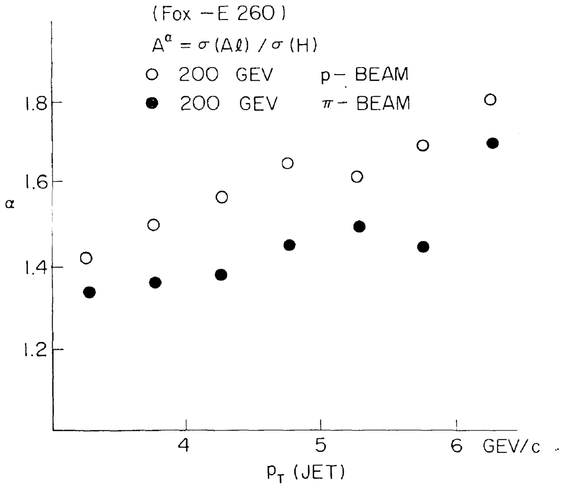

Fig. 6.

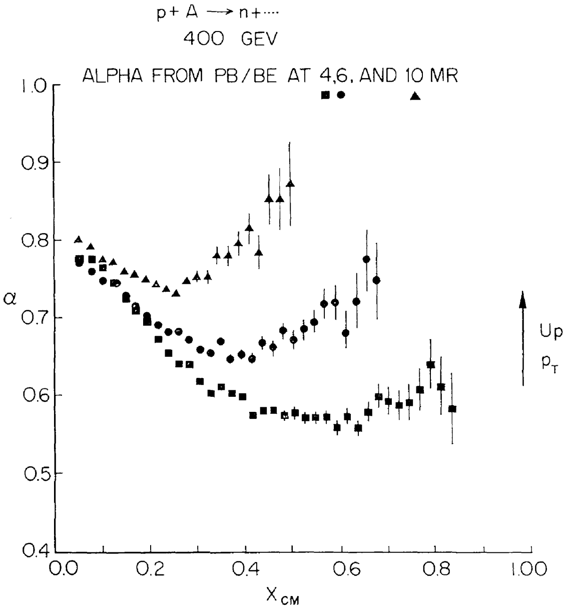

Fig. 7.

Figure 7 displays data of Whalley *et al.* on neutron production at moderately large angles (4,5 and 10 mrad) as a function of Feynman X. The values of α, from a comparison of lead and beryllium data, show the increase with p_T observed for majority particles (at $X_{CM} \simeq 0.4$, for example, α increases from 0.6 at $p_T \simeq 0.65$ GeV/c to $\alpha \simeq 0.8$ at $p_T \simeq 1.6$ GeV/c). Figure 8, again, from Whalley *et al.*, shows that at 0° α rises dramatically for $X_{CM} > 0.6$. The latter result is similar to the increase in α observed by Chaney *et al.* for large η. This effect in the data of Whalley *et al.* has been attributed entirely to contributions from electromagnetic production.[9]

Figure 9 displays results of Band *et al.* pertaining to a small violation of the Hypothesis of Limiting Fragmentation (HLF) in

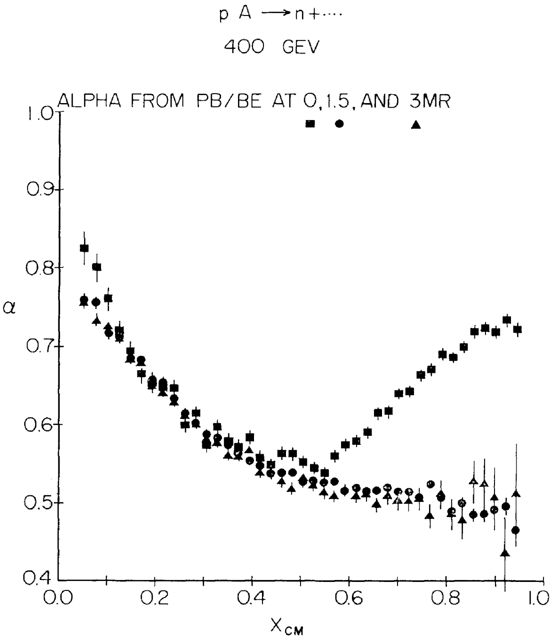

Fig. 8.

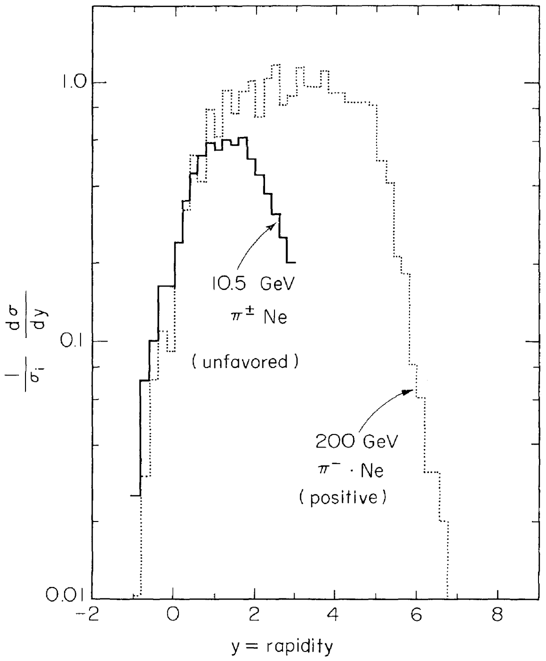

Fig. 9.

the regime of target break-up for π–Ne collisions. The comparison of produced-particle multiplicity between 200 GeV π^-–Ne data and 10.5 GeV π^+–Ne data (for "unfavored" particles) exhibits the kind of scaling violations noted in pp data for $y_{LAB} \lesssim 0$.[10] KNO scaling of the integrated multiplicity in π–Ne collisions (and comparison to πp data) is displayed in Fig. 10 for data of Band *et al.* From these results it would appear that hadron-nucleus collisions display most of the characteristics observed in hadron–hadron collisions.

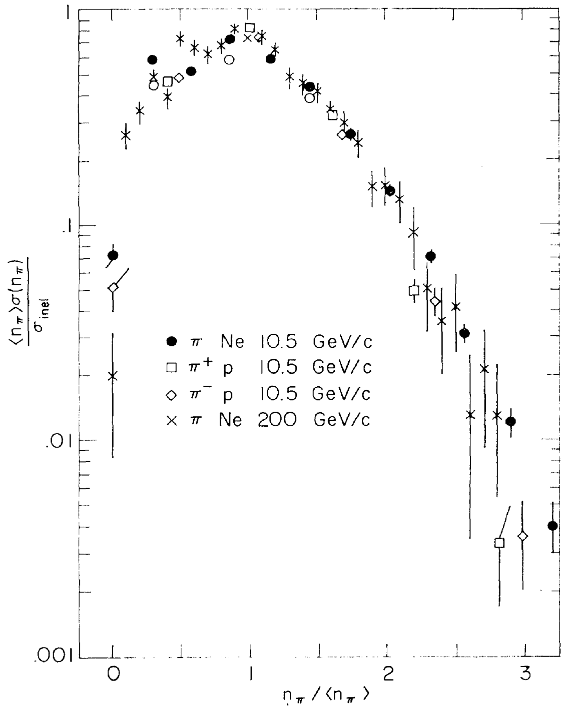

Fig. 10.

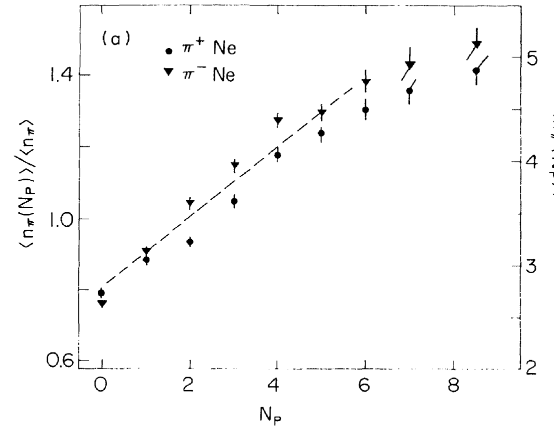

Fig. 11.

Band *et al.* have reported a large excess of fast protons observed in π–Ne collisions. Such an excess can be attributed to rescattering effects within the nucleus. (A similar result has been reported for ν–Ne reactions.[11]) Protons produced with momenta $\lesssim 1$ GeV/c have also been studied. Figure 11 shows a plot of the average number of produced pions as a function of number of detected protons, N_p (normalized by the average number of produced pions, integrated over N_p) for the $\pi^{\pm}$ Ne data of Band *et al.* at 10.5 GeV. The pion multiplicity is essentially proportional to N_p. Yuldashev *et al.*[12] (Fig. 12) have compared similar π–Ne data to the coherent tube model[13] (CTM) to extract an effective target mass

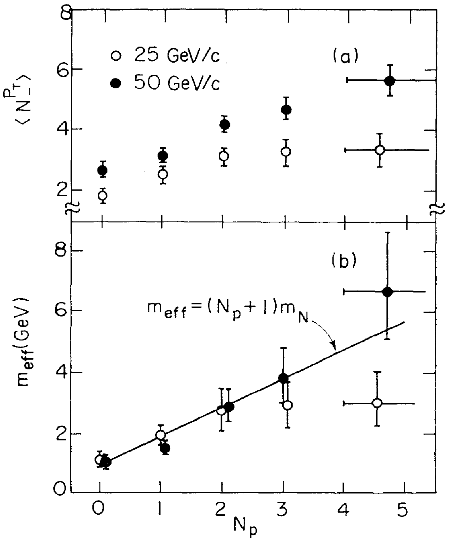

Fig. 12.

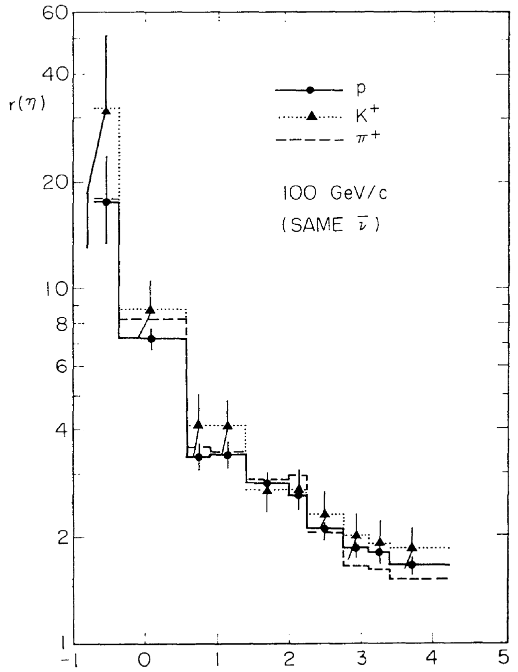

Fig. 13.

(or, equivalently, an effective value of energy in the center of mass, E_{CM}) for the collision as a function of N_p. They have found that the effective target mass for the multiplicity as a function of N_p is essentially $(N_p+1)m_p$ (as predicted by CTM) where m_p is the mass of the proton. Thus when $N_p=0$ the collision is hydrogen-like and for $N_p \neq 0$ the multiplicity behaves as if there were several (N_p+1) nucleons participating in the initial collision. Thus when $N_p \neq 0$ the multiplicity increases approximately by $\ln(N_p+1)$, reflecting the value of the effective C.M. energy $E_{CM} \sim \sqrt{2(N_p+1)m_p E}$ (E is the incident momentum in the laboratory).

C. K. Kim *et al.* have reported on a high statistics study of emulsion data. They classify their events into the number of heavily ionizing tracks N_h (essentially N_p), and into shower-type of particles n_s (having $\beta > 0.7$). They confirm previous findings that on an event-by-event basis the average value of CM rapidity $\langle y_{CM} \rangle$ is essentially only a function of N_h. They also find that for fixed N_h and n_s, averaging over all events, $\langle\langle y_{CM} \rangle\rangle$ is a function of N_h and of the KNO variable $n_s/\langle n_s \rangle$. The specific functional form given is $\langle\langle y_{CM} \rangle\rangle = A' + B'\langle n_s \rangle / n_s$, where A' has essentially all the N_h dependence, and B' is very weakly dependent on N_h. Because the distribution in N_h is known to essentially scale with energy,[12] hence the only dependence on incident energy appears in the second term in $\langle n_s \rangle$.

The final histogram for the inclusive data in this summary is given in Fig. 13. The graph is from the recent publication by the Fermilab-MIT group of Elias *et al.*[14] and shows the dependence of the differential multiplicity on the nature of the projectile particle. The data are displayed in terms of the multiplicity normalized by that on hydrogen, as a function of η, at 100 GeV/c. The multiplicity for all projectiles is found to be independent of target thickness when the latter is expressed in terms of the parameter $\bar{\nu} = A\sigma_{hp}/\sigma_{hA}$, where σ_{hp} and σ_{hA} are respectively the inelastic hadron–proton and hadron-nucleus total cross section. (The parameter $\bar{\nu}$ represents the average number of inelastic collisions a specific projectile h would undergo in traversing a given nucleus of atomic number A.) This is a remarkable result, suggesting that subsequent to the initial collision in a nucleus, produced particles behave as if they were identical in character to the incident projectiles. Thus, for a nucleus of fixed A, the growth of multiplicity in nuclear matter is weaker for incident pions than for protons (this is similar to the results found for jet production in Fig. 6).

The kind of picture for hadron–nucleus collisions that emerges from the above data is as follows: The incident particle emits a leading parton core and secondary parton chains (from the leading core), which "touch" (*i.e.*, interact with) several nucleons in the nucleus. Multiplication can occur only in regions of small rapidity, where rescattering of wee

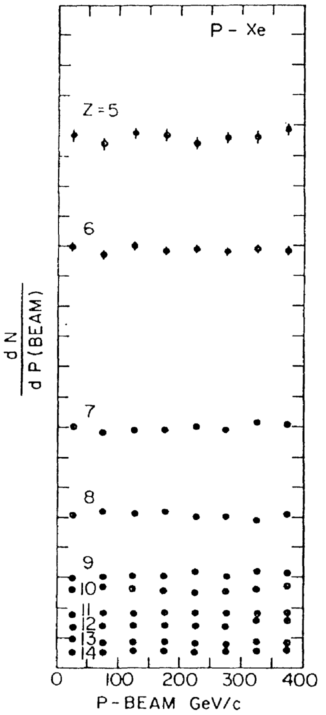

Fig. 14.

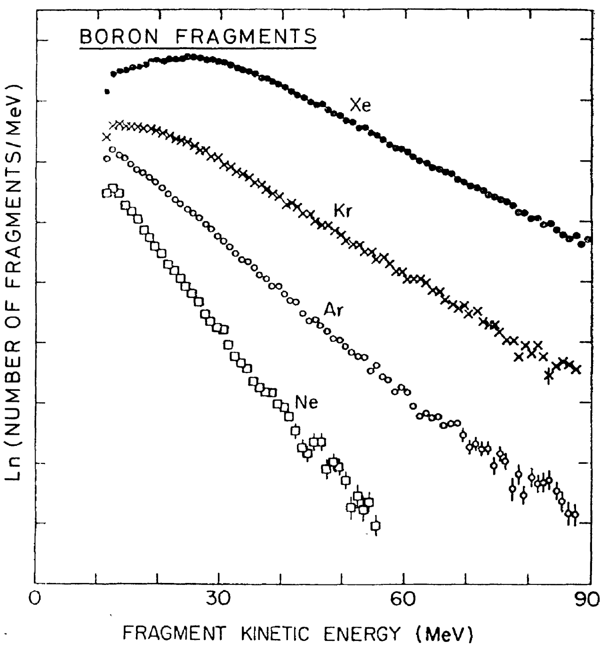

Fig. 15.

partons can contribute. There is very little multiplication at large rapidities (in fact, some attenuation is possible) because the leading fast partons are generally well downstream of the nucleus by the time the interaction (touching of the individual nucleons) is completed. (A graphic image of the interaction might be that of a christmas tree-like hadron, with the branches representing extended parton chains from the main trunk (the leading core). Multiplication occurs near the ends of the branches—where they touch the ornament-like nucleons.)

I now wish to turn to a series of experiments dealing with the production of nuclear fragment in p–Ne, p–Ar, p–Kr and p–Xe collisions. The work of Gaidos *et al.*, has been made possible by the advent of the warm gas-jet facility at the internal target laboratory of Fermilab. The experimenters study the production of nuclear fragments in the angular interval $33^\circ < \theta < 76^\circ$ (in the laboratory), for incident protons of 20–400 GeV/c momentum. The detector consists of several Si-detector telescopes set for specific ranges of fragment energies.

Gaidos *et al.* report evidence for the following sequence of events in nuclear de-excitation: The initial step involves an essentially simultaneous emission of about 20 nucleons, some of which coalesce into light fragments. The remaining nuclear remnant then breaks up, in a quasi-two-body mode, into two nuclear fragments.

Figure 14 displays the lack of energy dependence in the fragment-production process. The data for fragments of different Z are for p–Xe collisions. (The authors also state that there is very little dependence of the cross section on angle.) Figure 15 displays energy spectra for the production of Boron fragments off different nuclear targets. The fall off of the distributions, at least for Ar, Kr and Xe is quite similar, suggesting the presence of a common mechanism for the production of these fragments. The authors have assumed a simple model for the isotropic break up of the remnant into two fragments. In this model the kinetic energies of the fragments are specified by a Maxwell–Boltzmann distribution, with the energy variable being given by the energy of the fragment in the rest frame of the remnant. Folding in the kinematics of the two-body decay of the remnant, the authors extract a consistent set of parameters for their model, obtaining an effective temperature of $\sim$15 MeV for the break up of Kr and Xe into remnants heavier than nitrogen. For lighter fragments (below N) the picture is somewhat more complicated because of additional contributions from the coalescence of the initial $\sim$20 nucleons. The authors' interpretation of their data has certain fascinating implications: The initial simultaneous emission of ~ 20 nucleons, for example, can lead to a compression of the remaining nuclear matter, which has fundamental bearing on problems pertaining to nuclear fusion as well as on questions related to exotic and dense states of nuclear matter.[15]

I wish to thank Professor A. M. Baldin for inviting me to be a mini-rapporteur at his session.

References

1. I thank W. Busza and C. Halliwell for sending me the most recent analysis of their data prior to publication.
2. See, for example, C. Halliwell's review in Proc. VIIIth International Symposium on Multiparticle Dynamics (Kayserberg 1977), R. Arnold *et al.*, eds.
3. See, for example, the recent review by T. Ferbel in the Proc. of The International Meeting on Frontier of Physics at Singapore (1978), K. K. Phua, ed.
4. J. Cronin *et al.*: Phys. Rev. **D11** (1975) 3105.
5. D. Garbutt *et al.*: Phys. Letters **67B** (1977) 355.
6. J. H. Kühn: Max-Planck-Institute preprint (1978).
7. Presented by G. Fox at this Conference.
8. See, for example, K. Heller *et al.*: Phys. Rev. **D16** (1977) 2737.
9. Private communication from M. Longo.
10. See, for example, R. Schindler *et al.*: Phys. Rev. Letters **33** (1974) 862.
11. Private communication from H. Lubatti.
12. B. Yuldashev *et al.*: Acta Physica Polonica **B9** (1978) 513.
13. G. Berlad, A. Dar and G. Eilam: Phys. Rev. **D13** (1976) 161; I wish to thank A. Dar for a helpful correspondence regarding the CTM and for providing the predictions for α as a function of y and η for the data of Chaney *et al.*
14. J. Elias *et al.*: Phys. Rev. Letters **41** (1978) 285.
15. I thank L. Gutay for a helpful conversation concerning these data.

PROC. 19th INT. CONF. HIGH ENERGY PHYSICS
TOKYO, 1978

B 11

Big Hadron Model—A Unified Description of Multiple Production off Hadrons and Nuclei—

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§1. Collective tube model (CTM) or big hadron model (BHM)

In this talk, I discuss some controversial points of CTM. As a typical application of CTM, I also present results of calculation of the cross section for the so-called cumulative production of pions off nuclei.

CTM or BHM[1] asserts that a nucleus A or its effective part A_e (nuclear tube) will behave like "a big hadron" (a collective tube) rather than a group of quasi-free nucleons when it is hit by a hadron h (and possibly by a lepton) with high momentum, thus raising the energy effectively available for particle production in comparison with hadron–nucleon collisions at the same incident laboratory momentum. It therefore predicts that multiple production in h–A collisions at a certain energy is identical with that in h–nucleon collisions at some higher energy (universality hypothesis). However, there is a matter that demands a special attention when one compares h–A collisions with h–nucleon collisions in terms of the universality.

§2. Separation of leading particles and central pionization component

A schematic illustration of BHM is given in Fig. 1. Both the tube nucleus and the residual spectator nucleus contribute to the target fragmentation region, the leading hadron h' contributes to the projectile fragmentation region and the excited hadronic matter (EHM) contributes to the central pioni-

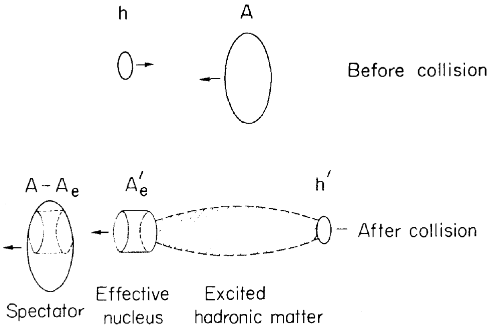

Fig. 1.

zation. We identify the universality with the attribute of EHM. Therefore, one should apply the universality to only those quantities which are dominated by the central pionization component. Furthermore, one should apply the universality hypothesis to those quantities averaged over A_e-distribution (or n_h-or n_g-distribution) and not to those quantities with a fixed A_e (or n_h or n_g), where A_e is the effective mass number and $n_h(n_g)$ is the number of heavily ionizing (grey) prongs. This is based on an observation that the summation over A_e in h–A collisions will correspond to the integration over the impact parameter in h–nucleon collisions.

§3. Universality of excited hadronic matter

There may be two aspects about the universality of EHM. (i) The decay properties of EHM are determined by its mass only. (ii) The mass spectrum of EHM is approximately universal, *i. e.*, it is uniquely determined by $\bar{M}_X^2$ (the mean square mass of EHM) except for those processes where there is no leading particle at all. However, we do not expect the universality of the momentum spectrum of EHM in general.

§4. *A*-dependent leading particle effect

The mass dependence of the mean decay multiplicity of EHM can be inferred from data on p–p collisions and $\bar{p}p$ annihilation. By using a power-law fit $\bar{n}(\bar{M}_X^2)\propto(\bar{M}_X^2)^{0.232}$, we obtain a prediction that

$$R_{hA}\equiv\frac{\bar{n}_s^{hA}}{\bar{n}_c^{hp}}\simeq(\omega_{hA}^2\bar{A}_e/\omega_{hp}^2)^{0.232}$$

for large p_{lab}, where $\bar{A}_e$ is the mean effective mass number and ω_{hA} is the mass conversion ratio:

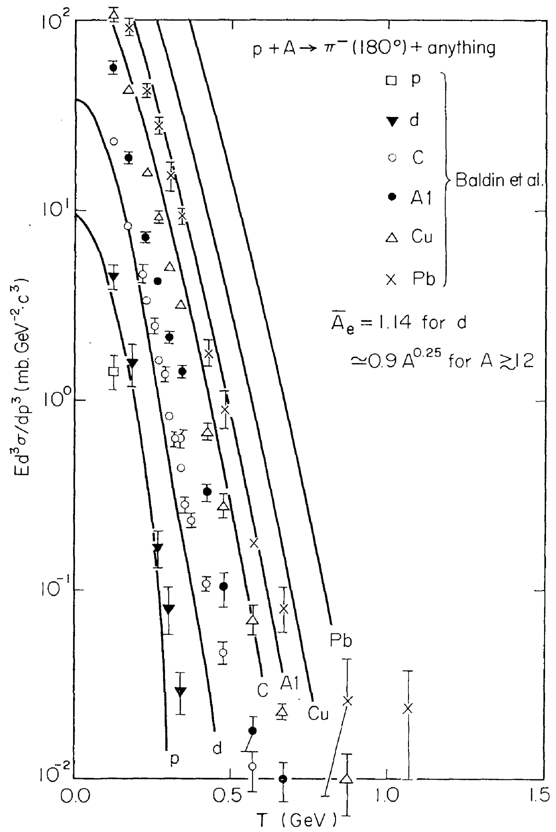

Fig. 2.

$$\omega_{hA}(p_{lab})\equiv\{\bar{M}_X^2(hA\,;p_{lab})\}^{1/2}/E_{av}^{hA}(p_{lab}),$$

$$E_{av}^{hA}(p_{lab})\simeq(2\bar{A}_e m_N p_{lab})^{1/2}\text{ for large }p_{lab}.$$

Note that the A-dependence of the mean multiplicity ratio R_{hA} can be stronger than that of $\bar{A}_e^{0.232}$ if ω_{hA} is a monotonically increasing function of A.

§5. Target fragmentation—cumulative particle production—

The big hadron picture leads us to the hypothesis that the nuclear tube A_e will behave like a big hadron which consists of $3A_e$ valence quarks, the associated sea quark–antiquark pairs and gluons. The distribution of quark parton in the effective nucleus may be determined by a suitable counting rule. To proceed further, we need a specific model for hadron fragmentation. Inclusive spectra of π^- emitted backward in p–A collisions has been calculated by combining Das–Hwa's parton recombination model[2] with Brodsky–Gunion's quark exchange/annihilation model.[3] One example of the results is shown in Fig. 2 together with the data at 8.4 GeV/c.[4] The theoretical curves should be regarded as a prediction for the scaling limit.

§6. Conclusions

There are various uncertainties in the experimental data available at present. In particular, the following problems must be resolved before proving or disproving BHM (or CTM): (i) the contamination of fast knocked-out protons in shower particles: (ii) the contamination of slow pions in heavily ionizing prongs.

We believe that multiple production and probably lepton-pair production off nuclei will provide extremely useful information on hadron dynamics at high energies. BHM or CTM has been invented just as a guiding model to look for systematically such unique information. Note that BHM alone has not a very strong predictive power because it merely provides a framework to analyze high energy nuclear data. It must be combined with an appropriate model (or models) for multiple production in ordinary hadron–hadron collisions in order to give a detailed prediction. In this sense, BHM serves as a framework where any particular model for multiple production is tested on nuclear data.

References

1. D. S. Narayan and K. V. L. Sarma: Progr. theor. Phys. **31** (1964) 93; W. D. Walker: Phys. Rev. Letters **24** (1970) 1143; A. Z. Patashinskii: JETP Lett. **19** (1974) 338; F. Takagi: Lett. Nuovo Cimento **14** (1975) 559; Progr. theor. Phys. **57** (1977) 939; S. Fredriksson: Nucl. Phys. **B111** (1976) 167; G. Berlad, A. Dar and G. Eilam: Phys. Rev. **D13** (1976) 161; Meng Ta-chung: Phys. Rev. **D15** (1977) 197.
2. K. P. Das and R. C. Hwa: Phys. Letters **68B** (1977) 459.
3. S. J. Brodsky and J. F. Gunion: Phys. Rev. **D17** (1978) 848.
4. A. M. Baldin, *et al.*: Sov. J. Nucl. Phys. **20** (1975) 629.

PROC. 19th INT. CONF. HIGH ENERGY PHYSICS
TOKYO, 1978

B 11

A Comment to F. Takagi's Talk

A. WROBLEWSKI

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I would like to make few comments on how the CTM model works for hadron–deuterium collisions. In our Davis–Krakow–Seattle–Warsaw Collaboration we have data on π^-d collisions at 205 and 360 GeV/*c*. By using standard technique we have divided π^-d events into two classes: i) "π^-n" which contains only single scatters on neutrons and ii) "π^-p" which is a mixture of single scatters on protons and double scattering events (D. S.). (See K. Dziunikowska, *et al.*: Phys. Letters **61B** (1976) 316 and K. Moriyasu, *et al.*: Nucl. Phys. **B137** (1978) 377.) Then, by using simple assumptions about interference terms (see H. J. Lubatti: VTL HEP Note-57 (1977) and K. Moriyasu, *et al.*, to be published) we have derived statistically properties of the double scattering sample such as multiplicity distribution, rapidity distribution etc. The method amounts essentially to determine differences between the "π^-p" sample and the π–p sample obtained in hydrogen at the same energy, properly normalized to the single scattering cross section in deuterium. Using this method we have analyzed all published hadron–deuterium data in the 15 to 360 GeV/*c* $P_{\rm lab}$ range and made a compilation of the properties of D. S. events. The CTM prediction for double scattering in deuterium at a given $P_{\rm lab}$ is that D. S. events should look the same as single scattering events on nucleons at twice the $P_{\rm lab}$. Our conclusions are:

1) The average charged multiplicity of D. S. sample is quite well described by the CTM, although the BLRW model (M. Baker, *et al.*: Phys. Rev. **D17** (1978) 826) gives slightly better predictions.

2) The shape of the D. S. charged multipli-

city distributions (*e. g.*, the higher moments) is quite well described by the CTM at low P_{lab}, but at higher P_{lab} the difference between data and the CTM get larger. The BLRW model works adequately for all energies.

3) The rapidity distributions of D. S. events is rather similar to that of π^-p events at the same P_{lab} but differs from π^-p at twice the P_{lab} contrary to the CTM.

PROC. 19th INT. CONF. HIGH ENERGY PHYSICS
TOKYO, 1978

B 11

Fluctons and Large Momentum Transfer

Presented by D. BLOKHINTZEV

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The hypothesis about fluctons, a tight k-nucleon fluctuation of nuclear matter has more than ten years history[1] and was initiated by experimental observation[2] of significant yield of high-energy nuclear fragments (D, T, ^{3}He) in proton nucleon collision.

If the momentum transfer q is large, so that

$$\hbar/q < \text{dimension of hadron} \sim 10^{-13}\ \text{cm}$$

it is natural to think that all k nucleon of the flucton form an object which acts similar to $3k$-quark elementary particle. One of the most spectacular argument in favour of this hypothesis comes from the large Q^2-behavior of deuteron form-factor, $F_{\mathrm{D}} \sim Q^{-10}$, which is just the well-known quark counting power.[3]

New evidence in favor of the flucton hypothesis comes from discovering[4] and experimental study[5] of the so-called cumulative hadron production $B+A \to C+X$. Introducing the usual invariant variables $s=2p_{\mathrm{A}}p_{\mathrm{B}}$, $t=-2p_{\mathrm{A}}p_{\mathrm{C}}$, $u=-2p_{\mathrm{B}}p_{\mathrm{C}}$ it is not difficult to see that in the beam energy region $E \gtrsim 10$ GeV and secondary hadron energy $\varepsilon \gtrsim 1$ GeV all these variables and also ut/s are larger than squares of hadron masses (≈ 1 GeV^2) just as in high $p_\perp$ processes. This gives the basis for considering cumulative production as a result of hard scattering of parton of incident particle with that of flucton in nuclei[6] (Fig. 1).

Starting from the usual hard scattering formula it is not difficult to obtain approximately

$$d\sigma_{\mathrm{A}} \simeq \sum_k \beta_{\mathrm{A}}^k \cdot d\sigma_{\mathrm{N}}\left(x_1, \frac{x_2}{k}\right) \cdot \left(1 - \frac{x_2}{k}\right)^{\sigma(k-1)}$$

where $x_1 = -t/s_{\mathrm{N}} = \varepsilon/E \gg 1$, $x_2 = -u/s_{\mathrm{N}} \simeq (\varepsilon - p_{\parallel})/m_{\mathrm{N}} > 1$, the factor β_{A}^k is the probability of k-nucleon flucton formation in A. $d\sigma_{\mathrm{N}}$ is the cross section of the process on one nucleon and the last factor is due to the extra number of passive quarks. This expression naturally explains such features of cumulative production as scaling, production angle asymmetry for large p, back-to-back correlation of cumulative hadron with other secondaries. Concerning the atomic number behavior one can see that it depends on β_{A}^k, *i. e.*, on what the flucton is.

Two extreme points of view seem possible in relativistic case.

a) The flucton is a coherent group of nucleons from the incident particle point of view. In the lab frame of reference this group forms a "coherent tube."

b) The flucton is a sort of quasiresonance

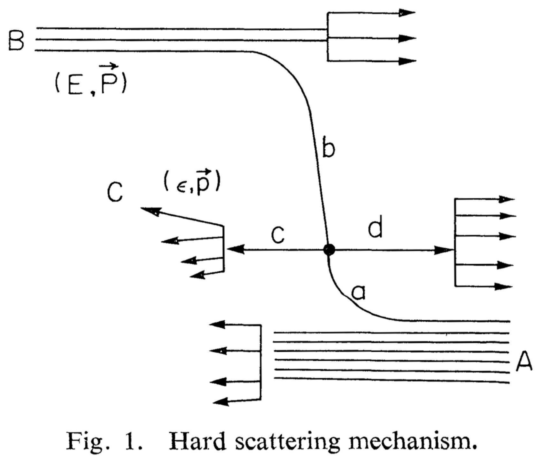

Fig. 1. Hard scattering mechanism.

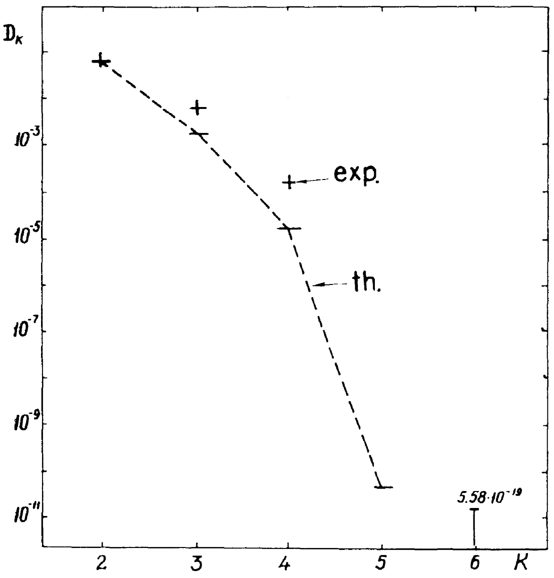

Fig. 2. Probability of flucton formation.

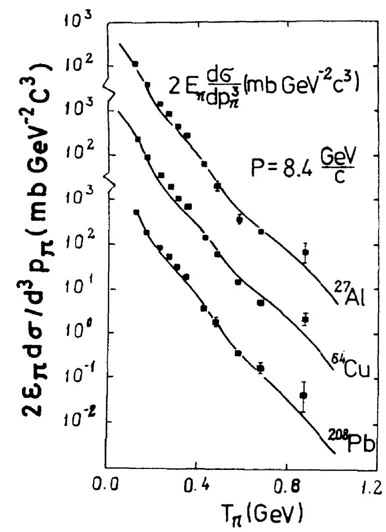

Fig. 3. Numerical calculation of cumulative π production.

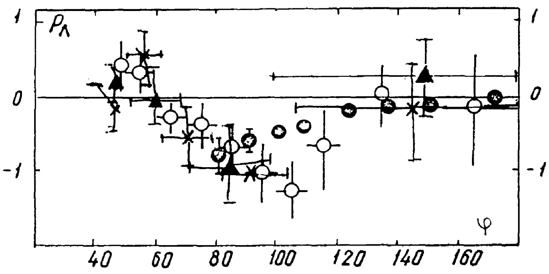

Fig. 4. Polarization of Λ-particle in the process
i) $p+Be\rightarrow\Lambda+X$, $E=200$ GeV, $x_F=0.3\sim0.7$ (● ref. 9)
ii) $\pi^-+(C+Xe)\rightarrow\Lambda+X$, $E=2.9$ GeV (○ ref. 10)
iii) $n+{}^{12}C\rightarrow\Lambda+X$, $E=7$ GeV (▲ ref. 11).
iv) $\pi^-+{}^{12}C\rightarrow\Lambda+X$, $E=4$ Gev (✱ ref. 11).

state, and consequently the coherence volume is a sphere in lab frame.

In both cases

$$d\sigma_A\sim A^n,\ \text{but}\ \begin{array}{ll} n-2/3\sim x_2/3 & \text{for a)},\\ n=1 & \text{for b)}.\end{array}$$

The calculations of β^k_A in MIT-bag type model (b-type flucton) was done recently in the work.[7] The result of the calculations are presented in Figs. 2, 3, where $D_k=\beta^k_A/b^k_A$ and b^k_A is a combinatorial factor. In fact, D_k is a probability of phase transition. One of the predictions is a quick decrease of cumulative production cross section when the cumulative index $x_2>4$.

One of the features of the cumulative effect is the polarization of Λ-baryons. This phenomena was considered in hard scattering model.[8] Assuming the scaling of hard scattering density matrix $\rho_{\mu\nu}d\sigma/dt'\sim(1/s')^n\varphi(s'/t')$ one can obtain that

$$P_\Lambda=I(x_1,x_2)\sin\varphi$$

where φ is the beam-target angle in the Λ's rest frame, and I is a function which weakly depends on x_1 (energy scaling of polarization), x_2 and sort of target. Assuming I=const. one can compare the known data[9] in proton fragmentation region and in cumulative data.[10,11]

It allows us to conclude that P_Λ is energy independent indeed and has the same magnitude for proton and nuclear fragmentation. The flucton really acts as heavy elementary particle.

As for the future experiments it seems interesting: 1) to come to the region of $k=4\sim5$ and check whether the rapid decrease of cumulative production really exists, ii) accurate measurements of A-dependence, iii) deep inelastic lepton–hadron scattering in cummulative region and iv) accurate measurement of heavy fragments yield. All this would bring deeper understanding of the flucton's nature. The hard scattering mechanism needs in more accurate v) correlation measurements in cumulative region and vi) investigation of polarization in the Serpukhov–Fermilab energy region.

References

1. D. I. Blokhintzev: JETP **33** (1957) 1295.
2. Adjgirey, *et al.*: JETP **33** (1957) 1185.
3. Matveev, *et al.*: Lett. Nuovo Cimento **7** (1973) 719; S. Brodsky and G. Farrar: Phys. Rev. Letters **31** (1973) 1153.
4. See A. M. Baldin: Elem. Part. and Atomic Nucl. **8** (1977) 429.

5. A. M. Baldin.: Report at this Conference.
6. A. V. Efremov.: Jad. Fiz. **24** (1976) 1208.
7. V. V. Burov, *et al.*: Phys. Letters **76B** (1977) 46; V. K. Lukjanov, *et al.*: JINR preprint P2–11049 (1977).
8. A. V. Efremov, Jad. Fiz. **28** (1978) 166 (preprint E2–11244, 1978).
9. G. Bunce, *et al.*: Phys. Rev. Letters **36** (1976) 113.
10. G. A. Leksin and A. V. Smirnitski.: Preprint ITEP–87 (1977).
11. B. Shahbazian: Preprint JINR El–11519 (1978).