PHYSICAL REVIEW D VOLUME 33, NUMBER 9 1 MAY 1986

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Alpha-particle interactions with nuclei at 12*A* GeV/*c*

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(Received 7 October 1985)

Pseudorapidity-density distributions of shower particles from 12A-GeV/c α-emulsion interactions are presented. As compared to extrapolations from p-nucleus data, the central $\alpha+$(Ag,Br) interactions exhibit an excess of particles in the middle pseudorapidity region. The correlation between $\langle\eta\rangle$ and $\langle n_s\rangle$ can be understood within a wounded-nucleon model.

It is of special interest to study nucleus-nucleus interactions in the energy range 10–15A GeV since it has been suggested that nuclear stopping can create maximum baryon density in this energy range.[1] We have undertaken this study of α-nucleus collisions in order to investigate to what extent the data at 12A GeV/c can be understood in the framework of a wounded-nucleon model.

Four stacks, each consisting of 30 pellicles Ilford G5 emulsion of the size $0.06\times7.5\times10$ cm^3, were exposed to a 12A-GeV/c α beam from the CERN Proton Synchrotron (PS). Because of the high beam intensity ($\approx 2\times10^5$ cm^{-2} per spill) the scanning was restricted to the first 4 cm of the stack. Along-the-track scanning was used to collect the interactions. In addition, 11 events ($N_h\geq35$) were collected by area scanning. Interactions resulting in a ^{3}He or a ^{4}He projectile fragment are not included in the analysis.

The particles emitted from the interactions were divided into two categories. Singly charged particles with $\beta\geq0.7$ are mainly mesons and some fast protons. Such particles are called shower particles and n_s denotes the number of these in an event. The remaining particles are named heavily ionizing particles (heavy tracks). These are charged target fragments and also a few low-energy mesons (E_π < 60 MeV). N_h denotes the number of heavy tracks in an event.

In Table I, the number of events, $N_{\rm int}$, and the average values of n_s, N_h, and η for different N_h groups are given. The events with $N_h\geq35$ are regarded as central $\alpha+$Ag interactions since the charge number of the bromine nucleus is 35. The intervals $10\leq N_h\leq15$ and $26\leq N_h\leq34$ are classified as interactions with the heavier emulsion components (Ag,Br) since hydrogen, carbon, nitrogen, and oxy-

TABLE I. The number of events, $N_{\rm int}$, and average values of N_h, n_s, and η for each N_h interval are presented.

	N_h group				
	0,1; $n_s=2$	0–2	10–15	26–34	≥35
$N_{\rm int}$	28	100	44	36	37
$\langle N_h\rangle$	0.36 ± 0.09	0.74 ± 0.08	11.59 ± 0.26	29.00 ± 0.39	40.14 ± 0.59
$\langle n_s\rangle$	2	4.52 ± 0.30	9.68 ± 0.72	16.28 ± 0.75	20.19 ± 0.85
$\langle\eta\rangle$	5.25 ± 0.17	3.24 ± 0.08	2.24 ± 0.06	1.68 ± 0.04	1.43 ± 0.03

gen all have charge numbers below 10. The interval $0 \leq N_h \leq 2$ consists of collisions between α and the H and (C,N,O) components of the emulsion and peripheral α + (Ag,Br) interactions. The groups $N_h = 0, 1$, $n_s = 2$ are mostly interactions where the α projectile breaks into two singly charged particles and neutrals.

The emission angles θ of all shower particles were measured. The standard deviation of the angular measurements is estimated to be ≈ 1 mrad for tracks with $\theta < 5°$. For the rest of the shower particles the corresponding figure is ≈ 6 mrad.

In Fig. 1, we have plotted the pseudorapidity- [$\eta = -\ln\tan(\theta/2)$] density distributions of shower particles in different N_h intervals. The shown error bars are from statistics only. In Fig. 1(e), the solid unit-normalized curve represents the η region where the nucleon spectators are expected to appear. The η values are calculated from longitudinal- and transverse-momentum components, parametrized by Gaussian distributions in the rest frame of the α projectile. In an experiment[2] with colliding α particles at the CERN Intersecting Storage Rings (ISR) the widths (standard deviations) of these Gaussian distributions were estimated to be 70 ± 3 MeV/c and these values have been used here. The Gaussian distributions describe the Fermi motion of the nucleons in the α particle prior to breakup.

Nucleons scattered quasielastically are expected to be found in the η space given by the dashed curve (unit normalized). The differential elastic pp scattering cross section can be parametrized as

$$d\sigma/dt \sim e^{bt} , \tag{1}$$

where t is the squared four-momentum transfer. We have used $b = 7.66 \pm 0.11$ (GeV/c)$^{-2}$, which is measured at $\sqrt{s} = 4.93$ GeV ($E_{\text{lab}} = 12.0A$ GeV) in the t region $[-1.0, -0.1]$ (GeV/c)^2 (Ref. 3). Under the assumption of small scattering angles, longitudinal- and transverse-momentum distributions for the scattered protons are derived from Eq. (1). These distributions are convoluted with the Gaussians describing the Fermi momentum in order to obtain the distributions for the quasielastic scattered protons. The fragmentation model and the procedure for the estimation are described in detail in Ref. 2.

As can be seen in Fig. 1(e), the shower particles from the $N_h = 0, 1$, $n_s = 2$ type of events appear in the η regions where the spectator protons and the quasielastic scattered protons are expected to fall.

As N_h increases, the yield of quasielastic scattered nucleons and spectators decreases and for events with $N_h \geq 35$, the spectator region is empty. The density of charged particles increases with N_h.

In Fig. 2, the distribution of the number of participating nucleons from the target, P_A, are given for all impact-parameter events ($1 \leq P_B \leq 4$) and for spectator-veto events ($P_B = 4$). P_B denotes the number of projectile nucleons that take part in the interaction. The points result from a Monte Carlo simulation of ^{4}He + ^{108}Ag interactions.[4] Generated target nuclei are bombarded by a beam of generated projectile nuclei. By counting the number of hit nucleons in each interaction and using a frozen straight-line geometry the distribution of wounded nucleons are obtained. A nucleon is considered to be struck whenever a

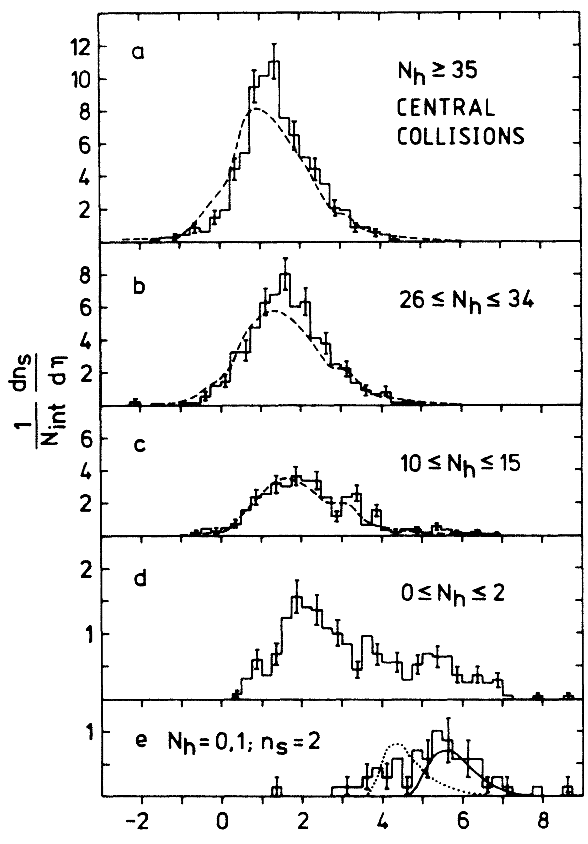

FIG. 1. Pseudorapidity-density distributions of shower particles in selected N_h bins. The dashed lines give the densities extrapolated from p-emulsion data. The solid and the dotted lines represent the η regions where the spectator protons and the quasielastically scattered protons should fall, respectively.

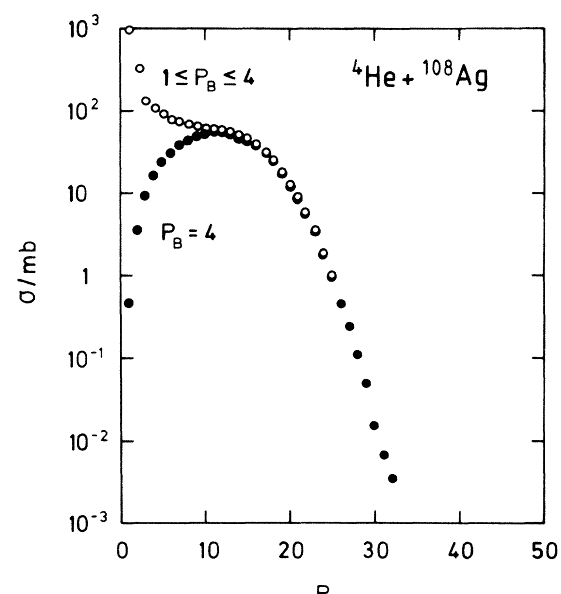

FIG. 2. P_A distributions resulting from Monte Carlo simulation of ^{4}He + ^{108}Ag interactions. Observe that only the production cross section is given. The curve $P_B = 4$ represents events where all projectile nucleons have participated in the interaction (spectator-veto events).

hadron passes within a distance of $\sqrt{\sigma_{hN,\mathrm{inel}}/\pi}$. (For details and further references, see Ref. 4.) For the spectator-veto events the average value of P_A is equal to 11.8 and the most probable value of P_A is 11. For all events ($1 \leq P_B \leq 4$) the corresponding values are 6.7 and 1, respectively.

Several models describe p-nucleus and nucleus-nucleus collision data.[5-7] Here we have used a simple wounded-nucleon model.[8] The dashed curves in Figs. 1(a), 1(b), and 1(c) are derived from this model. The particle density is given by

$$\rho(y,k) = P_B \rho_0(y)[1+\beta(y)(k-1)] = P_B \rho_{pA}(y,k) \ , \qquad (2)$$

where k is defined as $k = P_A/P_B$, and $\rho_0(y)$ is the rapidity density in nucleon-nucleon collisions at the corresponding energy. The function $\beta(y)$ is determined from nucleon-nucleus data. A detailed description is found in Ref. 8. We have used proton-emulsion data in order to determine the distributions $\rho_{pA}(y,k)$, where the k values are taken from Fig. 3 (see text below). As can be seen, the model represents the data fairly well. However, with increasing N_h there is a statistical significant excess of particles in the middle pseudorapidity region, and for $N_h \geq 35$ type of events the particle density in the target region is lower than what is predicted by the model. Possible explanations for these deviations might be phenomena not accounted for in the model, such as the following. (i) The rapidity density of particles produced in the intranuclear cascade in central α-nucleus collisions could be smaller than the corresponding densities extrapolated from p-nucleus collisions. (ii) An excess of target protons with $\beta > 0.7$ could occur in α-nucleus collisions compared to the case of p-nucleus collisions. (iii) An increase could occur in p_T of the observed particles in comparison with p-nucleus collisions.

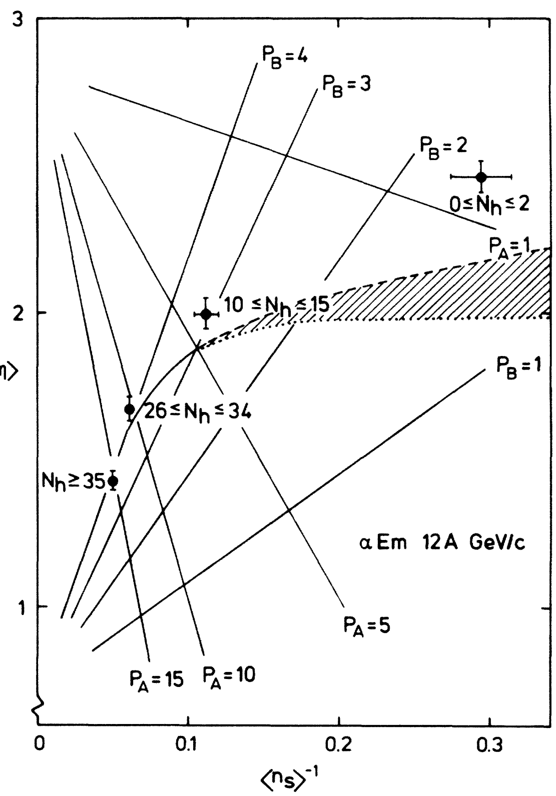

FIG. 3. $\langle\eta\rangle$ vs $\langle n_s\rangle^{-1}$. The solid lines represent the expected number of participants from the projectile P_B and from the target P_A, respectively. The dashed curve results when P_A is held fixed and one calculates the average P_B. The dotted curve is obtained by the reverse procedure. The lines are derived from a parametrization of proton-emulsion data and the curves are the result of Monte Carlo simulations. The error bars shown are from statistics only.

Figure 3 shows $\langle\eta\rangle$ for different N_h intervals as a function of $\langle n_s\rangle^{-1}$. $\langle\eta\rangle$ and $\langle n_s\rangle$ are calculated with a cut at $\eta = 4.5$ in order to exclude spectator protons. In an earlier paper[9] it has been shown that for p + emulsion interactions $\langle\eta\rangle$ increases linearly with increasing $\langle n_s\rangle^{-1}$. To make this more quantitative, let us assume that a projectile and a target nucleon on the average contribute to the shower-particle yield with n_P and n_T, respectively. We can write n_s as

$$n_s = n_P + \nu n_T \ , \qquad (3)$$

where ν is the number of struck target nucleons. We then have

$$\langle\eta\rangle = (n_P\langle\eta_P\rangle + \nu n_T\langle\eta_T\rangle)/(n_P + \nu n_T) \ , \qquad (4)$$

where $\langle\eta_P\rangle$ ($\langle\eta_T\rangle$) is the average η value for the shower particles connected to the projectile (target). Equation (4) can be rewritten as

$$\langle\eta\rangle = \langle\eta_T\rangle + n_P(\langle\eta_P\rangle - \langle\eta_T\rangle)\langle n_s\rangle^{-1} \ . \qquad (5)$$

It is important to realize that the intercept with the $\langle\eta\rangle$ axis, $\langle\eta_T\rangle$, and the slope factor $n_P(\langle\eta_P\rangle - \langle\eta_T\rangle)$ are energy dependent. From scaling arguments the energy dependence can be assumed to be

$$\begin{aligned} \langle\eta_T\rangle &= \alpha \ln E + \beta \ , \\ \langle\eta_P\rangle - \langle\eta_T\rangle &= \gamma \ln E + \delta \ , \end{aligned} \qquad (6)$$

where E is the incoming kinetic energy in GeV. A simultaneous fit of all p + emulsion data from 4 to 400 GeV gave $\alpha = 0.366$, $\beta = -0.164$, $\gamma = 0.558$, and $\delta = 0.763$, where we have used $n_P = \langle n_{\mathrm{ch}}\rangle/2$, i.e., half the averaged charged pp multiplicity. At 12*A* GeV/*c*, $\langle n_{\mathrm{ch}}\rangle$ is 3.46.[10] Using Eq. (6) we obtain $\langle\eta_T\rangle = 0.72$ and $\langle\eta_P\rangle = 2.83$. The line $P_B = 1$ in Fig. 3 is obtained from Eq. (5). The lines $P_B > 1$ are calculated by multiplying the slope of this line by the corresponding P_B values since, in a wounded-nucleon model, a proportional increase of both P_A and P_B results in the same increase of $\langle n_s\rangle$ while the $\langle\eta\rangle$ value remains the same.

The lines labeled $P_A \geq 1$ are constructed in a similar way. Equation (4) is now rewritten as

$$\langle\eta\rangle = \langle\eta_P\rangle + \nu n_T(\langle\eta_T\rangle - \langle\eta_P\rangle)\langle n_s\rangle^{-1} \ . \qquad (7)$$

$\langle n_s\rangle$ is calculated from a parametrization of p + emulsion data and at 12*A* GeV/*c* one achieves $\langle n_s\rangle = 3.97$.[11] If one connects the point ($\langle\eta\rangle = \langle\eta_P\rangle$, $\langle n_s\rangle^{-1} = 0$) and the point given by the intercept of the lines $P_B = 1$ and $\langle n_s\rangle^{-1} = (3.97)^{-1}$ one finally gets the line $P_A = \langle\nu\rangle = 2.64$, i.e., the average ν value for proton-emulsion interactions. Thus the lines $P_A = 1$ and $P_A > 1$ can be constructed.

The deviations from a straight-line behavior for the α + emulsion data can now be understood as a decrease of P_B when one goes to less central interactions. The two points representing the groups with the highest N_h values in Fig. 3 (central and near-central collisions) are in good agreement with the naïve expectation that all the projectile nucleons are participating, i.e., $P_B = 4$. Furthermore, the P_A values for these points agree quantitatively with the values expected from the simulated P_A distribution for $P_B = 4$ type of events (see Fig. 2) which peak at $P_A \approx 12$.

From probability distributions of P_A and P_B, obtained by Monte Carlo simulations of interactions between α and the different nuclei of the emulsion, we have calculated the two curves in Fig. 3. The dashed curve results when average P_B values are calculated for different P_A values. The dotted one is obtained by the reverse procedure. The experimental points should fall within the hatched area. However, since the Monte Carlo simulation only considers inelastic cross sections, the point $0 \leq N_h \leq 2$ is expected to be above this region because of the contribution from quasielastic scattered protons.

Besides the $\alpha\alpha$ and dd experiments at the CERN ISR, this is the first study of nucleus-nucleus collisions at energies above $5A$ GeV performed in an accelerator-based experiment. The energy domain discussed in this paper is of special interest because of the possibilities of reaching maximum baryon densities, and it will soon be available for studies of heavy-ion interactions induced by ions up to sulfur at the BNL Alternating Gradient Synchrotron (AGS). We have observed a strong correlation between the multiplicity of produced particles and the multiplicity of target-associated fragments (N_h). We have, in different N_h intervals, measured the pseudorapidity-density distributions for shower particles emanating from $12A$ GeV/c α+emulsion interactions. The pseudorapidity-density distributions and the correlation between $\langle\eta\rangle$ and $\langle n_s\rangle$ can be reasonably well understood from a wounded-nucleon model. However, when compared to the model, for the central $\alpha + (\mathrm{Ag, Br})$ interactions an excess of particles appears in the middle pseudorapidity region.

We are much obliged to Dr. Lothar Hoffman and the staff at the CERN PS for their valuable help during the exposure of our emulsion stacks at CERN. Visnja Kopljar is thanked for her efficient scanning work. We gratefully acknowledge financial support from the Swedish National Science Research Council, the University Grants Commission (India), and the Department of Science and Technology and Department of Atomic Energy (Government of India). One of us (L.K.M.) thanks the International Seminar (Sweden) for financial support while staying in Lund.

*Deceased.

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