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Single-Particle Spectra Associated with High-Multiplicity Events in 800-MeV/Nucleon Ar on KCl and Pb

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High-multiplicity events were selected in collisions of 800-MeV/nucleon Ar on KCl and Pb. In these events, projectile fragments are highly suppressed, and the angular distributions of high-energy protons are almost isotropic in a moving frame whose rapidity is y_0 ($y_0 \simeq 0.60$ for KCl and 0.43 for Pb targets). Comparisons with inclusive proton data are used to estimate the relative importance of single and multiple *NN* collisions. Pion spectra in high-multiplicity events are also presented.

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If one describes high-energy heavy-ion collisions in terms of *NN* (nucleon-nucleon) collisions, inclusive particle production would originate from both single *NN* collisions (clean knockout process) and subsequent multiple *NN* collisions (multiple cascade process), because the mean free path of nucleons inside the nucleus[1] is known to be comparable to the typical reaction size of the colliding nuclei.[2,3] In fact, the importance of both processes has been clearly demonstrated in a recent two-proton correlation experiment.[4,5]

High-multiplicity events (hereafter called HME) are events in which a large number of nucleons are actively involved. We thus expect that the detection of HME tends to select small impact parameters and to enhance multiple *NN* collisions. Because several collective phenomena have been predicted for events where multiple *NN* collisions dominate, selecting HME is of special interest. The results reported here focus mainly on high-energy protons and pions in HME, and can be considered to be complementary to those of Stock *et al.*,[6] who measured mainly low-energy protons (≤ 200 MeV).

In order to select HME, we used nine sets of tag-counter telescopes placed at 40° with respect to the beam direction and arranged almost symmetrically in azimuth. Each telescope consisted of two plastic detectors with an absorber sandwiched in between. We selected only high-energy particles, typically $E_{\text{proton}} \geq 100$ MeV, since low-energy protons below 50 MeV could come from target evaporation which is not the type of HME in which we were interested. The solid angle of each telescope was 48 msr which subtended $\Delta\theta = 10°$ and $\Delta\varphi = 22°$. We measured energy and angular distributions of light fragments with a magnetic spectrometer[4] as a function of the particle multiplicity in these telescopes. Typically, spectra of protons between 50 and 2000 MeV were measured by the spectrometer at laboratory angles of 10°–110°.

In order to understand our tag-counter system, especially to study the relationship between the total event multiplicity (M_{tot}) and the measured tag-counter multiplicity (M_{tag}), we have done Monte Carlo calculations. The assumptions involved are that (a) all particles are protons, (b) emitted particles are not correlated with each other, (c) energy and angular distributions are the same as those observed in inclusive spectra, and (d) the multiplicity distribution, $P(M_{tot})$, is approximated by a linearly decreasing function of M_{tot} with maximum multiplicity $M_{tot}{}^{max}$ (and thus $\langle M_{tot}\rangle = \frac{1}{3} M_{tot}{}^{max}$). Streamer-chamber results are consistent with assumption (d).[7] Because the total yield of π^- is about 10% of that of protons[4,8] at 800 MeV/nucleon, assumption (a) caused an error in the total multiplicity of 20% (including both π^+ and π^-). Nevertheless, the distribution of M_{tag} was very well reproduced by such simple calculations. Using these calculations we also evaluated the total event multiplicity when HME were selected by the tag counters. For example, if we selected $M_{tag} \geq 4$ for Ar + KCl, we expect $\langle M_{tot}\rangle \simeq 25$. Similarly, $M_{tag} \geq 5$ for Ar + Pb corresponds to $\langle M_{tot}\rangle \simeq 49$.

Figure 1 shows how proton angular distributions change in collisions of Ar + Pb when the tag-counter multiplicity M_{tag} was varied. Inclusive spectra show a strong forward peaking, but for HME the forward emission is highly suppressed. Similar forward suppression was observed by Stock *et al.*[6] for low-energy protons in Ne + U collisions, although the mechnism of suppression could be different between the two cases, as will discussed later.

This forward suppression can be understood more clearly if the proton invariant cross sections are plotted in the plane of rapidity (y) and normalized transverse momentum $p_T/m_p c$ (see Fig. 2). Here, both HME and inclusive events are shown for comparison. The selection of $M_{tag} \geq 5$ corresponds to the highest multiplicity attained in the present experiment with reasonably high statistics. Each contour line connects the same invariant cross section, and is observed in the small-p_T region at $(y, p_T) = (y_T, 0)$. For HME, however, the effect of projectile fragments completely disappears, which results in the forward suppression seen in Fig. 1.

According to the participant-spectator model[9,10] the whole Ar nucleus overlaps with the Pb nucleus to form the participant when small impact

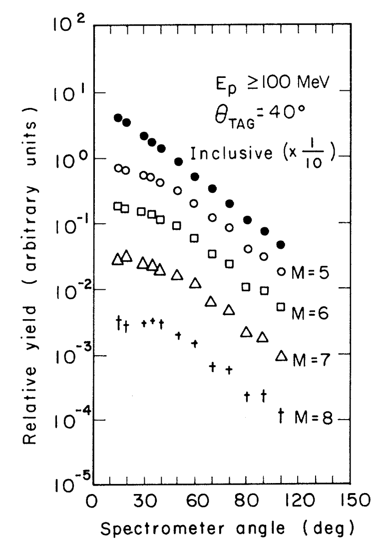

FIG. 1. Proton angular distributions in 800-MeV/nucleon Ar + Pb as a function of the tag-counter multiplicity M.

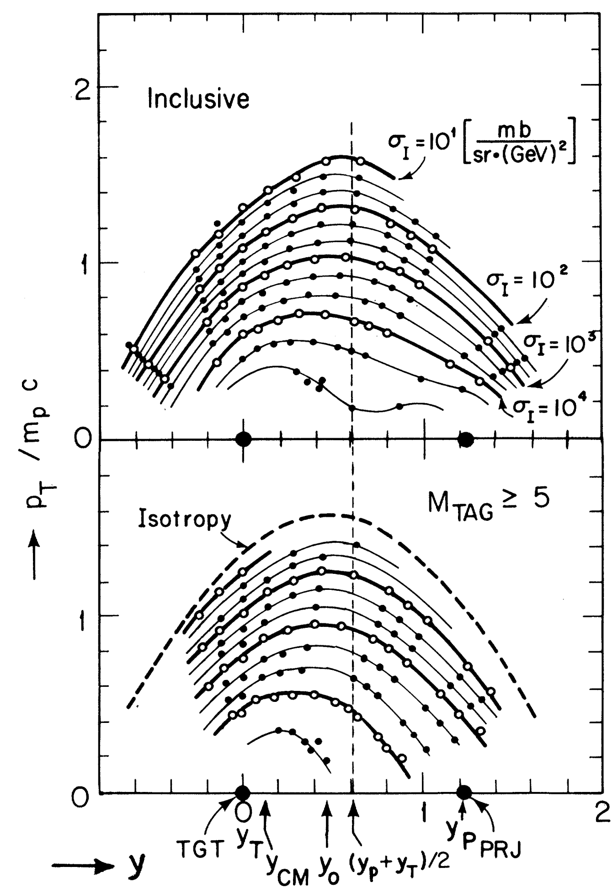

FIG. 2. Proton spectra in 800-MeV/nucleon Ar + Pb for inclusive (above) and high-multiplicity (below) events. Projectile and target rapidities are indicated by y_P and y_T, respectively.

parameters are selected. Complete suppression of projectile fragments for HME is therefore consistent with the picture that the present measurements are selecting small impact parameters. Figure 2 also shows that the angular distribution of high-energy protons in HME is approximately symmetric about lines passing through $y = y_0 = 0.43 \pm 0.03$. Assume that y_0 represents a moving source, the participant, formed from a certain number of nucleons, $N_{\rm Pb}$, from the Pb nucleus and a certain number, $N_{\rm Ar}$, from the Ar projectile. Simple kinematical calculations based on the velocity of the source show then that $N_{\rm Pb} \simeq 1.6 N_{\rm Ar}$. Since $1.6 \simeq (A_{\rm Pb}/A_{\rm Ar})^{1/3}$, the simplest picture is that the participant comes from straight-line trajectories in which the Ar nucleus completely overlaps with the Pb nucleus. Our result that $y_0 = 0.43 \pm 0.03$ should be contrasted with that of Stock *et al.*,[6] who find that for low-energy protons ($E_{\rm lab} \leq 200$ MeV) the shape of the contour lines is roughly semicircular about rapidities ranging from 0 to about 0.2.

In Fig. 3 angular distributions of protons in the frame of $y = y_0$ are plotted for both inclusive events and HME. Three sets of proton energies, 200, 400, and 600 MeV measured in that frame, were selected. For Ar + KCl, $y_0 = 0.60$, which is close to the rapidity of the nucleon-nucleon c.m. frame. We observe now that the angular distribution of 600-MeV protons is almost isotropic for HME, while it is forward and backward peaked for inclusive events.

Forward suppression for HME as seen in Fig. 2 and the almost isotropic angular distribution for HME as seen in Fig. 3 suggest that HME are dominated by the multiple-*NN*-collision component through which the initial memory of the beam direction is averaged out to all directions.

Since the inclusive proton yield arises from single and multiple *NN* collisions, one may assume that it can simply be expressed as

$$(d\sigma/d\vec{p})_{\rm inclusive} = a(d\sigma/d\vec{p})_{\rm CKO} + b(d\sigma/d\vec{p})_{\rm HME}, \quad (1)$$

where the first term is the clean knockout (CKO) component, and the second term, which is the multiple-collision component, is simply replaced by the observed data for HME. Two quantities, a and b, are normalization constants. $(d\sigma/d\vec{p})_{\rm CKO}$, calculated by Hatch and Koonin,[11] are shown in Fig. 3 by dashed curves. For Ar + KCl the calculated ratio of forward to 90° yields is much larger than the observed ratio for the inclusive spectra, and we clearly see that inclusive spectra are not well reproduced by the first term in

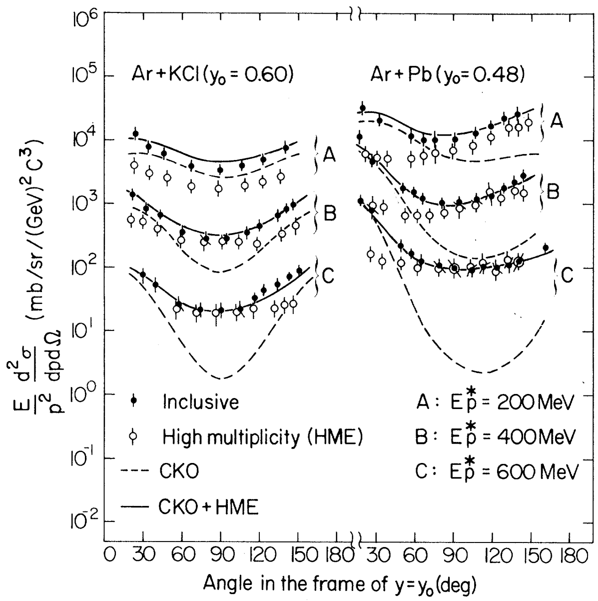

FIG. 3. Proton angular distributions for inclusive and high-multiplicity events plotted as a function of the angle in the frame whose rapidity is y_0 in collisions of 800-MeV/nucleon Ar on KCl and Pb.

Eq. (1) only. However, if we calculate the inclusive yield as a sum of two components, as shown by Eq. (1), the results, which are plotted by solid curves in Fig. 3, are in excellent agreement with the observed inclusive data.

Define the fraction of the CKO component, P, as

$$P = a\,\frac{(d\sigma/d\vec{p})_{\rm CKO}}{(d\sigma/d\vec{p})_{\rm inclusive}}. \quad (2)$$

Then, from the above fits the value P can be estimated for protons emitted over a wide kinematical region. Typical features of P obtained for Ar + KCl are as follows:

(1) For 600-MeV protons emitted at 90°, we have $P \simeq 0$. This implies that large-p_T fragments are mainly from multiple *NN* collisions.

(2) Large values of P are obtained at small angles, implying that protons emitted at forward angles are mostly from single *NN* collisions.

(3) For $E_p^* = 200$ MeV at 90° we have $P \simeq 0.6$. Both single- and multiple-*NN*-collision components are intermingled in proton emission into this kinematical region. This result is consistent with the two-proton correlation data in Ref. 5, because $P \simeq 0.5$ was obtained there for protons emitted into this kinematical region.

In the case of Ar + Pb the forward emission in inclusive events is mainly from the clean knock-

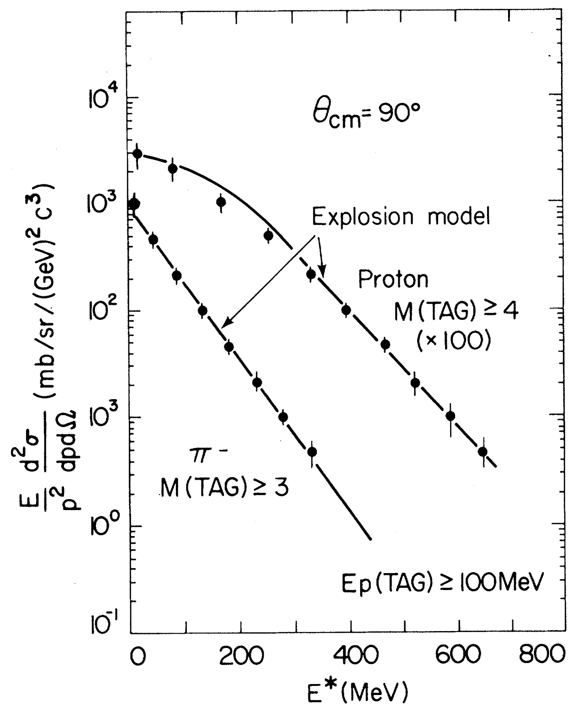

FIG. 4. Proton and pion energy spectra for high-multiplicity events of 800-MeV/nucleon Ar + KCl. Coincidence efficiency of the tag counters was not corrected for in the data, and therefore the absolute values have no solid meaning. Absolute scales of the curves calculated by the explosion model (Ref. 12) were adjusted to fit the data.

out process, whereas it is highly suppressed in HME. The important conclusion drawn from the above study is that the fraction P is strongly dependent on the kinematical region which we are dealing with.

Finally let us discuss whether there is some evidence of collective phenomena when HME are selected. Figure 4 shows proton and pion spectra for HME (the absolute scales are arbitrary). We selected the highest multiplicity in which the data were still statistically meaningful. Typical features of the data are (a) the nonexponential shape for low-energy protons and (b) the steeper exponential falloff for pions than for protons. Although both features (a) and (b) have already been observed in inclusive spectra,[4,8] we emphasize the fact that the flattening of the proton spectra in the low-energy region as well as the discrepancy of the exponential slope between protons and pions are more pronounced for HME. So far the best fits to these data have been obtained with the explosion model of Siemens and Rasmussen[12] in which a radial explosion flow from the compressed nuclear matter is assumed. However, other models such as the cascade model[13] are also consistent with the data.

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