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## LEADING PARTICLE DISTRIBUTIONS IN 200 GeV/c p+A INTERACTIONS

K. ABE <sup>a</sup>, G. ALEXANDER <sup>b</sup>, E.D. ALYEA Jr. <sup>c</sup>, M. BADIAC <sup>d</sup>, P. BEILLIERE <sup>e</sup>, M. BLOOMER <sup>f</sup>, T. BOBER <sup>g</sup>, J.E. BRAU <sup>g</sup>, D.H. BRICK <sup>h</sup>, E.B. BRUCKER <sup>i</sup>, W.M. BUGG <sup>g</sup>, W. BUSZA <sup>f</sup>, C. CASTOLDI <sup>j</sup>, B. COLE <sup>f</sup>, H.O. COHN <sup>k</sup>, G.T. CONDO <sup>g</sup>, R. DIMARCO <sup>d</sup>, R. DOLFINI <sup>j</sup>, T.A. FRANK <sup>f</sup>, T.A. FUESS <sup>f</sup>, E. GALLIGARICH <sup>j</sup>, N. GEL'FAND <sup>l</sup>, L. GRODZINS <sup>f</sup>, J. GRUNHAUS <sup>b</sup>, E.S. HAFEN <sup>f</sup>, T. HANDLER <sup>g</sup>, H.J. HARGIS <sup>g</sup>, P. HARIDAS <sup>f</sup>, E.L. HART <sup>g</sup>, K. HASEGAWA <sup>a</sup>, Y. HAYASHINO <sup>a</sup>, M. HIGUCHI <sup>m</sup>, D. HUANG <sup>l</sup>, H.Z. HUANG <sup>f</sup>, R. HULSIZER <sup>f</sup>, L. INTROZZI <sup>j</sup>, P.F. JACQUES <sup>d</sup>, M. KALELKAR <sup>d</sup>, V. KISTIAKOWSKY <sup>f</sup>, T. KITAGAKI <sup>a</sup>, E.L. KOLLER <sup>i</sup>, R.J. LEDOUX <sup>f</sup>, A. LEVY <sup>b</sup>, T. LUDLAM <sup>n</sup>, P. LUTZ <sup>e</sup>, C. MILSTENE <sup>f</sup>, J.L. NARJOUX <sup>c</sup>, S. NOGUCHI <sup>f</sup>, S.H. OH <sup>f</sup>, Y. OTANI <sup>a</sup>, R.J. PLANO <sup>d</sup>, I.A. PLESS <sup>f</sup>, S. RATTI <sup>j</sup>, A. RAFATIAN <sup>g</sup>, A.H. ROGERS <sup>g</sup>, M. SATO <sup>m</sup>, P.E. STAMER <sup>o</sup>, S.G. STEADMAN <sup>i</sup>, R. STEINER <sup>n</sup>, T.B. STOUGHTON <sup>f</sup>, V. SUCHOREBROW <sup>f</sup>, B. TAFT <sup>l</sup>, K. TAMAI <sup>a</sup>, S. TANAKA <sup>a</sup>, S. TETHER <sup>f</sup>, P.C. TREPAGNIER <sup>f</sup>, B.F. WADSWORTH <sup>f</sup>, M. WIDGOTT <sup>h</sup>, Y. WU <sup>f</sup>, A. YAMAGUCHI <sup>a</sup>, R.K. YAMAMOTO <sup>f</sup> and H. YUTA <sup>a</sup>

<sup>a</sup> Tohoku University, Sendai 980, Japan

<sup>b</sup> Tel Aviv University, 69978 Ramat-Aviv, Israel

<sup>c</sup> Indiana University, Bloomington, IN 47401, USA

<sup>d</sup> Rutgers University, New Brunswick, NJ 08903, USA

<sup>e</sup> Collège de France, F-75231 Paris Cedex 05, France

<sup>f</sup> Department of Physics and the Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

<sup>g</sup> University of Tennessee, Knoxville, TN 37016, USA

<sup>h</sup> Brown University, Providence, RI 02912, USA

<sup>i</sup> Stevens Institute of Technology, Hoboken, NJ 07030, USA

<sup>j</sup> University of Pavia and INFN, I-27100 Pavia, Italy

<sup>k</sup> Oak Ridge National Laboratory, Oak Ridge, TN 37830, USA

<sup>l</sup> Fermilab, Batavia, IL 60510, USA

<sup>m</sup> Tohoku Gakuin University, Tagajyo, Miyagi, Japan

<sup>n</sup> Yale University, New Haven, CT 06520, USA

<sup>o</sup> Seton Hall University, South Orange, NJ 07079, USA

Distributions of the leading positive particle have been measured in collisions of a 200 GeV/c proton beam with hydrogen, Mg, Ag and Au targets using the FNAL Hybrid Spectrometer. Estimates of the rapidity loss of the projectile have been obtained as a function of the target mass, the multiplicity of negative particles and the number of recoil protons. We obtained a lower limit of the rapidity loss of  $2.0 \pm 0.2$  for central p+Au collisions. The impact parameter dependence of the momenta of the first few leading particles has also been investigated with important implications to estimates of energy densities obtained in central collisions.

*1 Introduction.* There has been considerable progress in recent years in understanding the statistical properties of strongly interacting systems by means

of QCD lattice-gauge calculations [1]. One result, which has generated much interest, is the possibility of a phase transition from hadronic matter to a plasma of deconfined quarks and gluons at high temperatures and/or densities [1,2] (both energy and

<sup>l</sup> Deceased

baryon). Many authors have speculated that a quark-gluon plasma (QGP) may be formed and observed in high energy nucleus-nucleus (A+A) collisions. The advent of accelerators, at CERN and Brookhaven National Laboratory, which can now produce relativistic heavy ions with energies from 15 to 200 A GeV should make possible the study of nuclear matter at high baryon and energy densities [3,4].

There do not yet exist calculations of soft hadronic processes based on a fundamental theory such as QCD. The only estimates of the baryon and energy densities achievable in A+A collisions are based on phenomenological models which attempt to extrapolate from p+A to A+A collisions. Most of these models assume that the leading baryon is the main projectile fragment (i.e., carries the largest fraction of the beam momentum and the baryon number of the beam) and that there exists a correlation between the rapidity loss of the proton in p+A collisions and the baryon and energy densities that may be achieved in A+A collisions.

The data available on leading baryon distributions in p+A collisions are very incomplete [5-8], consisting primarily of proton distributions measured over restricted kinematic ranges, with no information on impact parameter. There exists an even more limited set of inclusive neutron distributions [9]. This incomplete body of data has led to an inability to differentiate between competing models for p+A collisions and thus to ambiguities in estimates of properties of A+A collisions.

This paper reports on the results of 200 GeV/c p+A measurements made using the Fermilab Hybrid Spectrometer [10]. The momenta of all charged particles can be measured and particle identification obtained for momenta less than 1.5 GeV/c. The rapidity distribution of the leading positive particle has been obtained as a function of the target mass (A), the multiplicity of produced particles and the number of slow protons ( $n_p$ ). It is shown that these distributions set limits on the rapidity loss of the proton in p+A collisions. The impact parameter dependence of the first few leading particles is also investigated, with important implications to estimates of energy densities obtained in central collisions.

**2. Experimental procedure.** The Fermilab Hybrid Spectrometer consists of a 30" hydrogen bubble

chamber in a 2 T magnetic field, followed by electronic tracking chambers. Two sets of Mg, Ag, and Au plates were placed just inside the bubble chamber entrance, with enough space available for a  $4\pi$  visual measurement of tracks. The tracking chambers provided improved momentum resolution for particles going forward in the center of mass. Particle identification was obtained from measurements of the ionization in the bubble chamber and enabled  $\pi$ -p separation for tracks with momenta  $< 1.5$  GeV/c.

The data reported in this paper consist of 312, 96, 237 and 180 events for the p, Mg, Ag, and Au targets, respectively. The total inelastic cross sections for the nuclear targets [10], uncorrected for possible scanning inefficiencies for low multiplicity events, are 0.36, 1.05 and 1.37 b for the Mg, Ag and Au targets, respectively.

**3. Results and analysis.** We begin by extracting the rapidity distributions of the leading positive particle as a function of target mass A, the negative particle multiplicity, and the quantity  $\bar{\nu}(n_p)$ . The A dependence can be expressed in terms of the variable  $\bar{\nu} = A(\sigma_{pp}^{\text{inel}}/\sigma_{pA}^{\text{inel}})$ , where  $\bar{\nu}$  is referred to as the "mean number of collisions" since its definition is consistent with taking the mean path length through the target nucleus divided by the p+p mean free path. To obtain an event-by-event measure of the impact parameter [11] we use the quantity  $\bar{\nu}(n_p) = C_A \sqrt{n_p}$ , where  $n_p$  is the number of observed protons with  $p < 1.5$  GeV/c (i.e., the target protons) and  $C_A$  is a constant chosen for each target such that  $\langle \bar{\nu}(n_p) \rangle = \bar{\nu}$  for that target. The values of  $C_A$  obtained from the present set of measurements are 1.8, 1.8, and 1.9 for the Mg, Ag, and Au targets, respectively. The average number of produced particles is linear with  $\bar{\nu}(n_p)$ , in agreement with previous data [11].

The leading positive particle rapidity distributions are shown in fig. 1a for the four targets, and are re-plotted in fig. 1b for cuts on  $\bar{\nu}(n_p)$ . The p+p distribution in fig. 1b was gated on total multiplicities  $\geq 3$  to compensate for the different scanning biases in the p+p and p+A data at low multiplicities. The exact gating regions are given in table 1. The uncertainty in rapidity is typically 0.1 units, which is much less than the bin size. In all the distributions the leading positive particle (i.e. highest momentum

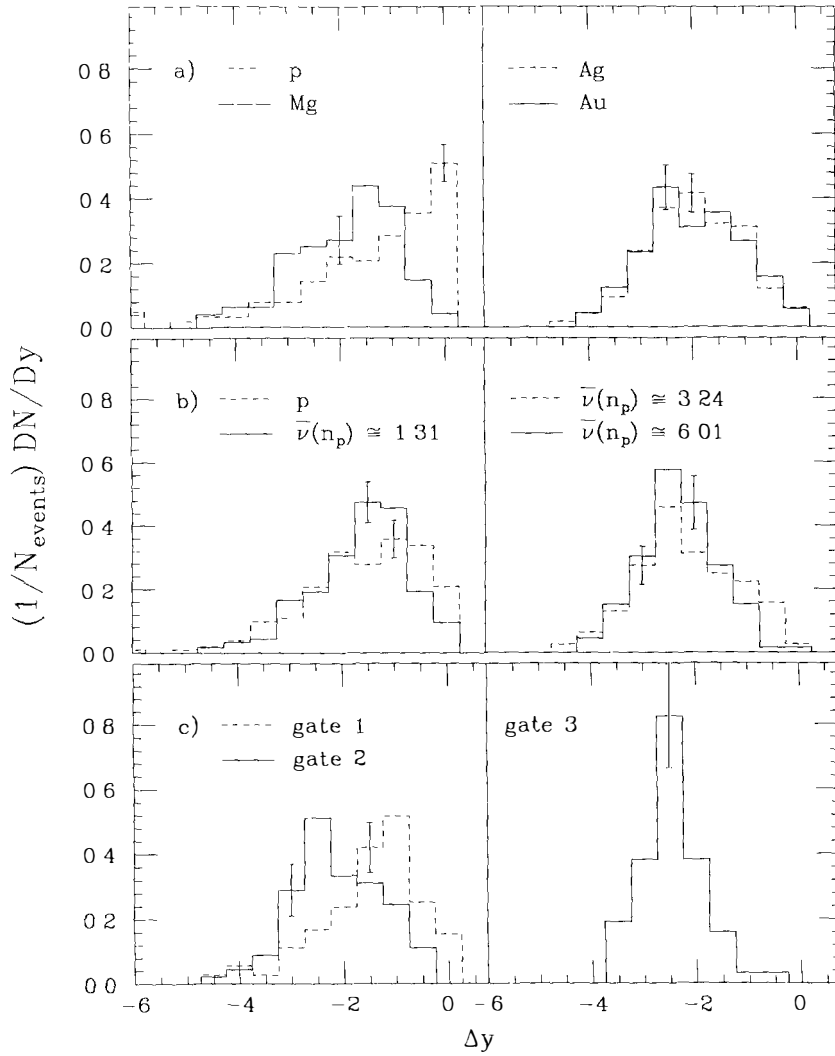


Fig. 1. Normalized rapidity loss distributions for the leading positive particle (a) p, Mg, Ag and Au targets (b) p target and nuclear targets gated on  $\bar{\nu}(n_p)$  (c) Nuclear targets gated on  $\bar{\nu}(n_p)$  and negative particle multiplicity. The leading positive particle is assigned the mass of a proton  $\Delta y \equiv y_{\text{beam}} - y_{\text{leading particle}}$ , where  $y_{\text{beam}} = 6.06$  for a 200 GeV/c proton beam. All distributions are normalized to unity. See table 1 for more information.

particle) was assigned the mass of the proton. Because of possible misidentifications, caution should be exercised in comparing these distributions with the results of inclusive distributions from spectrometer experiments [5–8] which identify the leading proton. It is shown below, however, that important limits can still be set on the *mean* rapidity loss of the incident proton.

Figs. 1a and 1b reveal that the distributions shift

to lower rapidities (i.e. larger rapidity losses) with increasing  $A$  and  $\bar{\nu}(n_p)$ . This effect is much more dramatic for higher cuts on  $\bar{\nu}(n_p)$ , since the averages over a target are dominated by peripheral collisions. Fig. 1c was generated by gating on both  $\bar{\nu}(n_p)$  and negative particle multiplicity. These gates (listed in table 1) were chosen to investigate whether the correlation of  $\bar{\nu}(n_p)$  and multiplicity better define the impact parameter. Fig. 1c shows that a cut on large

Table 1

Gating regions used in generating fig. 1. Also included are the measured  $\langle \bar{\nu}(n_p) \rangle$ ,  $\langle \text{negative particle multiplicity} \rangle$ , and mean rapidity shift ( $\Delta y = y_{\text{beam}} - y$ ,  $y_{\text{beam}} = 6.06$ ) of the leading positive particle.  $f^+$  is the ratio of the number of events in which the leading charged particle is positive to the total number of events.

Figure	Target	Events	$\bar{\nu}(n_p)$	Negative multiplicity	$\langle \bar{\nu}(n_p) \rangle$	$\langle \text{multiplicity} \rangle$ $\pi^+/\pi^-$	$f^+$	$\langle \Delta y \rangle$
1a	p	312	all	all	1.4	5.1/1.9	0.85	1.4
	Mg	96	all	all	2.0	12.1/5.1	0.74	1.8
	Ag	237	all	all	3.1	16.6/7.2	0.69	2.0
	Au	180	all	all	3.6	18.8/8.2	0.71	2.0
1b	p	201	all	total mult $\geq 3$	1.3	7.3/2.9	0.82	1.6
	plates	228	0-2.0	all	1.3	10.3/4.3	0.80	1.6
	plates	153	2.0-4.5	all	3.2	16.2/7.2	0.62	2.2
	plates	132	4.5-10.0	all	6.0	27.7/12.0	0.64	2.3
1c	plates	143	0-2.0	0-4	1.2	6.7/2.6	0.85	1.5
	plates	90	2.0-4.5	5-11	3.3	16.4/7.3	0.66	2.1
	plates	63	4.5-10.0	$\geq 12$	6.4	36.9/16.3	0.52	2.4

$\bar{\nu}(n_p)$  and high multiplicity better selects central collisions than a cut on  $\bar{\nu}(n_p)$  alone.

The mean rapidity shifts for different cuts on the data are listed in table 1. Mean rapidity shifts of approximately 2.4 units are obtained for events gated on large  $\bar{\nu}(n_p)$  and high multiplicities. However, before a lower limit can be set on the mean rapidity loss of the incident proton, corrections must be made for possible misidentifications in which the leading positive particle is not a proton.

If the leading particle is a  $\pi^+$  and the leading baryon is a proton, this leads to an underestimate of the rapidity loss of the leading baryon. Of greater concern for obtaining a lower limit of the rapidity loss in central p+A collisions is the misidentification of a  $\pi^+$  as a leading proton, for events in which the leading baryon is an unobserved neutron. The correction to our estimate depends on the fraction  $\alpha$  of the total events in which the leading baryon is a neutron. This fraction is likely to be a function of  $\bar{\nu}(n_p)$ , with estimates in the range between 0.25 and 0.5 for central collisions [8,12]. The uncertainty in the mean rapidity loss of the leading proton can be estimated from the expression

$$\langle y \rangle_{\text{Ipos}} = (1 - \alpha) \langle y \rangle_{\text{Iprot}} + \alpha \langle y \rangle_{\text{I}\pi^+}, \quad (1)$$

where  $\langle y \rangle_{\text{Ipos}}$  is the measured mean rapidity of the leading positive particle assuming it has the mass of

a proton. Here,  $\langle y \rangle_{\text{Iprot}}$  is the unknown mean rapidity of the leading proton, and  $\langle y \rangle_{\text{I}\pi^+}$  is the mean rapidity of a leading  $\pi^+$  which is misidentified as a leading proton for events in which a neutron is the leading baryon. An estimate of  $\langle y \rangle_{\text{I}\pi^+}$  can be obtained by gating on events in which the leading particle is positive and generating the second leading particle rapidity distribution assuming the mass of a proton for all charged particles. If the proton and neutron distributions are identical, then this distribution should be an accurate representation of the leading  $\pi^+$  distribution from events in which a neutron is the leading baryon. The value of  $\langle y \rangle_{\text{I}\pi^+}$  thus attained is  $3.3 \pm 0.3$  for central collisions. Solving (1) with  $\alpha = 0.5$ , which will result in a lower limit of the rapidity loss, yields  $\langle \Delta y \rangle_{\text{Iprot}} = 2.0 \pm 0.2$ .

These results can be compared to analyses of p+A  $\rightarrow$  p+X data. The Busza and Goldhaber [13] analysis of the data of Barton et al. [7] yields an extrapolated value of  $\langle \Delta y \rangle_{\text{central}} = 2.5 \pm 0.5$ . Other authors have analyzed the same data and obtained similar results [14]. Jezabek and Rozanska [12] have analyzed the data of Bailey et al. [8] in the context of the dual parton model and obtained  $\langle \Delta y \rangle_{\text{central}} \simeq 1.5$ . An intermediate value was obtained by Daté et al. [15], using the multi-chain model. The present set of data is inconsistent with the results of Jezabek and Rozanska [12].

A question remains as to where the energy lost by

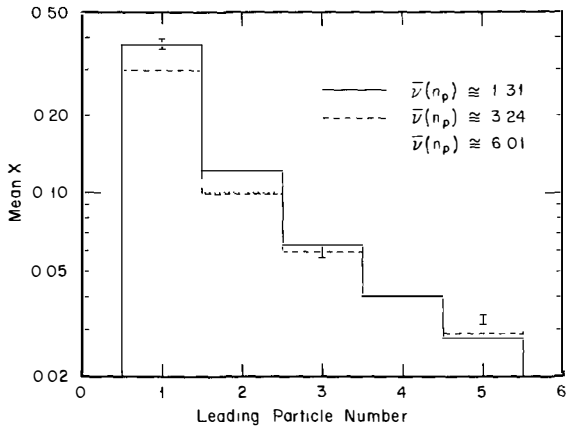


Fig 2 Mean momentum fraction  $x(\equiv p_{\text{lab}}/p_{\text{beam}})$  for the first five leading particles from nuclear target events gated on  $\bar{\nu}(n_p)$ . The gates are  $0 \leq \bar{\nu}(n_p) < 2$ ,  $2 \leq \bar{\nu}(n_p) < 4.5$ , and  $4.5 \leq \bar{\nu}(n_p) < 10$

the leading baryon goes. The exact nature of the rapidity distribution of produced particles is very important in estimating the maximum energy densities that may be achieved in A+A collisions. Of particular interest would be the correlation of the energy of the leading baryon and that of leading pions. Without particle identification for leading particles this comparison cannot be done. However, some important observations can be obtained by examining the energy contained in leading particles without regard to particle identification.

Fig. 2 displays the mean momentum fraction,  $x = P_{\text{total}}/P_{\text{beam}}$  (this is approximately Feynman  $x$ ) for the  $n$ th leading particles gated on  $\bar{\nu}(n_p)$ . The decrease in  $x$  of the first leading particle is consistent with the results shown in table 1 for  $\langle \Delta y \rangle$  of the leading positive particle. We emphasize that particles of both signs except for identified slow protons have been included in fig. 2.

The impact parameter dependence of the leading particle is stronger than that of the second leading particle. The  $\langle x \rangle$  for the third leading particle is 0.05 (10 GeV/c) and has no impact parameter dependence within the present statistics. The  $\langle x \rangle$  for the 4th and 5th particles appears to be increasing with  $\bar{\nu}(n_p)$ . Approximately 35% of the total beam energy is observed in charged particles with  $x > 0.05$  in central collisions. These results suggest that even in central collisions there is a significant amount of energy possessed by the three leading charged particles. This

energy is not likely to be available for producing local regions of high energy density and may in fact represent the fragments of the incident proton.

The present set of data is consistent with a picture in which the incident proton suffers a rapidity loss of approximately 2 units in central p+A collisions. Using simple hydrodynamical arguments and assuming that  $\Delta y$  is energy independent [2,13,15,16] this result suggests that maximum baryon densities of approximately 7 times that of ground state nuclear matter may be achieved in 30 A GeV fixed target of 4 A GeV collider A+A collisions. The above results also suggest that it may be more difficult to estimate energy densities directly from the rapidity loss of the beam, since 35% of the total energy is accounted for in just 3 fast particles in central p+A collisions. The inclusion of neutral particles would presumably increase this fraction further. Therefore, it will be necessary to make detailed measurements of the energy distribution of produced particles before reliable estimates of energy densities in p+A and A+A collisions can be made.

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