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STUDY OF THE A-DEPENDENCE OF INCLUSIVE p , $\bar{p}$, Λ AND $\bar{\Lambda}$ PRODUCTION

IN π^+ -NUCLEUS INTERACTIONS AT 30 GeV/c

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ABSTRACT

We present the first results on the production of fast ($p > 10$ GeV/c) p , $\bar{p}$, Λ and $\bar{\Lambda}$ from π^+ hydrogen and nucleus interactions at 30 GeV/c using the CERN Ω' spectrometer. We have used five nuclear targets (C, Al, Cu, Sn, Pb) to study the A-dependence of the inclusive particle distributions in the region $0.3 < x_F < 0.6$. The high statistical level of our experiment allows us to demonstrate the different A-behaviour of baryon and anti-baryon inclusive reactions. We relate this difference to the final state interaction inside a nucleus using the formation-zone model.

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1. INTRODUCTION

It is generally agreed that high energy hadron-nucleus interactions offer a unique possibility to investigate an early state of the hadron-production process [1], which is not yet well understood. More specifically, the inclusive spectra of the fast particles produced in hadron-nucleus interactions are expected to yield information on the quark fragmentation and recombination process [2].

Results from e^+e^- annihilation [3] and deep inelastic μ -p scattering [4] indicate that baryon production plays an important role in the quark fragmentation and should be included in any realistic description of the fragmentation process. In hadron-nucleus interactions however the study of proton production is limited, at present, to the low momentum region ($p \lesssim 5$ GeV/c), where their number is related directly to the number of intranuclear collisions [5]. Very little is known on the fast proton and antiproton spectra, in particular in pion-nucleus interactions where the projectile does not carry baryon number.

We present data on inclusive p , $\bar{p}$, Λ and $\bar{\Lambda}$ production by 30 GeV/c π^+ and π^- on hydrogen and on five nuclear targets (C, Al, Cu, Sn, Pb). The preliminary results of this experiment, but without the hydrogen data, were already presented elsewhere [6]. The high statistical level of our experiment allows us to demonstrate the difference in A-behaviour of baryon and antibaryon inclusive reactions. We relate this difference to the final state interaction inside a nucleus using the formation-zone (FZ) model [7].

2. THE APPARATUS

The experiment was performed during a 10-day run using the Ω' spectrometer installed in the West Hall at CERN [8]. The experimental layout is shown in fig. 1.

A set of 15 forward proportional chambers inside the 1.7 T magnetic field and two "lever arm" drift chambers measured the charged particle momenta. The two large multicell threshold Cherenkov counters C1 and C2, placed downstream the magnet, were used for particle identification. Their

thresholds for π , K and p were 2.8, 9.8 and 18.3 GeV/c and 5.0, 17.8 and 33.9 GeV/c for C1 and C2 respectively. The hodoscopes H1, H2, and H3 were composed of vertical slabs giving logical channels of 6, 9 and 20 cm width.

The trigger used for the proton/antiproton production study accepted events with at least one fast ($p > 10$ GeV/c) particle giving no light in the corresponding cells of C1 and C2. The above trigger condition was made possible by the momentum-position correlation, produced by the magnetic field, and by selecting the wanted hodoscope and Cherenkov (H1C1H2C2H3) patterns with the MBNIM system [9]. The charged particle multiplicity was measured on-line by a 24 element cylindrical barrel counter surrounding the target and by a 500 μm -pitch MWPC closing the downstream end of the barrel counter.

The multiplicity condition $n \geq 2$ was only partially used in the trigger condition but it was applied systematically in the off-line analysis.

The incident particles in the positive or negative beam (S1 beam of intensity $\sim 10^6/\text{burst}$) were identified by a threshold and a differential Cherenkov counter.

The beam particle position and angle was measured in a set of four proportional chambers placed upstream of the target. The targets were placed consecutively in the same position. Table 1 gives thickness of the nuclear targets. The hydrogen target was 60 cm long corresponding to about 10% of an interaction length.

3. DATA PROCESSING

About 4×10^6 events recorded under various combinations of beam, target and trigger conditions were analyzed by the TRIDENT reconstruction program [10]. Only events with a main vertex found within the target region and with at least one secondary track satisfying the trigger conditions were selected for further analysis (50% reduction factor). After applying different cuts to avoid ambiguities in particle identification and large acceptance or efficiency corrections we were left with a

final sample of 8×10^5 events having a proton or an antiproton in the x-Feynman region $0.3 < x_F < 0.6$ and with transverse momentum $p_T > 0.2$ GeV/c, accompanied by at least one additional charged particle leaving the target.

The inclusive particle production cross sections have been corrected for geometric and trigger acceptance. These corrections are important only at the ends of the investigated kinematical region. Since the different nuclear targets have negligible thickness, the acceptance has essentially no A dependence. Another correction (typically 5%) was applied to account for the background and secondary interactions. Also a small correction accounting for the trigger multiplicity cut (ranging from 3 to 5%) was included. Other global corrections coming from particle absorption in the spectrometer (0.885 for protons and 0.839 for anti-protons) and from hodoscope efficiency (0.898) are not important for the A-dependence study. We believe that relative errors corresponding to different targets are only statistical. The overall normalization is estimated to be correct within 20%.

4. EXPERIMENTAL RESULTS

4.1 Cross sections

This paper is devoted to the A-dependence study, and the detailed inclusive distributions will be discussed in a separate publication. Nevertheless, in order to fix a scale of different cross sections, we show in fig. 2 the inclusive p and $\bar{p}$ production cross sections for $x_F = 0.5$ ($x_F = p^*/p_{\max}^*$) obtained using our data from the x_F region 0.48-0.52. The presented cross sections are integrated over the transverse momentum, i.e.

$$\sigma_{\text{incl}}(x_F) = \frac{1}{p_{\max}^*} \int_0^\infty E^* \frac{d^3\sigma}{dx_F dp_T^2} dp_T^2 \approx x_F \frac{d\sigma}{dx_F}, \quad (1)$$

where an asterisk indicates quantities measured in the πp centre-of-mass system. The straight solid lines in fig. 2 represent a power law (A^α) fit to the nuclear data. The broken lines are model predictions normalized to the hydrogen cross sections as discussed in sect. 5.

We make the following observations:

(a) Proton production is larger than antiproton production for both beam signs. The ratio $p/\bar{p}$ is about 7.5 for π^+ beam and 1.7 for π^- beam.

(b) The fast protons are produced more abundantly in π^+ than in π^- interactions and the inverse is true for the antiprotons, i.e.

$$\sigma_{\text{incl}}(\pi^+ \rightarrow p) > \sigma_{\text{incl}}(\pi^- \rightarrow p) \text{ and}$$

$$\sigma_{\text{incl}}(\pi^- \rightarrow \bar{p}) > \sigma_{\text{incl}}(\pi^+ \rightarrow \bar{p})$$

(c) The hydrogen cross sections are about a factor 2 below the extrapolated values using the A^α fit obtained for nuclei.

(d) The proton/antiproton production ratio increases slowly as $A^{0.04 \pm 0.01}$.

All the discussed cross sections together with the hydrogen cross sections at 100 GeV/c [11] are given in table 2. One can see that the cross section ratios $\sigma_{\text{incl}}(\pi^+ \rightarrow p)/\sigma_{\text{incl}}(\pi^- \rightarrow p)$ and $\sigma_{\text{incl}}(\pi^+ \rightarrow \bar{p})/\sigma_{\text{incl}}(\pi^- \rightarrow \bar{p})$ for hydrogen are practically the same at 30 GeV/c and 100 GeV/c. However, for each beam charge the $p/\bar{p}$ ratio is about twice larger at lower energy. This is probably due to the energy dependent contribution of target valence quarks in the quark recombination process. As it was stated already this $p/\bar{p}$ ratio increases slowly with the mass number A.

4.2 A-dependence of the cross sections as a function of x_F and p_T^2

As mentioned above, the A-dependence of the inclusive cross sections at $x_F = 0.5$ is stronger for protons than for antiprotons. This feature persists at all other x_F values, what is shown in fig. 3. We note a decrease of α with x_F , more marked for p than $\bar{p}$; above $x_F = 0.45$ the data are consistent with constant α . In the same figure we present also the A-dependence obtained from a fit to the inclusive Λ ($\bar{\Lambda}$) production cross sections on five nuclear targets. The decaying Λ ($\bar{\Lambda}$) were accepted by our fast proton trigger. We have not corrected the Λ ($\bar{\Lambda}$) data for the trigger acceptance but it has no importance for the A^α fit for fixed x_F bins. As in the case of p ($\bar{p}$) we observe no significant dependence of $\alpha(x_F)$ on the incident pion sign, and the α values are larger for baryon (Λ) than antibaryon ($\bar{\Lambda}$).

Our statistics allows us to detect a dependence of α on the nature of the produced particle. This finding is in disagreement with a previous claim of α universality [12]. It is interesting to note, that also in the case of proton induced reactions, strange particles (at 400 GeV/c) and antiprotons (at 24 GeV/c) do not obey the α -universality [12]. For comparison we show also in fig. 3 results obtained for $\pi^+ + A \rightarrow p + X$ inclusive reaction at 100 GeV/c [12] (at fixed $p_T = 0.3$ GeV/c), which are consistent with our α values.

Finally, we present in fig. 4 the parameter α as a function of p_T^2 after the integration over our x_F range (0.3-0.6). There is no strong p_T dependence. The proton-antiproton difference is again evident and possibly increasing with p_T .

5. FORMATION ZONE MODEL

The difference between α_p and $\alpha_{\bar{p}}$ may be explained in a natural way by the formation zone (FZ) approach [7]. In this model the particle production in meson-nucleus interaction is considered as a three-step process:

- (a) One of the constituent quarks of the meson interacts (non diffractively) with a single nucleon of the target, giving rise to hadrons in the central region of the rapidity interval.
- (b) The other constituent, the spectator, propagates through nuclear matter where it may, in turn, interact; otherwise it will fragment into predominantly fast hadrons after passing a mean distance λ called "formation length". This length is assumed to grow linearly with the momentum of the observed hadron [13].
- (c) The produced hadrons can still interact with the target nucleons if their formation has taken place inside the nucleus and influence an observed A-dependence.

In this picture the observed A dependences of the fast hadron yields are determined by the quark-nucleon, hadron-nucleon cross sections and by the formation length. The x_F region measured in our experiment corresponds to particle momenta 11-19 GeV/c, where the p and $\bar{p}$ non-diffractive cross sections are 23 mb and 32 mb respectively. These cross sections are found

assuming that the diffractive cross sections are equal to elastic ones, i.e. $\sigma_{nd} = \sigma_{tot} - 2 \sigma_{el}$. The quark cross sections have been estimated using the non-diffractive $\pi^\pm p$ and pp cross sections and applying the additivity assumption. The values of the quark cross sections are: $\sigma_u^- \approx \sigma_d^- = 9.4$ mb, $\sigma_u = \sigma_d = 7.7$ mb.

In [7] only nuclear cross sections were used; now we can perform a more severe test of the FZ model using also our measured hydrogen cross sections.

The final formula of the FZ model reads

$$d\sigma_A = d\sigma_H \cdot A \cdot \int d^2b dz \rho(\vec{b}, z) \{1 - P_i(\vec{b}, z) - P_f(\vec{b}, z)\}^{A-1}, \quad (2)$$

where $d\sigma_H$ is the corresponding inclusive cross section on hydrogen, P_i is the probability of initial state absorption before the production point $(\vec{b}, z)$ and P_f is the probability of final state absorption. This final state is a mixture of quark and hadron states governed by an exponential quark "decay" law with mean decay length λ .

Having fixed all cross section values we are left only with one free parameter λ . We determine it by fitting the cross section ratio $\sigma(\pi^- + Pb \rightarrow \bar{p} + X) / \sigma(\pi^- + C \rightarrow \bar{p} + X)$ and we get $\lambda = 22_{-6}^{+8}$ fm.

As can be seen in fig. 2 the model reproduces correctly all the nuclear cross sections, at given x_F , using only as input the hydrogen cross section and the mean formation length λ . Moreover with the same λ value the model describes well the other channels $\pi^+ \rightarrow \bar{p}$, $\pi^+ \rightarrow p$ and $\pi^- \rightarrow p$.

Since the errors in fig. 2 are mainly statistical and a small systematic error ($\leq 5\%$) between hydrogen and nuclear cross sections cannot be excluded, we can conclude that the agreement between the FZ model and the data is very good. We note that the FZ model predicts a slight difference from the phenomenological power law A^α , which is however a good approximation within the investigated nuclei range.

The other version of the FZ model, in which the intermediate state is defined as an excited π (and assuming $\sigma_{\pi^*} = \sigma_{\pi}$), does not fit our data, even for very large λ values. The A-dependence in this case (dotted-broken line in fig. 2) is too weak.

We have limited our analysis to $x_F = 0.5$, where according to the AQM model [14] the particle spectra are dominated by the spectator quark contribution. In consequence, the AQM predicts flattening of the $\alpha(x_F)$ dependence near $x_F = 0.5$, which is consistent with our data. At lower x_F values one could get higher formation length values in contradiction with the FZ model expectation that λ should be proportional to the hadron momentum; approaching the central region however we increase the contribution from the wounded quark, which is assumed not to participate in the fast hadron production. At higher x_F values the model predicts an increase of λ ; our statistics does not allow us to detect such an increase. It would be of interest to repeat our measurements at higher energy (≥ 150 GeV/c), where according to the FZ model the $\alpha_p - \alpha_{\bar{p}}$ difference should disappear.

6. CONCLUSIONS

We have performed a high precision study of p and $\bar{p}$ inclusive production by $\pi^\pm$ meson beam on nuclei and hydrogen at 30 GeV/c in the 0.3-0.6 x_F range.

We observe important differences between proton and antiproton inclusive cross sections. This is in contradiction with the simple picture of the spectator quark fragmenting independently on the nearby hadronic matter. This picture would in fact predict symmetry between the processes: $\pi^+ \rightarrow p$, $\pi^- \rightarrow \bar{p}$ and $\pi^+ \rightarrow \bar{p}$, $\pi^- \rightarrow p$.

The observed excess of protons seems to indicate that quark recombination processes, or in an "old language" baryon exchange processes [15] cannot be neglected at this energy. The weak dependence of the p/ $\bar{p}$ ratio with A suggests that the nuclear medium does not influence significantly this recombination process.

We found that at a fixed x_F -value, the inclusive cross sections for p , $\bar{p}$, Λ and $\bar{\Lambda}$ follow the A^α law. Our statistics allow us to detect a "fine structure" of the exponent α for the produced baryons. We observe that, independently of the beam charge, one has:

$$\alpha(\bar{\Lambda}) \approx \alpha(\bar{p}) < \alpha(p) < \alpha(\Lambda)$$

while the total cross sections for $\bar{p}$, p and Λ interactions on nucleons follow the reverse order. This hints to a final state absorption effect and has motivated us to attempt a determination of the hadronic formation length from the observed A -dependence. From the $\bar{p}$ data we determine a formation length of 22 fm at $x_F = 0.5$. Using this value as an input we can describe correctly also the inclusive production of protons.

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TABLE CAPTIONS

Table 1 Nuclear targets used in this experiment.

Table 2 Inclusive cross sections for p ($\bar{p}$) production at $x_F = 0.5$
given in mb.

PHYSICAL REVIEW

REVIEW OF THE PHYSICAL PROPERTIES OF THE NUCLEI

TABLE 1

Properties of the targets used in the experiment

Target A	C	Al	Cu	Sn	Pb1	Pb2
	12.0	27.0	63.5	118.7	207.2	207.2
Thickness [cm]	1.00	0.814	0.294	0.194	0.103	0.208
l/λ_{int} [%]	3.1	3.1	3.1	1.4	1.0	2.1

TABLE 2

Target Reaction	H, 100 GeV/c [11]	H	C	Al	Cu	Sn	Pb
		This experiment					
$\pi^+ \rightarrow p$	0.46 ± 0.03	0.691 ± 0.008	4.82 ± 0.06	8.57 ± 0.12	14.1 ± 0.2	20.2 ± 0.3	27.3 ± 0.4
$\pi^+ \rightarrow \bar{p}$	$0.14^{(a)}$	0.090 ± 0.003	0.700 ± 0.26	1.20 ± 0.05	1.89 ± 0.08	2.43 ± 0.12	3.90 ± 0.18
$\pi^- \rightarrow p$	$0.23^{(a)}$	0.328 ± 0.008	2.51 ± 0.04	4.29 ± 0.09	7.58 ± 0.14	10.6 ± 0.2	13.9 ± 0.3
$\pi^- \rightarrow \bar{p}$	0.27 ± 0.02	0.229 ± 0.006	1.67 ± 0.04	2.71 ± 0.07	4.09 ± 0.11	6.21 ± 0.17	8.24 ± 0.26

(a) Our estimate from the points given for $E \frac{d^3\sigma}{dp^3}$ in [11].

FIGURE CAPTIONS

- Fig. 1 Experimental layout of the Omega Prime Spectrometer.
- Fig. 2 Inclusive cross sections at $x_F = 0.5$ for p ($\bar{p}$) production on hydrogen and on 5 nuclear targets. The solid lines are A^α fits to the nuclear cross sections. The broken lines are the formation zone model predictions (see text) based on hydrogen cross sections and with the formation zone length fixed to $\tau = 22$ fm. The statistical errors are contained within the cercles.
- Fig. 3 α -values as a function of x_F , obtained from a fit of the inclusive p , $\bar{p}$, Λ and $\bar{\Lambda}$ production cross sections to the A^α power law.
- Fig. 4 α -values as a function of p_T^2 , obtained from a fit of the inclusive p , $\bar{p}$, Λ and $\bar{\Lambda}$ production cross sections to the A^α power law.

Fig. 1

Fig. 2

Fig. 3

Fig. 4