Precision measurements of inclusive hadron production in pp and pC interactions at the CERN SPS

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In the framework of a general study of hadron production in elementary and nuclear interactions at the CERN SPS the NA49 experiment has produced new and complete sets of inclusive meson and baryon cross sections in p+p and p+C interactions. This work is aimed at providing precision data over most of the available phase space with a special emphasis on completeness, internal consistency and on the comparison to a wide range of existing experimental results. The corresponding physics analysis allows for a model-independent study of soft hadronic production with a view to a critical assessment of the applicability of the current approaches to the non-perturbative sector of QCD. In this context the precision study of p+A interactions opens a new access to the scrutiny and understanding of multiple hadronic collisions concerning specifically detailed nuclear and isospin effects including strangeness. In addition these data may serve as a reference for neutrino and astro-particle physics.

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1. Introduction

In the absence of quantitative predictions in the non-perturbative sector of QCD, the study of soft hadronic physics has to rely on self-consistent high statistics data sets, including a variety of projectile and target combinations. In addition full phase space coverage with complete particle identification and small systematic uncertainty are required.

The NA49 experiment aims at providing such data sets ranging from elementary hadron-proton collisions to hadron-nucleus and nucleus-nucleus interactions, obtained using the same detector layout combining wide acceptance, systematic uncertainty of less than 3% and complete particle identification via measurement of specific energy loss. It is therefore well suited for the comparison of the different processes and to a detailed scrutiny of the evolution from elementary to nuclear hadronic phenomena and thus providing a basis for a model independent study of the underlying production mechanisms.

In the framework of this extensive experimental program the NA49 experiment has already published papers concerning pion [1], baryon [2] and kaon [3] production in p+p collisions, and pion and baryon production [4, 5, 6, 7] in p+C collisions. In this paper the study of baryon production and new results of kaon production in p+C collisions will be discussed.

2. Data sets

The data sets obtained by the NA49 experiment at the CERN SPS at 158 GeV/c beam momentum are summarized in Fig. 1.

<table>
<thead>
<tr>
<th>hadron-proton</th>
<th>hadron-nucleus</th>
<th>nucleus-nucleus</th>
</tr>
</thead>
<tbody>
<tr>
<td>p + p</td>
<td>d + p</td>
<td>Pb + Pb</td>
</tr>
<tr>
<td>n + p</td>
<td>p + C</td>
<td></td>
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<tr>
<td>π⁺ + p</td>
<td>π⁻ + Pb</td>
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<tr>
<td>π⁻ + p</td>
<td>π⁺ + Pb</td>
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</tbody>
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Table 1: The data sets obtained by the NA49 experiment at 158 GeV/c beam momentum

3. Variables and cross section definition

The NA49 experiment establishes the invariant double differential cross sections

\[
 f(x_F, p_T) = E(x_F, p_T) \cdot \frac{d^3 \sigma}{dp_T^3}(x_F, p_T). \quad (3.1)
\]

Here \( p_T \) is the transverse momentum and \( x_F \) is the reduced longitudinal momentum:

\[
 x_F = \frac{p_L}{\sqrt{s}/2} \quad (3.2)
\]
where $p_L$ denotes the longitudinal momentum component in the center-of-mass system (cms). For the neutrons, due to the lack of transversal granularity of the NA49 calorimeter, only $p_T$-integrated density distributions:

$$dn/dx_F = \pi/\sigma_{\text{inel}} \cdot \sqrt{s}/2 \cdot \int f/E \cdot dp_T^2$$

will be presented, with $\sigma_{\text{inel}}$ being the total inelastic cross section.

4. Baryon production

4.1 Double differential and $p_T$ integrated distributions

Double differential inclusive cross sections of protons and anti-protons have been derived in both p+p [2] and p+C [6] interactions. The results feature wide phase space coverage, from -0.8 to 0.95 in $x_F$ and from 0 to 1.9 GeV/c in $p_T$ for protons and from 0.2 to 0.4 in $x_F$ and from 0 to 1.5 GeV/c in $p_T$ for anti-protons, and systematic errors of 4% or less. An example of proton $x_F$ distributions in p+C collisions is shown in Fig. 1. Existing data [8], which are complementary to the NA49 measurements in the far backward hemisphere were used to extend the coverage into the region of intra-nuclear cascading, see [6]. The corresponding $x_F$ distributions cover the phase

![Figure 1: Invariant cross sections at fixed $p_T$ as a function of $x_F$ for protons in p+C collisions at 158 GeV/c beam momentum. Full circles: NA49 data, open circles: data from [8]. The thin lines show the cross section at fixed angles of 10°, 30° and 50°](image-url)
space from \(x_F = -2\) up to the kinematic limit at \(x_F \sim +1\). Both the NA49 data (full circles) and [8] (open circles) are plotted.

The \(p_T\) integrated density distribution \(dn/dx_F\) for neutrons are also available from NA49 experiment for both p+p and p+C interactions [2, 6]. They are presented in Fig. 2 together with the \(p_T\) integrated densities for protons and anti-protons.

\[\text{Figure 2: The } p_T \text{ integrated density distribution } dn/dx_F \text{ for protons, anti-protons and neutrons as a function of } x_F \text{ in a) p+p collisions and b) p+C collisions. In panel a) the results for protons and anti-protons at positive } x_F \text{ are reflected into negative } x_F.\]

\[\text{4.2 Three component mechanism}\]

The final state of p+A collisions consists of three basic components:

- The fragmentation of the projectile particle
- The fragmentation of the target nucleons
- The intra-nuclear cascading, generated by the interaction of the participating nucleons and secondary produced hadrons inside the nucleus.

The separation and extraction of these three components can be done relying only on the experimental data. To achieve this one can define "net" baryon production which is the difference between the total yield and the pair produced baryons of the same type. In the case of protons, the pair produced protons can be extracted from measured anti-proton yields taking into account the isospin symmetry. Then the overlap function between target and projectile fragmentation of "net" protons, which obeys baryon number conservation, can be extracted by fixing a baryon at large \(|x_F|\) and studying the correlation function \(\rho^c\). The ratio of correlated and inclusive cross sections \(\rho^c/\rho^{incl}\) for forward and backward selection of baryons in p+p collisions is shown in Fig. 3. In the two cases this ratio equals to 0.5 at \(x_F = 0\) and reaches values of 0 or 1 at \(x_F\) of about 0.2.

A similar extraction can be performed also in p+C collisions, see [6]. As in p+C collisions there is a third component, namely the nuclear cascading, an assumption about the target component has to be made. The target component can be predicted from p+p interaction by forming...
Precision measurements of inclusive hadron production ...

Figure 3: $p_T$ integrated and $p_F$ averaged constrained net proton density ratios $F_p^{\text{net}}$ as a function of $x_F$, a) for forward net proton selection and b) for backward net proton selection. The full lines shown represent the overlap functions and arrows indicate the $x_F$ of the tagging baryon.

The isospin average between net neutron and net proton densities and multiplying this average by the mean number of collisions $\langle v \rangle$ in p+C interactions. $\langle v \rangle$ is measured to be 1.6, [5]. With this assumption for the target fragmentation one can extract the three independent components in p+C collisions as shown in Fig. 4b. In Fig. 4a the result in p+p collisions is presented.

Figure 4: The independent components for net protons in a) p+p and b) p+C collisions.

5. Meson production

5.1 Double differential distributions

Inclusive meson cross section have already been published by the NA49 experiment – pions in p+p [1] and p+C [1] collisions and kaons in p+p [3]. New results on kaon production as a function of $x_F$ in p+C collisions are presented in Fig. 5. The data cover a wide kinematic range from -0.4 to 0.4 in $x_F$ and from 0 to 1.5 GeV/c in $p_T$. 
5.2 Particle ratio

Using the above results one can form $\pi^+/\pi^-$ and $K^+/K^-$ ratios. They are shown in Fig. 7, where results from [7] and measurements from Fermilab in p+p [9] and p+Ta [10] interactions are used to extend the $x_F$ range.

A distinctive difference in the behaviour of pion and kaon ratios in the target hemisphere in p+A collisions is observed. While the $\pi^+/\pi^-$ ratio is close to 1, the $K^+/K^-$ ratio reaches values of
more than 20 and reproduces the ratio found in p+p interactions. This striking difference is due to the different production mechanism of pions and kaons.

This observation has an important consequence for the interpretation of $K^+/\pi^+$ ratios when passing from p+p to p+A interactions. An example of $K^+/\pi^+$ ratios as a function of $x_F$ at $p_T = 0.3$ GeV/c in p+p and p+C collisions is shown in Fig. 7. Here the increase of the ratio at negative $x_F$ in p+C collisions can be wrongly interpreted as "strangeness enhancement", while it is entirely due to the isospin effect.

![Figure 7: Ratio $K^+/\pi^+$ as function of $x_F$ at $p_T = 0.3$ GeV/c in p+p and p+C collisions](image)

6. Conclusions

New results from NA49 experiment on inclusive production of mesons and baryon in p+p and p+C collisions at 158 GeV/c beam momentum are presented. The three independent components of hadronization in p+C collisions are extracted experimentally. The importance of isospin effects for the interpretation of the $K^+/\pi^+$ ratio when passing from p+p to p+A interactions is demonstrated.

References