Coherent inelastic interactions of $\pi^+$ and $K^+$-mesons on Al and Au nuclei at 250 GeV/c

EHS-NA22 Collaboration


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Abstract. Cross-sections are obtained for coherent interactions of $\pi^+$ and $K^+$-mesons with Al and Au nuclei at 250 GeV/c, leading to three, five and seven charged mesons. The total coherent cross-section is $(4.3 \pm 0.5)\%$ of the inelastic cross-section for each of the four meson-nucleus interactions. In $85\%$ of the coherent events, the charged meson production is accompanied by neutral mesons. Effective mass distributions are presented for coherently produced particles, including charged mesons and photons, carrying total measured energy of more than $85\%$ of the initial energy. Charged particle and $\pi^0$ spectra are analysed. No charge asymmetry is observed within the coherently produced cluster.

1 Introduction

The process of inelastic diffractive dissociation of high energy hadrons is a significant part of the inelastic hadron-nucleon and hadron-nucleus cross sections. If the momentum transfer to the target is small, coherent scattering of the hadron wave can take place on a nuclear target. In this kind of interaction, the nucleus is not destroyed but conserved as a whole.

The condition for coherent interaction is:

$$q R < l \quad (1)$$

where $q$ is the momentum transfer to the target, $R$ is the radius of the target (nucleon or nucleus) and $l$ is a limit of order unity to be defined in Sect. 3 below. For scattering at zero angle, the coherence condition reduces to:

$$q || R < l \quad (2)$$

where $q ||$ is the longitudinal component of the momentum transfer $q$.

In studies of diffractive and coherent processes, both on nucleons and on nuclei, the problem of extraction of non-coherent background is essential.

Coherent production of $(3\pi)$-systems in $\pi$-meson collisions with different nuclei has been studied in detail with electronic detectors [1-5] over the momentum range 9-200 GeV/c. The differential $(3\pi)$-production cross-section is well reproduced by the optical model where the coherent contribution dominates.

Total coherent diffraction cross sections of hadrons on nuclei are measured in [6-8] in nuclear emulsion over the momentum range 16-400 GeV/c. Theoretical predictions [9, 10] agree with the experimental data. The values expected for the total inelastic coherent cross section of $\pi$-meson interactions with Al and Au nuclei at 250 GeV/c are 17 mb and 100 mb, respectively.

A measurement of coherent scattering of $\pi$-mesons in the Coulomb field of the nucleus at momenta of 156 and 260 GeV/c is reported in [11]. This process takes place at four-momenta squared $t < 0.005$ (GeV/c)$^2$ and does not exceed 1 mb for Pb. It is, therefore, negligible compared to the value of the inelastic cross section, but contributes of the order of 1% to the coherent cross section on heavy nuclei. A review of results on coherent interactions at lower energies can be found in [12].
incident mesons and protons at Feynman $x_F > 0.5$, where a difference in $A$-dependence has been observed for meson and proton beams [13].

The paper is organized as follows. Section 2 briefly describes the experiment. The method of separation of coherent interactions and the estimate for the coherent cross sections are presented in Sect. 3. The $A$-dependence of the coherent cross sections and effective mass distributions in coherent events are discussed in Sect. 4. Particle distributions for coherent events are presented in Sect. 5. The main results are summarized in Sect. 6.

2 The experiment

The experiment has been carried out by the NA22 Collaboration with the European Hybrid Spectrometer in a positive meson-enriched beam from the CERN SPS accelerator at an energy of 250 GeV [14, 15]. The Al and Au foils with thickness of 0.5% of an interaction length, were placed in the liquid hydrogen bubble chamber RCBC at a distance of 15.5 cm from the entrance window. The experimental conditions were identical for both targets.

The scanning and measuring of tracks on film permitted the registration of slow particles and the identification of protons with laboratory momentum $p_{lab} < 1.2$ GeV/c and electrons and positrons with $p_{lab} < 200$ MeV/c. In the analysis of $K^+$-interactions, particles of positive charge and momentum $p_{lab} > 120$ GeV/c are given the kaon mass. All other charged particles are given the pion mass.

A total of more than 8000 interactions in foils have been measured and reconstructed, where 6000 are $\pi^+$ and 2000 are $K^+$ interactions.

The measurement error on the momentum of fast charged particles $(\Delta p/p)$ varies from a maximum value of 2.5% at 30 GeV/c to 1.5% for tracks of particles with momentum larger than 100 GeV/c.

The trigger efficiency for events with all charged particles at $x_F < 0.8$ is 100%. This gives practically 100% efficiency for the coherent events on nuclear targets with 3 or more charged particles.

Photons are measured by two $\gamma$-detectors [16]. To correct for photon losses, weights are applied as defined in [17].

The events used in this analysis satisfy the following conditions:
1) absence of any sign of excitation or destruction of the nucleus;
2) narrow collimation of the particles in the forward cone;
3) conservation of the quantum numbers of the initial hadron in the produced system of particles (charge, strangeness, G-parity).

Coherent interactions can be observed in the following reactions:

$$\pi^+ A \rightarrow \pi^+ \pi^0 \pi^0 A$$

$$\rightarrow \pi^+ \pi^+ \pi^- A$$

$$\rightarrow \pi^+ \pi^+ \pi^+ \pi^- A$$

$$\rightarrow \pi^+ \pi^+ \pi^- \pi^0 \pi^0 A$$

etc.

$$K^+ A \rightarrow K^+ \pi^+ \pi^- A$$

$$\rightarrow K^0 \pi^+ \pi^0 A$$

$$\rightarrow K^+ \pi^+ \pi^+ \pi^- \pi^- A$$

$$\rightarrow K^0 \pi^+ \pi^+ \pi^- \pi^0 A$$

$$\rightarrow K^+ \pi^+ \pi^- \pi^0 \pi^0 A$$

etc.

Therefore, the coherent events have odd charged particle multiplicity. In this experiment, one-prong interactions on the nuclear targets are not measured and the reactions (3) and (8) are not studied.

In Fig. 1, the charged particle multiplicity $n$ distributions are shown for $\pi^+ A$ and $K^+ A$ interactions. For $n = 3$ an excess of events is seen with respect to $n = 4$, in particular for the Au target.

The coherence condition (2) is used for the selection of coherent events. As the nucleus is not observed in this experiment, the value of $q_\parallel$ must be inferred from the momenta of the measured particles. Using energy and momentum conservation, one may write:
The change of the nuclear energy is
\[ E_0 + m_A = E_A + \sum_j E_j \]  
(12)
\[ p_0 = q_{||} + \sum_j p_{||j} \]  
(13)
\[ q_{||} + (E_0 - p_0) + (m_A - E_A) = \sum_j (E_j - p_{||j}) \]  
(14)
where the summation runs over all measured secondary particles including photons, where \( E_0 \) and \( p_0 \) are the energy and momentum of the incident hadron in the lab system, and \( E_j \) and \( p_{||j} \) the energy and longitudinal momentum of the secondaries; \( E_A \) is the energy of the target nucleus of mass \( m_A \) after the collision. The value of \( (E_0 - p_0) \) is 0.03 and 0.5 MeV for incident \( \pi^+ \) and \( K^+ \)-mesons, respectively. The change of the nuclear energy is \( (E_A - m_A) \approx q^2 / 2m_A \). So, both terms in the left hand side of (14) are small compared to \( q_{||} \) and the right hand side of (14) gives an estimate of the longitudinal momentum transferred to the nucleus:
\[ q_{||} \approx \sum_j (E_j - p_{||j}) \approx q_{||} \]  
(15)
The variable \( q_{||} \) has been proposed as an estimator for \( q_{||} \) in [18], where it is called the "effective target mass". This variable can be used in experiments not measuring the longitudinal momentum \( q_{||} \) of the recoil nucleus.

Only events with net charge \( Q = +1 \) and without visible protons and electrons have been analysed.

The \( q_{||} \)-distributions for \( \pi^+A \) and \( K^+A \)-collisions are presented in Fig. 2 for all events with \( n = 3, 5, 7 \) combined. In all distributions, a maximum is observed at low \( q_{||} \). This is expected to correspond to the coherent events. It has been verified that the position of the maximum shifts to larger \( q_{||} \) values with increasing \( n \) (not shown).

Besides the coherent events, the distributions of Fig. 2 contain non-coherent background due to interactions on nuclear neutrons or on the nucleus as a whole, but destroying the nucleus. This background can be estimated from the \( q_{||} \)-distribution of events with small excitation of the nucleus. This is taken as the sample of events with \( n = 4, 6, 8 \), including one slow proton, and net charge \( Q = +1 \) after exclusion of the proton. The \( q_{||} \)-distributions of these events are shown by dashed histograms in Figs. 2. In the calculation of \( q_{||} \) for even topology events, all charged and neutral particles are included, except the identified proton. Comparison of the \( q_{||} \) distributions for even and odd topology shows that, at small \( q_{||} \), the non-coherent background is small compared to the statistical error.

The fact that meson interactions on free nucleons do not contribute at very small \( q_{||} \) is illustrated in Fig. 3, where the data for \( \pi^+p \) are shown from the same experiment. The solid line is the \( q_{||} \) distribution for \( n = 4 \) events with an identified proton. The dashed histograms show the same distributions for events with proton longitudinal momentum less than 150 MeV/c and in the interval 150-250 MeV/c, respectively. In these distributions, the maximum is shifted to values larger than those of the solid lines in Fig. 2, in a manner similar to that in the data for non-coherent events on nuclear targets (shaded histograms).

To define the limit \( l \) of the coherence condition (1), we use the position \( t^* \) of the first minimum in the differential diffractive cross section \( d\sigma/dt \). The total coherent cross section then corresponds to the integral over the cross section in the region of squared momentum transfer \( t \leq t^* \). According to [1], the location of this minimum is \( \sqrt{|t^*|} = 3.6/R \) and \( R = 1.12A^{1/3} \) fm (the radius of the nucleus). This gives a boundary of longitudinal momentum transfer \( |q_{||}| = 0.15 \text{ GeV/c} \) for Al and 0.08 GeV/c for Au. Using formula (10) of [12], one obtains estimates of \( |q_{||}| = 0.09 \text{ GeV/c} \) for Al and 0.05 GeV/c for Au.

Table 1. Inelastic cross sections (in mb) for hadron-nucleus interactions interpolated to 250 GeV/c [19]

<table>
<thead>
<tr>
<th>Beam particle</th>
<th>( A_{\text{Al}}^{27} )</th>
<th>( A_{\text{Au}}^{97} )</th>
<th>( \alpha )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi^+ )</td>
<td>( 327 \pm 10 )</td>
<td>( 1420 \pm 50 )</td>
<td>( 0.74 \pm 0.03 )</td>
</tr>
<tr>
<td>( K^+ )</td>
<td>( 291 \pm 10 )</td>
<td>( 1360 \pm 50 )</td>
<td>( 0.76 \pm 0.03 )</td>
</tr>
</tbody>
</table>
Table 2. Topological coherent cross sections (in mb) at 250 GeV/c

<table>
<thead>
<tr>
<th>n</th>
<th>π⁺Al</th>
<th>π⁺Au</th>
<th>K⁺Al</th>
<th>K⁺Au</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>7.6 ± 1.1</td>
<td>46.6 ± 4.8</td>
<td>7.5 ± 1.4</td>
<td>49.5 ± 8.8</td>
</tr>
<tr>
<td>5</td>
<td>4.8 ± 0.9</td>
<td>10.0 ± 3.1</td>
<td>1.1 ± 0.9</td>
<td>13.4 ± 4.6</td>
</tr>
<tr>
<td>7</td>
<td>1.2 ± 0.5</td>
<td>2.8 ± 1.3</td>
<td>0.9 ± 0.5</td>
<td>2.2 ± 1.5</td>
</tr>
<tr>
<td>Σ_{n=3,5,7}</td>
<td>13.6 ± 1.5</td>
<td>59.4 ± 5.8</td>
<td>9.6 ± 1.7</td>
<td>65.1 ± 10.</td>
</tr>
<tr>
<td>3-7</td>
<td>15.5 ± 1.5</td>
<td>60.2 ± 5.8</td>
<td>11.4 ± 2.3</td>
<td>58.2 ± 8.3</td>
</tr>
</tbody>
</table>

Table 3. Contribution of the coherent cross section to the inelastic cross section (in percent)

<table>
<thead>
<tr>
<th>n</th>
<th>π⁺Al</th>
<th>π⁺Au</th>
<th>K⁺Al</th>
<th>K⁺Au</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>2.3 ± 0.3</td>
<td>3.3 ± 0.3</td>
<td>2.6 ± 0.5</td>
<td>3.6 ± 0.6</td>
</tr>
<tr>
<td>5</td>
<td>1.5 ± 0.3</td>
<td>0.7 ± 0.2</td>
<td>0.4 ± 0.3</td>
<td>1.0 ± 0.3</td>
</tr>
<tr>
<td>7</td>
<td>0.4 ± 0.2</td>
<td>0.2 ± 0.1</td>
<td>0.3 ± 0.2</td>
<td>0.2 ± 0.1</td>
</tr>
<tr>
<td>Σ_{n=3,5,7}</td>
<td>4.2 ± 0.5</td>
<td>3.3 ± 0.4</td>
<td>4.8 ± 0.6</td>
<td>4.6 ± 0.7</td>
</tr>
<tr>
<td>3-7</td>
<td>4.3 ± 0.5</td>
<td>4.2 ± 0.4</td>
<td>3.9 ± 0.8</td>
<td>4.3 ± 0.6</td>
</tr>
</tbody>
</table>

Thus, the numbers of coherent events are found from the $|q_n|$-distributions of odd topology events by subtracting the background distributions of events with even topology, normalized to the numbers of the odd prong events in the intervals $|q_n| = 0.1-0.4$ GeV/c for Al and 0.05-0.4 GeV/c for Au. The coherent cross section is calculated by normalizing the number of events to the inelastic hadron-nucleus cross section presented in Table 1 [19]. The topological coherent cross sections are presented in Table 2. (The last line in Table 2 corresponds to data in Fig. 2, the previous line shows the sum of topological cross sections). These values are in agreement with the calculations of coherent cross sections in [9,10] (see Sect. 1) and the results from nuclear emulsion experiments [6-8].

4 A-dependence of coherent interaction cross section and effective mass spectra of secondary particles

In Table 3, the coherent cross sections are presented as percentages of the inelastic hadron-nucleus cross sections of Table 1. The total coherent cross section represents the same fraction of the inelastic cross section for all four types of collisions considered. This implies that the total coherent cross section has the same A-dependence as the inelastic cross section. The power $a$ of the A-dependence of the inelastic cross section, is shown in the last column of Table 1. In general, the value of $a$ depends on the type of reaction (3)-(11), as well as on the effective mass and the quantum numbers of the produced system (see, for example, [2,3]). One can see from Table 3, that a larger part of the coherent cross-section is concentrated at $n = 3$ for meson-Au interactions than for meson-Al interactions.

To study the effective mass spectra of the secondary particles produced in coherent interactions with $n = 3$ and $n = 5$, we select 3-prong events with $|q_n| < 0.05$ GeV/c and 5-prong events with $|q_n| < 0.075$ GeV/c, where the total measured energy of the secondaries (charged and neutral) is more than 85% of the initial energy $E_0$. Since there are no essential differences between reactions initiated by $\pi^+$ and $K^+$ mesons, we add $\pi^+$ and $K^+$ events for the study of the A-dependence of the effective mass distribution for $n = 3$ (Fig. 4a,b). For $M^\star$Au-interactions (Fig. 4b) a maximum is observed around $M = 1.5$ GeV/c². The spectrum is considerably broader in $M^\star$Al interactions. The $A$-dependence of the coherent cross section for $n = 3$ can be obtained from the cross-section values given in Table 2. Parametrized as $A^a$, it corresponds to $a = 0.91 \pm 0.12$. The statistical uncertainties are too large to be able to draw conclusions on the $a$-values for different intervals of effective mass. However, there is a tendency for $a$ to decrease with increasing $M$ from $a = 1.1$ at $M = 0.8 - 1.4$ GeV/c² to $a \approx 0.7$ for $M > 2.4$ GeV/c².

In Fig. 4c, the effective mass distribution is shown for the sum $\pi^A$ of the coherent $\pi^\star$Al and $\pi^\star$Au events with $n = 3$. The dashed histogram shows the same distribution for events without $\gamma$ (or $\pi^0$) production. These events correspond to ($3\pi^\star$) production in reaction (4). As observed at lower energies, the effective mass of the ($3\pi^\star$)-system is concentrated near $M = 1$ GeV/c². Reaction (4) contributes to all coherent events with $n = 3$ with a fraction of (23 ± 3)%. This corresponds to a cross section of 1.8 ± 0.3 mb for Al and 10.9 ± 2 mb for Au. The average effective mass value of the ($3\pi^\star$)-system is $\langle M \rangle = 1.3 \pm 0.1$ GeV/c².

It is known that the main contribution to ($3\pi^\star$)-production is the $J^P = 1^+$ state corresponding to the $a_1$-resonance (see for example [2,3,12]). The cross section for reaction (4) with effective mass in the interval $M = 1.0 - 1.4$ GeV/c² can be used as an upper limit of the $a_1$ cross section. It is $1.2 \pm 0.4$ mb for $\pi^\star$Al and 7.8 ± 3 mb for $\pi^\star$Au.

In Table 4, the average effective mass values are presented for the different coherent reactions. Note, that in $\pi^\star$p interactions at 250 GeV/c the effective mass distribution of the diffractively produced ($3\pi^\star$)-system has a maximum at $M = 0.8 - 1.4$ GeV/c² and a tail up to 3 GeV/c² [20, 21].
Table 5. Average transverse momentum in coherent interactions (in GeV/c)

<table>
<thead>
<tr>
<th>n</th>
<th>π⁺Al</th>
<th>π⁺Au</th>
<th>K⁺Al</th>
<th>K⁺Au</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.35±0.02</td>
<td>0.33±0.02</td>
<td>0.34±0.02</td>
<td>0.34±0.03</td>
</tr>
<tr>
<td>5</td>
<td>0.35±0.01</td>
<td>0.34±0.02</td>
<td>0.34±0.02</td>
<td>0.37±0.05</td>
</tr>
</tbody>
</table>

In inclusive diffraction-dissociation on protons, the effective mass reaches values up to $M \approx 8 - 10$ GeV/c$^2$ [22].

The analysis of the effective mass in coherent events with $n = 3$ shows that in 77% of such events $\pi^0$'s are produced, corresponding to reactions (6), (10), (11), etc. with five or more mesons in the final state. The charged particles carry away $(75 \pm 8)$% of the initial energy $E_0$ in events with $n = 3$ and nearly 80% in events with $n = 5$.

5 Particle distributions

Lab frame rapidity $y_{lab}$ distributions for charged particles from coherent events in M⁺A interactions with $n = 3$ and 5 are presented in Fig. 5a,b, respectively. For photons they are shown for $\pi^+$ (Fig. 5c,d) and $K^+$-A-interactions (Fig. 5e,f), separately. The selection of coherent events is the same as for the effective mass distributions presented in Sect. 4. The rapidity distributions are observed to depend on the topology of the event: the majority of the charged particles in events with $n = 3$ have $y_{lab} > 5$, whereas for events with $n = 5$ the charged particles are symmetrically distributed around $y_{lab} = 5$. Note, that the c.m.s. for meson-nucleon interactions is at $y_{lab} = 3.1$ (arrow in Fig. 5), which is also the geometrical acceptance limit for $\gamma$'s in our experiment. The shape of the $\gamma$-spectra is practically the same for reactions with incident $\pi^+$ and $K^+$-mesons and for both topologies.

The distribution in the cluster c.m.s. rapidity $y_S$ is shown in Fig. 6 for particles with positive and negative charge for the topologies $n = 3$ and 5. The $y_S$ distributions have their maximum at $y_S \approx 0$ and are close to being symmetric.

The difference of the distributions of particles with positive and negative charge is shown in Figs. 6e) and f). This difference corresponds to the distribution of the net charge in coherent clusters. In events with $n = 3$, more of the net charge is concentrated in the forward hemisphere of the cluster, in events with $n = 5$ in the central region.

The contribution of coherent events in the meson fragmentation region of meson-nucleus interactions can be analysed in terms of the Feynman variable $x_F$. The $x_F$ distributions are presented in Fig. 7 for $n = 3$ and 5 combined, but separately for Al and Au targets. The spectra are similar for the two targets. The $A$-dependence of the particle cross section at $x_F > 0.4$ corresponds to $\alpha = 0.7 \pm 0.1$. In contrast, the inclusive particle spectra in meson-nucleus interactions at large $x_F$ have $\alpha$ values lower than the inelastic meson-nucleus cross section [23].

In Fig. 8, the transverse momentum squared $p_T^2$ distribution is shown for charged particles in coherent events. A fit of the function $\exp(-Bp_T^2)$ in the region $p_T^2 \in (0, 0.6)$ (GeV/c)$^2$ yields the parameter value $B = 7.6 \pm 0.3$ (GeV/c)$^{-2}$.

The average $p_T$ values for charged particles are presented in Table 5. No differences are observed within statistical errors between the different reactions. The $(p_T)$-value for charged particles in all coherent events is $0.34 \pm 0.01$ GeV/c.

Fig. 5. Lab frame rapidity distributions in coherent interactions for charged particles (a and b) and $\gamma$-quanta (c to f). The arrows indicate the c.m.s. for meson-nucleon collisions.

Fig. 6. Cluster c.m.s. rapidity distributions of particles with positive and negative charge, and the differences of these distributions.
This value is 10% lower than that for particles in the inclusive inelastic meson-nucleus interactions in this experiment [24]. The weaker A-dependence of fast particle yield and the larger \( \langle p_T \rangle \) in inclusive processes (mainly non-coherent) could be expected due to the secondary intrainuclear scatterings which play a significant role in inclusive processes.

6 Conclusions

Coherent interactions of 250 GeV/c \( \pi^+ \) and \( K^+ \)-mesons with Al and Au targets of charge multiplicity \( n = 3,5,7 \) are selected from meson-nucleus interactions registered in the NA22 experiment using the EHS set-up.

The results of the analysis can be summarized as follows.

1. The total coherent cross section for events with \( n = 3,5,7 \) is \( (4.3 \pm 0.5)\% \) of the inelastic meson-nucleus cross section. The A-dependence of the coherent cross section is the same as that of the inelastic cross section. A large part of the coherent cross section (about 53% on Al and nearly 77% on Au) corresponds to events with \( n = 3 \).

2. In coherent events with \( n = 3 \) only \((23 \pm 3)\%\) correspond to \( (\pi^+\pi^+\pi^-) \) production. In the other 77% of the events, neutral mesons are produced and the total number of mesons in the final state is five or more.

3. The upper limit on \( a_4 \) production in \( \pi^+ \) interactions with Al amounts to 1.2 \( \pm 0.4 \) mb and with Au to 7.8 \( \pm 3 \) mb.

4. The power \( \alpha \) of the A-dependence of the coherent cross section for \( n = 3 \) is \( 0.9 \pm 0.1 \). The \( \alpha \) value is slightly higher for low effective masses than for large ones.

5. The particles from coherent clusters are emitted in the forward hemisphere of the meson-nucleon c.m.s., but are symmetrically distributed in the cluster c.m.s.. The net-charge distributions are slightly shifted towards the forward hemisphere of the diffractive cluster in events with \( n = 3 \) and are concentrated in the central region for events with \( n = 5 \).

6. In coherent events, the A-dependence of the particle cross section at \( x_F > 0.4 \) corresponds to \( \alpha = 0.7 \pm 0.1 \).

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