ππ CORRELATIONS AND PION ABSORPTION

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Abstract

An influence of pion absorption process on the correlations of pions emitted in heavy-ion collisions is discussed. The probability of pion absorption is related to the collision geometry defined by the value of impact parameter and orientation of the reaction plane. It makes a specific correlation pattern in two-particle characteristics of emitted pions. Absorption can change the effective size of the pion emission region. It affects also the form of two-pion correlation function. In the case of identical pions it can change the values of parameters which characterize the space-time development of pion emission process in interferometry measurements.

1 Introduction

Pions — particles which are copiously produced in the collisions of relativistic heavy ions interact strongly with the surrounding medium, thus registering history of their complicated life. Expectations that pions can be used as a probe of the development of heavy-ion interactions change in time from highly positive (optimistic) values in the middle-eightieth [1] to rather negative (sceptical) opinions some years later [2] and now appear to be again in the positive part of the expectation scale. Indeed, the complexity of pion interaction inside nuclear medium can reveal or obscure different features of the collision process. Let us list below some related questions.

• "Is collective pion flow anticorrelated to nucleon flow?" — the question of S.A. Bass and others in the title of their article in Physics Letters [3]. (Collective effects in pion emission are considered also by C. Hartnack in his talk at this Conference.)

• Is the radius of pion emission proportional to the size of the projectile or (more generally) the smaller colliding object? This question/suggestion of J. Bartke [4] is frequently applied in the analysis of the experimental data.
• Are resonances responsible for the measured size of pion emission? This problem is considered by R. Lednicky and T. Progulova and a set of variables is proposed to analyse the form of two-particle correlation function [5].

• Is collision dynamics present in interferometry measurements? M. Gyulassy says in 1982: "Special dynamical features... can lead to unexpected correlations at small relative momenta that have nothing to do with Hanbury-Brown and Twiss effect" [6].

• What is the relation between the pion and Kaon production cross-section and the sizes of their production volume? The series of interesting experiments at Brookhaven (E802, E859, E866) of O. Hansen and co-workers treats this question in details [7].

• Are the medium effects present in pion correlations? P. Schuck and co-workers consider this question and suggest to analyse the pion-pion correlations in order to find a signature of the σ resonance due to changes of its properties in a dense nuclear medium [8]. Such effects are usually related to the reaction plane in heavy-ion collisions.

• How to find the reaction plane experimentally? P. Danielewicz and G. Odyniec propose a simple but effective method which is frequently used in the experimental analysis of correlation effects [9].

This list can be continued... The questions listed above were selected to emphasize only one particular problem which form the title of this report and is repeated below in a pictorial version.

Fig. 1. Relations between ππ correlations and pion absorption process.
Two-pion correlations (different than those of kinematical nature) were observed a long time ago for charged [10] and neutral [11] pions and were explained by the effects of Bose-Einstein statistics. A lot of experimental and theoretical papers on this subject appeared after the pioneer works of Kopylov and Podgoretskii [12]. The related questions are discussed in some dedicated review-reports [13, 14, 15].

Recently, the experimental observations of collimated pion emission have been reported in many papers [16, 17, 18, 19, 20]. In analogy with the well established effects of "collective flow" of nucleons and nuclear fragments emitted in heavy-ion collisions, the effects of angular asymmetry in the emission of pions are called frequently "pion collective flow". However, the origin of this "flow" should not be obviously the same as in the case of baryonic systems.

Some experimental observations are listed below. In each case the name of detector, reaction and projectile energy is given together with a short relevant message.

- (Diogene, Ne + (NaF, Nb, Pb), \(E/A = 800 MeV\), [16]) The preferential emission of charged pions towards the projectile side was observed in the plane perpendicular to the reaction axis. Pion absorption was mentioned as a possible source of the observed effect. This result has then stimulated a lot of theoretical and experimental studies.

- (Plastic Ball, \(p + Au, 4.5, 60, 200 GeV\), [17]) Pions registered in the target fragmentation region are preferentially emitted "side-by-side" in the azimuthal plane. The effect is stronger for smaller energy of the projectile and is coherent with the assumption that pions are absorbed in excited spectator matter.

- (KaoS, \(^{197}Au + {^{197}Au}, 1 \text{ GeV/nucleon}\), [18]) In a symmetric heavy-ion reaction the direction of pion emission in the azimuthal plane changes from strong anticorrelation with respect to the projectile direction for fast pions emitted in peripheral collisions to preferred emission out of the reaction plane for semi-central collisions. A conclusion was made that fast pions are well suited to provide information of the equation of state of nuclear matter.

- (TAPS, \(Au + Au, 1 \text{ GeV/nucleon}\), [19]). "A squeezeout effect for neutral pions has been observed." An enhanced emission of \(\pi^o\)-mesons perpendicular to the reaction plane was more strong for greater pion transversal momenta. Pion absorption is suggested to be responsible for the observed azimuthal asymmetry.

- (FOPI, \(^{209}Bi + {^{208}Pb}, 1 GeV/nucleon\), [20]) Observed effects of pion flow are coherent with those obtained by the KaoS and TAPS Collaborations. The authors conclude however that the experimental observations: "do not allow an unambiguous determination of the origin of the observed pion flow".

A detailed theoretical analysis of "pion flow" was first performed in the frame of IQMD model [3]. Using the VUU theory the nonequilibrium and stochastic quantum effects were considered explicitly and the nuclear potential was incorporated.
as well. Effects of pion creation, rescattering and absorption were included via the
\( \Delta \) resonances and different isospin channels were taken into account. The results
of analysis were compared with the experimental observation of the Collaboration
Diogene [16]. In conclusion was stated that the flow of pions can be explained by
multiple \( \pi N \) scattering and not by pion absorption.

In the following analysis performed in the frame of the same approach an opposite
meaning has been presented however [21]. Preferential emission of fast pions out of
the reaction plane in the symmetric \( Au + Au \) collisions appears here as a result of
pion absorption which takes place predominately in the reaction plane. Rescattering
effects are weekly visible and only for pions with low perpendicular momenta.

3 Different sources of \( \pi\pi \) correlations

Keeping in mind different possible sources of correlations seen in the emission of
pions in heavy-ion collisions, a dedicated analysis of \( \pi^+\pi^- \) correlations has been
performed. The main idea of this work was to study the target mass dependence of
two-pion correlations in order to look for possible medium effects. The well known
correlations due to Bose-Einstein statistics were eliminated by taking pions with
different charges. Experimental data were taken from the Diogene detector and
from the propane bubble chamber irradiated in the beams of light ions at Dubna.
The details of analysis are described elsewhere [22]. Some results related to the
subject of this report are presented in the following figures.

The distribution of the invariant mass of two different charge pions emitted in
three reactions: \( p + (C, Nb, Pb) \) at 1.6 GeV is shown in the Fig.2. (black points) to-
tgether with the background distributions obtained by mixing of pions from different
events (for details see ref.[22].) Normalization was performed for \( M_{inv} > 500 MeV \).
No difference is seen between the coincidence and background distributions in the
case of the Carbon target. For heavy targets a clear enhancement above the back­
ground appears for \( M_{inv} \leq 420 MeV \).

Fig. 2.
Invariant-mass distributions of pion pairs
for three different targets: C - carbon,
Nb - niobium, Pb - lead. Open points
- background distribution, full points -
coincidence pairs.
In order to extract the correlation effect a difference between the measured and background distribution was calculated. The result is plotted in the Fig. 3(a). Corresponding distributions for the data from the bubble chamber are shown in the Fig. 3(b). The same effects are observed in both distributions.

Fig. 3. a) – Difference between the measured and background distribution divided by the total number of events for the Diogene data. b) – the same for the data from the propane bubble chamber (Dubna).

In order to find an origin of the observed correlations some different possible effects were considered:

- Final state, strong and Coulomb, interaction between emitted pions,
- Coulomb interaction with large positive charge of the emitting source.
- Reflection of the 3-body decays of \( \omega \) and \( \eta \) resonances.

It appeared that all these effects are relatively weak in comparison to that observed experimentally. As an example, Fig. 4 shows the correlation function defined as a normalized ratio of the measured and background distribution of \( \pi^+ \pi^- \) invariant mass. Difference in the shape of correlation function before (black points) and after corrections due to final state interaction appears in some first intervals and can explain only a weak positive correlation in the case of the carbon target.

Effects of pion rescattering and absorption were tested using dedicated transport calculations with the BUU code [23]. Protons, neutrons, \( \Delta \) and \( N^* \) resonances and pions were propagated and the interaction cross sections were taken from experiment. (Isospin symmetry and detailed balance was applied in order to obtain the unknown quantities.) In the considered energy region pion interactions in the nuclear medium are dominated by the two-step process \( N + N \leftrightarrow N + \Delta \leftrightarrow N + N + \pi \) in which the creation and reabsorption of pions is incorporated. In the elementary
scattering process the effect of Pauli principle was taken into account (for details see ref. [23]). Background distributions were obtained taking pions from events with random relative orientation of the reaction plane.

![Diagram](image)

**Fig. 4.**
Correlation function \( R \) defined as a ratio of coincidence and background distributions. Full points - uncorrected values, open points - corrected for the final state interaction.

![Diagram](image)

**Fig. 5.**
Comparison of the experimental correlation function with the results of calculations for carbon and lead targets. Good agreement seen for both light and heavy targets shows clearly that two pion correlations are sensitive to the development of pion creation/absorption process and are related to the geometrical effects defined by the orientation of the reaction plane.

![Diagram](image)

**Effects related to the reaction plane should be naturally visible in the azimuthal correlations of emitted pions. In our case, where the number of secondary particles is rather small, it is difficult to find the reaction plane experimentally. Nevertheless, pion collimation in the azimuthal plane should be also visible in the distribution of the "opening angle" in the plane perpendicular to the reaction axis. Fig. 6. presents**
the corresponding distributions for the pairs of pions emitted in the collisions of protons with C, Nb, and Pb targets at 1.6 GeV.

Small negative correlations seen in the case of interactions with the carbon target are related to the transverse momentum conservation as was proved by the simulation analysis. Clear positive correlations (enhancement at the region of small pion relative angles) which appear for heavy targets cannot be explained in this way. This effect appears as a consequence of the shadowing process due to pion absorption in the nuclear medium — as was proved by the comparison with the theoretical calculations (see above).

In order to learn more about the features of the observed effects we have analyzed the dependence of the mean pion multiplicity on the proton-like multiplicity, $N_{pl}$, which characterize the impact parameter in an event-by-event way, (greater values of $N_{pl}$, correspond to the smaller impact parameter). Fig.7. presents the results of our analysis.

Fig. 6. Distribution of the relative azimuthal angle between two pions for the Diogene data.

Fig. 7. Mean pion multiplicity as a function of the proton-like multiplicity for the Diogene data.
No clear dependence is seen in the case of the carbon target. Decreasing mean number of emitted charged pions with the increase of $N_{pl}$, which occurs in the case of heavy targets, can be directly related to the absorption of pions in the surrounding nuclear medium.

Similar effects were observed a long time ago, e.g. in the characteristics of pions produced in $\pi^{-}$-Xe collisions at 3.5GeV/c; Fig.8. [24]. With the increase of the collision centrality (characterized by the number of emitted protons) the mean number of emitted pions first increases (production in secondary intranuclear collisions) and then decreases as a result of absorption.

![Fig. 8. Mean pion multiplicity as a function of the number of emitted protons in $\pi^{-}$-Xe collisions at 3.5GeV/c. From ref. [24].](image)

![Fig. 9. Mean negative-pion multiplicity as a function of the number of participant nucleons in the La+La reaction at three incident laboratory energies. From ref. [25].](image)

There are also some other observations however. Fig. 9. shows the dependence of the mean number of negative pions emitted in the interactions of La+La at different energies on the number of "participant nucleons" which also characterize the collision centrality [25]. For all energies a linear dependence is seen indicating rather the increasing pion production. Is it proof that the effects of pion absorption are negligible in this case?

Let us notice first that the number of participant nucleons was determined there by the number of participant protons and the $A/Z$ ratio. An assumption that the ratio $A/Z$ reflects the number of emitted neutrons seems to be justified when the charge conservation is not important. In this case, the increasing positive charge of participant protons is correlated with the increasing number of negative pions which are frequently produced by the charge-exchange type reaction like $n+p \rightarrow p+p+\pi^{-}$ at these, relatively low, energies. Oppositely, creation of positive pions decreases the charge of participant nucleons; $n+p \rightarrow n+n+\pi^{+}$. A precaution is necessary before making conclusion from such dependences.

A direct experimental test of this feature is presented in the Fig.10. The dependence of the mean pion multiplicity on the proton-like multiplicity, $N_{pl}$, is examined
here for negative and positive pions separately. (High position of the first point for $N_{\pi^{\pm}} = 0$ is a result of the triggering conditions.)

Fig. 10. Dependence of the mean pion multiplicities as a function of the proton-like multiplicity for the Diogene data.  
upper - mean $\pi^+$ multiplicity,  
lower - mean $\pi^-$ multiplicity.

Clear decrease (increase) tendencies are seen for mean multiplicity of positive (negative) pions in the case of the carbon target. Note that it gives a practical lack of dependence when both charges are considered; cf. Fig.7. For heavy targets the effect of pion absorption leads to characteristic changes of the form of this dependence.

4 Pion absorption in interferometry results

Let us return now to direct relations between the process of pion absorption and $\pi\pi$ correlations. Effects seen in the invariant mass distributions are closely related to that observed in azimuthal correlations. Both arise due to shadowing made by pion absorption. The form of observed effects is also very similar to that of interference correlations due to Bose-Einstein statistics of identical pions. (Note that $Q_{\text{inv}}^2 = M_{\text{inv}}^2 - 4 \times m_\pi^2$). It is clear however that in the case of different charge pions the observed correlations "have nothing to do with Hanburry-Brown and Twiss effect", as was stated by Gyulassy [6]. In the case of identical particles both effects should act in the same direction thus increasing correlations. In order to verify it we have constructed distributions analogous to that presented in the Fig. 4. but for the pairs of identical pions, Fig.11 shows it for the interaction with the lead target. Correlation effect is clearly more strong than in the case of $\pi^+\pi^-$ pairs.

It seems probable that considered effects are present in some existing experimental results. Fig.12. shows the form of two-pion correlation function in the reaction of protons and antiprotons with the Hydrogen and Xenon target at 200 GeV [26].
The correlations are much stronger in the case of the Xenon target and the corresponding $\lambda$ parameter has a value considerably greater than 1. Similar effects were observed in $\pi^- - Xe$ reaction at 3.5 GeV/c \[27].

Some surprising results obtained by the WA80 Collaboration \[28\] can also be related to the questions considered here. In the reaction $^{16}O + (C, Cu, Au)$ at 200 A GeV the effect of interference correlations for pions emitted in the target fragmentation region appeared to be more narrow for the carbon target than for the gold one. Corresponding radius of pion emission region is smaller for the interactions with the gold nuclei than with the carbon target what has no clear explanation. Correlation effect extends in the case of the gold target until the $Q$ values about 300 MeV/c. 

Fig. 11. Correlation function $R$ for $\pi^-\pi^-$ pairs (left) and $\pi^+\pi^+$ pairs (right) from the Diogene data.

Fig. 12. Two-pion correlation functions for the interactions of protons and antiprotons with hydrogen (H) and xenon (Xe) targets at 200 GeV. From ref. \[26\]
what corresponds to the $M_{inv}$ about 420MeV and is similar to our observations for different charge pions. Note also that the effect of pion azimuthal correlations was clearly seen in the other results of WA80 Collaboration [17].

5 Conclusions

Effects of $\pi\pi$ correlations and pion absorption process are mutually related. Two forms of these relations can be distinguished:

- Absorption effects can change the real effective size of the pion emission region creating some "dead zone" due to shadowing by the spectator matter. It can be reflected in identical pion correlation (interferometry) measurements.

- Absorption effects can be present in the form of the correlation function measured for identical pions. Thus, if in subsequent interpretation of the shape of correlation function only interference effects are taken into account, some spurious results can be obtained which do not correspond to the real space-time parameters of the pion emission process.

It seems that these two effects can be separated experimentally however. Interference correlations are genuine two particle effect. Pion absorption is mostly one-pion effect which leads to two-pion correlations due to relation with other properties of the interaction process. Pion absorption is strongly related to the collision geometry defined by the reaction plane. It seems therefore that the effect of pion absorption in the results of interferometry measurements can be strongly suppressed by including the position of the reaction plane in the background generation procedure. Pairs of different charge pions can also be used for the same reasons.

Let us finish with a more general conclusion. Correlations of particles carry important information about the development of the interaction process. To extract it properly from the results of measurements all contributing effects should be taken into account, however. Meetings like CORINNE can stimulate the idea to create some unified approach allowing to explore the processes which occur in the space-time dimensions of the order of 1fm; ($1 \text{fm} = 10^{-15} \text{m} = 1 \text{femtometer}$).

The name for this developing branch of studies was proposed by Prof. G.A. Leksin from ITEP, Moscow. FEMTOMETRY — like micrometry in a different size scale can unify all the contributed effects, theoretical approaches and experimental methods of data analysis.

References


