THE STUDY OF FRAGMENTATION PROCESSES IN $\bar{p}p \to \bar{p}p\pi^+\pi^-$ REACTION AT 32 GeV/c MOMENTUM SEPARATED BY CLUSTERS SEARCH METHODS IN MULTIDIMENSIONAL PHASE SPACE*

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We have described the clusters search methods in detail. These methods were applied to $\bar{p}p \to \bar{p}p\pi^+\pi^-$ reaction at 32 GeV/c momentum and we have separated 7 clusters. The features of those clusters were obtained. This reaction is dominated by two production mechanisms, one-vertex fragmentation and simultaneous two-isobars excitation (two-vertex fragmentation). For a detailed study of one-vertex fragmentation, the clusters search method has been used in the rest frame of three particles selected from the final state and 6 clusters have been separated. The study of them shown the essential role of resonances amplitudes interference.

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1. Introduction

As the diffraction processes in elementary particles systems play a fundamental role in the study of matter structure, their separation methods have exclusively great importance. The low-multiplicity exclusive reaction is the source of information about fragmentation processes. Used methods such as LPS-analysis, rapidity gap method include the cuts and do not permit to separate mechanisms of reaction with background suppression. The methods used in this article do not have similar defects and they are further improvements of earlier published [1–5]. Application of these methods to

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study cosmic rays particles interactions with nucleons and nuclei may turn out fruitful. The investigation is carried out for the future comparison of experimental data obtained on accelerators with the results which will be obtained in interactions of cosmic rays particles with matter on complex detectors Adron-44 and Adron-55 located at an altitude 3340 m above sea level [6]. In the present article, there are described the methods of dusters search in the multidimensional phase space applied to four-particles final state

$$\bar{p}p \rightarrow \bar{p}p\pi^{+}\pi^{-} \tag{1}$$

from Mirabelle HBC exposed by antiprotons with 32 GeV/c momentum. The details of $\bar{p}p$ experiment are described in [7]. The number of events belonging to reaction (1) is equal to 5983. The investigation of reaction (1) was carried out earlier [8] by other methods on 3606 events statistics.

2. The methods of clusters search

In this section, the updated methods of those described earlier are proposed [3–5]. Two model-independent methods are used for cluster search, which permit to select the clusters with arbitrary form in multidimensional phase space. The comparison of distances between pair particles in phase space is the basis of those methods. The measure of distance between events A and B was determined as

$$d_{AB}^{2} = -\sum_{i}^{n}(P_{iA_i} - P_{iB_i})^{2}\,, \tag{2}$$

where P^{A} , P^{B} are particles four-momenta and the summation is over the corresponding particles of the two events. Also, it is necessary to consider a number of invariant transformations for $\bar{p}p\pi^{+}\pi^{-}$-final state, such as mirror reflection, charge conjugation, and three-dimensional rotation of one event relative to the second. Those transformations must be selected in order to minimize the distance d_{AB}. The above-mentioned invariant transformations for distances minimization must include permutations of identical particles, which are absent in our final state.

Expression (2) can be rewritten as follows considering the three-dimensional rotation and space inversion of B event:

$$d_{AB}^{2} = \sum_{i}^{n}\left(\overrightarrow{P}_{iA_i} - R\overrightarrow{P}_{iB_i}\right)^{2} - \sum_{i}^{n}(E_{iA_i} - E_{iB_i})^{2}\,, \tag{3}$$

where R is some orthogonal matrix. Matrix R must be selected in order to minimize (3) [3–5].

In order to take into account charge conjugation of $\bar{p}p\pi^+\pi^-$-final state, the combinations giving minimal d_{AB} were selected from the following combinations given in Table I.

TABLE I

The features of selected clusters.

P^{A}	P^{B}
$\bar{p}$	$\bar{p}p$
p	$p\bar{p}$
π^+	$\pi^+\pi^-$
π^-	$\pi^-\pi^+$

The cluster search in phase space is carried out by two methods in the following sequence: *the totality of densities in multidimensional phase space are constructed as will be explained below; all densities are put in order in accordance with their values; the classification of events is carried out step by step beginning with higher densities gradually passing to lesser.*

We pass on to the determination of local density and the description of classification rules for every method.

The first method is based on the building of a minimal spanning tree (MST). The local density in this method is related to a tree branch and its value is determined by the branch length. The minimal spanning tree and two local densities are shown in Fig. 1.

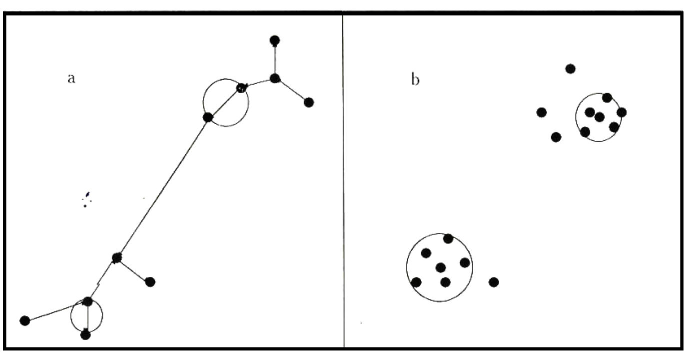

Fig. 1. The local density definition: (a) minimal spanning tree method and (b) distance analysis method for $k = 5$, where k is the number of nearest neighbors. (The diameter of the unfilled circle is the measure of local density.).

During the classification, all events are divided into two categories: *the event that has not been classified; the event that belongs to a cluster with some identifier.*

On the i^{th} classification step, the i^{th} local density (branch) is selected and the following classification rules are applied: If the events connected by the i^{th} branch are not classified, then a new cluster with identifier i is created and both events are joined to it. If only one event belongs to some cluster, then an unclassified event is simply joined to the same cluster. Finally, if the events belong to different clusters, then these clusters are merged and the combined cluster gets the identifier of the "older" cluster. The minimal spanning tree method was mainly used to transform all events according to two possible combinations of the $\bar{p}p\pi^+\pi^-$-final state given in Table I and to check the results produced by the next method.

The second method is a distance analysis or k-nearest neighbor's method [9]. This method is more flexible and stable than the previous one but has one essential defect: it does not allow taking into account the different combinations of the final state. But in the MST method, this (defect) shortcoming is taken into account. The local density in this method is related to an event and its value is determined by the distance to the k-nearest events (see Fig. 1). It was shown that for N from several hundred to several thousand events, the condition $5 \leq k \leq 10$ provides a reliable separation of clusters [10].

During the classification, all events are divided into three categories: *the event that has not been classified; the event that belongs to some cluster; the event that is the boundary event of some cluster.*

On the i^{th} classification step, the i^{th} local density (event with its "halo" or k-nearest neighbors) is selected and the following classification rules are applied:

— If the "halo" of the i^{th} event does not contain events belonging to any cluster, then a new cluster with identifier i is created and the i^{th} and unclassified "halo" events are assigned to the new cluster and its boundary accordingly.

— If events belonging to the same cluster are present in the "halo", the i^{th} and unclassified "halo" events are added to this cluster and its boundary accordingly.

— Finally, if events belonging to different clusters are present in the "halo", these clusters are merged and the combined cluster gets the identifier of the "old" cluster, and according boundary and unclassified events from the "halo" form its boundary.

An important advantage of the second method is its ability to separate correctly partially overlapping clusters in phase space without sufficient loss of statistics. During classification, the cluster separation goes on the lines along "valleys" between the clusters.

3. Experimental results

We applied the minimum spanning tree (MTD) procedure to reaction (1) since this procedure provides a minimum distance between two particles using specular reflection, charge conjugation, and other principles. As a result of carrying out the procedure of the events ordering takes place.

It is interesting to note that the number of events for which MST construction was attended by CP-conjugation proved to be equal to the number of events for which this transformation did not apply. After producing ordering of events by the MST method to all sets of the events, the "k-nearest neighbors" method was applied (at $K = 5$). This procedure permits to select 7 clusters from the total set of events. The features of these clusters are presented in Table II. We grouped them in accordance with their internal dynamics.

TABLE II

The features of selected clusters.

Cluster identification	Number of events	Cross section [μb]	Error [μb]	Comments
1	2779	576	± 11	One-vertex fragmentation
5	914	185	± 6	One-vertex fragmentation
70	773	156	± 6	One-vertex fragmentation
12	291	59	± 4	$\bar{p}p \to \Delta^{++}_{1232}\bar{\Delta}^{++}_{1232}$
46	540	109	± 5	$\bar{p}p\Delta^{++}_{1232}\bar{\Delta}^{++}_{1232}$
498	369	75	± 4	$\bar{p}p\Delta^{*++}_{1950}\bar{\Delta}^{++}_{1232}$
3228	258	53	± 4	$\bar{p}p \to \Delta^{*++}_{1950}\bar{\Delta}^{++}_{1232}$

As we can see from Table II, all sets of events belonging to exclusive reaction (1) are divided into two groups.

The first group is associated with the three-particle fragmentation process. It includes three clusters with the total number of events 4466 and the sum cross section of 0.908 ± 0.014 mb. This value coincides with the cross section of three-particle fragmentation obtained in [8].

The second group includes four clusters with the total number of events 1458 corresponding to two-particle kinematics with double production of isobars.

The splitting up on two clusters is due to the difference in orientation of the decay particle relative to heavy Δ^{++}_{1910} resonance movement. In the C3228 cluster (369 events), the protons fly along Δ^{++}_{1910} resonance movement (and accordingly π^+-meson against this direction). In the C498 cluster (258 events), the direction of decay changes into the opposite one. Antiprotons and π^--mesons in the both clusters are distributed in an identical manner. The carried out analysis permitted to observe the simultaneous production of two light isobars and simultaneous production of light and heavy isobars mechanisms. The resolving of the mechanisms was very distinct, which could not be got in a traditional manner [8]. The distributions on $\delta\sigma/\delta t$, where δt-four-momentum transfer from primary nucleon to isobar were plotted (the figure is not shown) for total events from clusters C12 + C46 (double production for light isobars) and for total events from clusters C498 + C3228 (double production of light and heavy isobars).

The obtained distributions were fitted by the Ae^bt expression. The results of the fitting are shown in Table III.

TABLE III

Parameters of fitting.

Cluster identification	Number of events	A	b (slope)
12 + C46	831	7.20 ± 0.07	-8.13 ± 0.46
498 + C3228	627	6.20 ± 0.07	-4.04 ± 0.021

For a more detailed study of fragmentation mechanisms, it is reasonable to go to a semi-inclusive consideration of three-particle combinations $p(\bar{p})\pi^+\pi^-$ using for that the clusters search method in 12-dimensional phase space.

For this aim, it is needed to go into the rest frame of the selected combination. The method of k-nearest neighbours was applied to the total fragmentation set including 4446 events. 6 clusters were selected. Their features are presented in Table IV.

TABLE IV

The features of selected clusters.

Cluster identification	Number of events	Cross section [μb]	Error [μb]	Comments
N1	798	159	±6	
N2	1196	247	±8	
N3	1196	242	±7	
N4	343	73	±4	
N5	619	124	±5	
N6	304	62	±4	

In the cluster N2, there is observed pronounced wave amplitudes interference of nucleon isobars Δ^{++}_{1232} and Δ^{0}_{1232}. This phenomenon can be seen in a two-dimensional plot, where the dependence of invariant mass $M(p\pi^+)$ from $M(p\pi^-)$ is shown.

4. Conclusion

From the 5983 events belonging to $\bar{p}p\pi^+\pi^-$-final state, the single-vertex dissociation was selected and the cross section of this process was evaluated to be 0.908 ± 0.014 mb, which coincide with earlier obtained results [3].

A quasi-two-particle channel with simultaneous production of two light Δ^{++}_{1232} and $\bar{\Delta}^{++}_{1232}$ isobars was separated and its cross section was evaluated as 168 ± 0.006 mb.

A quasi-two-particle channel with asymmetric excitation of both colliding particles up to isobars Δ^{++}_{1910} and $\bar{\Delta}^{++}_{1232}$ was separated and the cross section of isobars was evaluated as 0.128 ± 0.005 mb.

The splitting of clusters associated with simultaneous two isobars production was observed. This phenomenon is connected with the orientation of decay particles in the rest frame of resonances. These subclusters were registered and their cross sections were evaluated.

The invariant mass and other dynamic variables of secondary particles were obtained. The discovered difference of distributions on four-momentum transfer in clusters associated with simultaneous symmetric and asymmetric excitation colliding nucleons up to isobars has been demonstrated.

Using cluster searching approach during the transition to the state of rest of the three particle combination corresponding to single vertex fragmentation allowed to obtain the results that show the significant role of the interference mechanism.

The obtained results are illustrations of merits for clusters search methods in multidimensional phase space.

The presented in this article results may be useful for the detailed theoretical model construction taking into account spin orientation of resonance and its decay products.

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