Search For Dibaryonic De-Excitations In Relativistic Nuclear Reactions

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Abstract

Some odd characteristics are observed in the single particle distributions obtained from He + Li interactions at 4.5AGeV/c momenta which are explained as the manifestation of a new mechanism of strangeness production via dibaryonic de-excitations. A signature of the formation of hadronic and baryonic clusters is also reported. The dipionic signals of the dibaryonic orbital de-excitations are analyzed in the frame of the MIT - bag Model and a Monte Carlo simulation. The role played by the dibaryonic resonances in relativistic nuclear collisions could be a significant one.

Key words : Relativistic nuclear interactions negative pions, negative kaons,dipions, streamer chamber, dibaryons, MIT - bag model

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1 Introduction

In the last years a wealth of data have accumulated concerning relativistic nuclear interactions. The still growing interest on this branch of physics has its roots in the hope to obtain by the means of the relativistic nuclear physics information on a hypothetical state of matter - the quark gluon plasma, as well as on other genuine properties of the compressed hadronic matter. For reviews see references [Koch et al., 1986], [P.Carruthers, 1989], [Satz et al., 1987], [Baym et al., 1989], [Schmidt, Gutbrod., 1989], [Iannenbaum, 1989], [Salmeron, 1989], [Gutbrod, 1988], [Schukraft, 1991], [Bamberger et al., 1989].

In this paper we discuss some unusual results obtained in the frame of the SKM - 200 Collaboration from JINR - Dubna concerning the yield of negative charged particles produced in the $He + Li$ interaction at 4.5$AGeV/c$. Despite of the much higher energies available today, the few GeV sector is still interesting mostly because it offers the perfect frame to perform studies on the properties of the exotic multi - quark states, as those recently published on the production of non-strange dibaryons in neutron - proton interactions at 5.1$GeV/c$ [Besliu et al., 91 a, 92 a]. The theoretical description of those new states [Besliu et al., 92 a] and its non - trivial consequences that should manifest when they are produced inside a compressed nuclear matter as predicted in papers [Besliu et al., 92 b, 91 b] are the motivation of this work.

2 The Experimental Data

The results that we are going to analyze in the following are originating from 3857 central collision events between a He beam of laboratory momentum 4.5$AGeV/c$ on a $Li$ target inside the 2$m SKM − 200$ streamer chamber produced at the JINR - Dubna synchrophazotron and represent a subset of the $SKM − 200$ Collaboration data, which cover a broad range of nuclear beams and targets. The general experimental features are discussed in papers [Aksinenko et al., 80], [Anikina et al., 86], [Abdurakimov et al., 81]. Some particular results concerning the characteristics of the $\pi^−$ production in $O + Pb$, $O + Ne$ and in the bulk of $He$ induced reaction are already presented in references [Besliu et al., 85, 87, 88, 89]. The experimental data processing procedure was typical for streamer chamber experiments: as ionization measurements were not available, the only particles that could be positively identified were the negative pions. All tracks presenting secondary interactions with the gas filling the chamber or signs of decay during the flight inside the sensitive volume of the detector were removed in the first stages of the scanning. In those conditions the averaged pionic multiplicity for central $He + Li$ reaction is found to be $< n_{\pi^-} >= 1.757 \pm 0.157$. We note that a simulation Monte Carlo HIJING code generator [Wang and Gyulassy, 91], [Wang and Gyulassy, 92] applied in a Dual Parton Model variant give a value of 1.65 for pion multiplicities (we generate 50000 events) [Topor et al., 93]. In paper of [Anikina et al., 86] it is argued that the admixture of $K^−$ and $\Sigma^−$ that escaped the scanning filtering is less than 0.5%.

An experimental details that is significant for the discussion in the next sections is the position of the target inside the fiducial volume of the chamber. The fact that the target is situated upstream respective to the incident beam causes some loss in the detector selection power in the backward reaction hemisphere. Figure 1 depicts a very schematic picture of the chamber (drawn at scale) and indicates also the projections in the upper
plane of the spectrometer of the three photographic cameras (actually they are situated at 211.8 cm above that plane). Their "excentric" positions are determined by the presence of the magnetic coils above the chamber.

3 Peculiarities of Some Kinematical Single Particle Distributions

Most of the analysis published by the SKM−200 Collaboration are based on the study of the multiplicity of secondaries with respect to the beam-target combinations and different degrees of centrality. In the following we shall restrict our selves in the discussion of some general kinematical distributions.

Figure 2 presents the angular distribution (in the laboratory frame) of the negative particles, which are, in concordance with the statements in the second section, supposed to be π− mesons.

An unexpected high production of particles in the backward hemisphere (azimuthal angles higher than 137° thus in the cone represented in Figure 1) is striking. The same conclusion can be drawn from the rapidity distribution depicted in Figure 3. While in the rapidity range \( y > -0.7 \) the shape of the distribution is quite a normal one, at \( y < -0.7 \) the data manifest some abnormal behavior.

Both the angular and rapidity distributions show that mixed negative mesons of different origin are present in the experimental data. Furthermore, the anomalously high absolute values of the rapidity of this component (the rapidity being computed as those particles being pions) could be reduced if assuming the corresponding particles being more massive. The cut-off of the contributions of this puzzling component towards forward directions suggests that the filtering of negative pions through the scanning procedure is not operational in the upstream direction, namely in that direction characterized by significantly shorter distances available inside the fiducial volume of the chamber. Unfortunately such an interpretation is not offering a satisfactory explanation of the sharpness of the observed cut-off. We shall return to this problem in section 4 of this paper.

The most reasonable guess leading to an acceptable understanding of the manifested anomalies is to assume that an important amount of \( K^- \) mesons is produced during the interaction and that their decay escapes from detection within the active volume of the chamber when produced backwards.

If this assumption is true, then this kaonic component should be produced (according the conventional picture of high energy nuclear interaction) in an earlier stage of the hadronization, namely at higher temperature than the pionic component. Information about the production temperature could be extracted from the transverse momentum distributions. This distributions present also the advantage to be independent on the mass values of the particles involved, as momenta are direct observable in the experiment due to the magnetic deflection of the charged secondaries inside the chamber. Figure 4 depicts the \( p_\perp \) distribution for all the negative particles (the circles), the particles with \( y_{lab} \geq -0.7 \) which could be considered as \( \pi^- \) mesons (the squares) and for those with \( y_{lab} < -0.7 \), namely those we suppose to be \( K^- \) mesons (the rhomboids). The solid lines in Figure 4 are obtained by fitting the descending parts of the \( p_\perp \) spectra with exponential functions:
\[ \frac{\partial N}{\partial p_\perp} \propto \exp[-\beta \cdot p_\perp] \]

where the fitting parameter \( \beta \) should be in inverse proportionality with the source temperature. The results of those fits are listed in Table 1.

The conclusion that could be extracted from those results is that the anomalous negative particle component observed in the \( H e + Li \) central collisions at 4.5\( AGeV/c \) originates from an earlier stage of the interaction - as characterized by a higher temperature than the usual \( \pi^- \) component. This observation is supporting our claim that strong \( K^- \) production manifests in the investigated reaction.

Table 1: The parameters of the exponential functions describing the \( p_\perp \) spectra

| Selection | \( \beta(\text{GeV/c})^{-1} \) | \( \chi^2/N.D.F. \) |
|-----------|-----------------|----------------|
| all       | 1.61 ± 0.4  | 1.29           |
| \( y \geq -0.7 \) | 2.49 ± 0.03 | 1.66           |
| \( y < -0.7 \) | 1.02 ± 0.03 | 1.41           |

The high kaonic multiplicity \(< K^- > = 0.712 \pm 0.008\) should be analyzed in the context of the averaged number of participants nucleons in the investigated reaction. Taking into account that in the \( H e + Li \) reactions equal numbers of protons and neutrons are involved, one may estimate this number using the relation:

\[ < N > = 2 \times ( < Q - 2 \times n^- - n_s > ) \] (1)

where \( Q \) represents the charged particle multiplicity, \( n^- \) the number of negative particle/event and \( n_s \) the number of stripping particles/event. The value of \(< N >\) (averaged for all the 3857 investigated collisions) is \(< N > = 5.854 \pm 0.393\) \( p \) while the average number of participant protons is found to be \(< p > = 2.972 \pm 0.197\). Considering that the production of kaons is isospin symmetric, it would follow that the \( K/p \) ratio in \( H e + Li \) collisions at 4.5\( AGeV/c \) is \((95.8 \pm 6.9)\%\), about 20 times greater than in pp collisions \((2 - 5)\%\).

Such unexpectedly large kaonic production asks for an untrivial explanation. It may be argued that this ratio is even higher, due to the elimination in the initial scanning of the kaons produced in the forward direction but the production mechanism discussed in the next section rules out the possibility of such an extrapolation.

4 Strangeness Production Through Dibaryonic De-excitation

In paper of [Besliu et al., 92], a model for non-strange dibaryons is developed starting from the conventional M.I.T bag model calculations and its predictions are shown to be in good agreement with the experimental data, mostly those obtained at J.I.N.R. - Dubna
from the irradiation of the 1 m hydrogen bubble chamber with a quasi-monochromatic beam of neutrons. The originality of that description resides in assuming the dibaryonic system composed of a diquark (a bound but unconfined two quark aggregate) and a cluster of four nearly free quarks. This assumption enables the six quark bag to acquire some degree of stability even in the $l = 0$ orbital momentum state. The $l \geq 1$ states are found to have masses allowing their direct decay into $(NNn\pi)$ channels with $n = 1, 2$ and even 3. Experimental candidates for $n = 1$ are also identified in the $np$ experiment and are analyzed in the same paper. The experimental data published by [Besliu et al., 92a] allow us to estimate the importance of the dibaryonic production in nucleonic interactions at energies close to those of the $He + Li$ experiment. At $p_{inc} = 5.1 GeV/c$ the sum of the total cross sections of the three five - prong channels investigated is $\sigma_T = 1520 \pm 110 \mu b$, while the sum of the reported dibaryonic production cross sections is $\sigma_D = 601^{+30}_{-61} \mu b$, thus representing a percentage of $39.5\%^{+24.2\%}_{-21.1\%}$ of the total cross section (the asymmetry of the errors originates as shown earlier [Besliu et al., 92a], from the interference between the fit errors affecting the weights of the dibaryonic peaks and those of the fitted widths). The sum of the production cross sections of the $l = 1$ dibaryonic candidates exceeds about four times that corresponding to the $l = 0$ dibaryons $480^{+218}_{-51} \mu b$ versus respectively $120^{+83}_{-10}\mu b$. It must be noticed that in the conditions of the $np$ experiment, there are some forbidden dibaryonic isospin states, thus the results above are slightly underestimated. It must be also stressed that in that experiment the contribution of dibaryonic states with $l \geq 2$ was not taken into consideration, but their occurrence was signaled.

It was shown [Besliu et al., 92b], [Besliu et al., 91b] that the orbital de - excitations are likely to produce within different dibaryonic states. The cascade transitions $(l = 2) \Rightarrow (l = 1) \Rightarrow (l = 0)$ create a complicated structure of narrow maxima in the beginning of the di-pionic effective mass spectrum, while the direct $(l = 2) \Rightarrow (l = 0)$ de - excitations with the emission of a pair of pions are shown to lead to a significant bump in the $2\pi$ invariant mass spectra, near the threshold, quite similar to those reported in the $M_{\pi - \pi}$ effective mass spectrum from $O + Pb$ central collisions at 4.5 $A GeV/c$ [Besliu et al., 89]. This similarity supports the hypothesis of significant dibaryonic production in nucleus nucleus collisions in few GeV energy region.

Another important consequence of the diquark - four-quark cluster structure for the dibaryonic resonances, also discussed in papers of [Besliu et al., 92b], [Besliu et al., 91b] is the strong dependence of the dibaryonic mass spectra and of the slopes of the corresponding Regge trajectories on the density of the environmental nuclear matter. It was shown that if the density of the production region is high enough, the threshold for the production of kaons via dibaryonic de - excitations is over passed, thus opening supplemental channels of strangeness production and leading to $S = -1$ dibaryons in the ground orbital state.

A typical diagram describing a $\Delta l = 1$ dibaryonic de - excitation with the emission of a kaon is presented in Figure 5. The rearrangement of quarks (the s quark of the created pair is substituted by a nonstrange quark from the four - quark dibaryonic cluster) is quite mandatory, as the available de - excitation energy is not enough in order to allow the hadronization of the $(s, \bar{s})$ pair as $\eta$ meson. The resulting dibaryon should be observable as a resonant $(N\Lambda)$ state, as predicted by [I.Pop et al., 90] where a version of our dibaryonic model have been tested for the description of the $(p\Lambda)$ and $(p\Lambda\pi)$ observed candidates [Shahbazian et al., 88]. The absence of the $\bar{u}$ and $\bar{d}$ antiquarks in the system rules out the production through diagram (Figure 5) of both the $K^-$ and $\bar{K}^0$ meson.

From the kinematical point of view, the diagram (Figure 5) represents a two body de-
cay, in which only scalar particles are involved. In such conditions the ground state dibaryon 
and the emitted meson (kaon or, in the case of the gluon decay into a pair of nonstrange 
quarks a pion) are emitted with opposite momenta on a uniformly distributed direction 
with respect to the reference frame of the decaying state. As initial dibaryons are likely 
to be produced as a result of the interaction between the beam nucleons with the target 
ones, they should (in the laboratory reference system) move in the forward direction. Taking 
into consideration the fact that the $l = 0$ dibaryon carries out the most important fraction 
of the mass of the $l = 1$ one, it is reasonable to suppose that the de-excitation mesons are 
preferentially emitted in the backward hemisfere, so the kaon production in this direction 
should not be extrapolated to the forward region of the reaction. Those simple kinematical 
arguments may offer a convenient explanation to the fact that the observed anomalous 
backwards kaon production (at least in which concerns the positive unidentified kaons) 
should not manifest itself with the same intensity in the forward direction.

In order to appreciate the importance of the diagram depicted in Figure 5 to the 
total yield of straniety in our reaction, it is significant to analyze it in balance with the 
corresponding nonstrange diagrams which would lead to pion production. As pointed out 
in papers [Besliu et al., 92 1], [Besliu et al., 91 2], the increase of the dibaryonic Regge 
trajectories in the conditions of nuclear matter densities reasonable to expect in collisions 
involving light nuclei, results in de-excitation energies close to the kaonic threshold. We 
may then suppose that the diagrams without strangeness production would preserve in 
our experimental conditions, the leading role.

The explanation of abundant $K^-$ production is to be found by a different mechanism. As suggested by the $np$ experiment, the production of $l = 2$ dibaryonic states is also 
significant in nucleon nucleon collisions at close energies. In the conditions of collisions 
between relativistic nuclei, due mostly to the collective interactions, the production of 
such excited multiquark states could be enhanced. Those systems could de-excite to the 
ground state by a succession of two $\Delta l = 1$ processes as that described above (which 
would be less probable due to the finite life of the dibaryonic resonances), or directly as 
suggested by the diagram of the type presented in Figure 6.

The available energy for such a de-excitation process is two times that available in 
the previous cases so the strangeness production should be favor with respect to the 
nonstrange channels.

The first gluon exchanged between the four quark cluster and the diquark is supposed 
to leave the dibaryonic system in the $l = 0$ state and thus should carry two units of 
kineic momentum. If the gluon decays into a pair of quarks $(s, \bar{s})$ those quarks will be 
inhibited to hadronize due to their large relative orbital momentum. The hadronization 
becomes possible after the exchange of the second gluon between the two strange quarks 
that could decay into a $(u, \bar{u})$ or a $(d, \bar{d})$ quark pair, thus leading in the final state to 
the creation of the $(K^+, K^-)$ or a $(K^0, \bar{K}^0)$ pair, such a diagram being the only one 
that could be responsible of the anomalous $K^-$ production observed in our data. As the 
pair of mesons are simultaneously produced with a certain delay after the dibaryonic de-
excitation took place, the entire process could be regarded to be more likely a two-particle 
decay than like a three-particle one. It follows from this assumption that the kinematical 
distribution of the kaons is like to be shifted towards the backward hemisphere, from the 
same reason as in the previous case.

The diagram from figure 6 offers also the possibility to make semi-quantitative analysis 
of the conditions in which the observed yield of $K^-$ mesons is a reasonable one. As the
experimental values of \( < K^- > \) is about 0.7 and as the probability to obtain a negative kaon from the investigated process is 50%, the requested averaged number of dibaryonic \( \Delta l = 2 \) de-excitation in one \( He + Li \) interaction must be about 1.4. From the dibaryonic production cross sections measured in the \( np \) experiment it follows that the probability of the creation of such a resonance (only for the \( l = 0 \) and the \( l = 1 \) ones) is about 40% for each individual interaction. Assuming that in \( He + Li \) reaction the production of \( l = 2 \) dibaryons has the same order of magnitude and tacking into account the averaged number of participant nucleons \( < N > \approx 6 \), it follows that the expected number of \( l = 2 \) states should be about 1.2. As nuclear effects could actually enhance the excited dibaryonic production, such a mechanism could thus lead to a reasonable quantitative agreement with the experimental data.

We remark also that Jacob and Rafelski [Jacob and Rafelski, 1987] have pointed out that in a baryon rich environment which also contains high density of u and d quarks and antiquarks a higher relative abundance of strange quarks should be favored.

This result confirms also the recent identification of hadronic clusters in central collisions reported by El Naghy [El Naghy et al., 1991] by more complex analysis of the emission of the produced shower particles and target fragments in \( Si + Ag(Br) \) and \( Mg + Ag(Br) \). The observed back-to-back emission of these clusters reflects the sideward flow of nuclear matter in the studied interactions.

## 5 Di-Pionic Effective Mass Anomalies As Dibaryonic Signals

Assuming the above interpretation of hard negative secondaries measured in the backward hemisphere as being kaons produced through dibaryonic de-excitations, it follows that signatures of those controversial resonances should also manifest. In papers [Besliu et al., 1992a], [Besliu et al., 1991b], it was speculated that the dibaryonic de-excitation via pionic emission should lead to anomalous maxima in the low mass region of the invariant mass spectra of two pions. Such effects have been already reported, as observed in connection with dibaryonic production by neutron-proton interaction at a few GeV and could be a tentative explanation to the so-called "ABC" effect [Besliu et al., 1992b]. Strong anomalies in the \((\pi^-\pi^-)\) and \((\pi^-\pi^-\pi^-)\) invariant mass spectra have been also reported in \( O + Pb \) reaction at 4.5\,AGeV/c [Besliu et al., 1991a]. This last example belongs also to the SKM-200 Collaboration and it has been for the first time suggested that such maxima could be related to the dibaryonic production.

In Figure 7 we present the effective mass spectrum for the pions produced in the \( He + Li \) collisions at 4.5\,AGeV/c. The bin width was chosen in concordance with the estimated experimental resolution. The contribution of particles with \( y \leq -0.7 \) was omitted. It must be underlined that Figure 7 depicts only the low mass region of the spectrum. The tail of the invariant di-pionic mass distribution observed in our interaction expands till about 2\,GeV\,c\(^{-2}\), but for the signals we search for only the represented mass region is relevant.

In order to construct the background distribution, we have combined pions originating from a different event from a set of 200 interactions, obtaining the upper dotted (the larger dots) in Figure 7. By fitting the spectra with only this contribution we have obtained a value of the \( \chi^2/N.D.F. \) of 1.579. The inclusion of two components of the spectra...
simulated in papers [Besliu et al., 92 b, Besliu et al., 91 b] representing the contribution of the direct dibaryonic de-excitation with Δl = 2 and of cascade de-excitation from the predicted l = 3 states to l = 0 dibaryonic states by successive Δl = 1 transitions, represented in Figure 7 by the lower (smaller dots) dotted lines, resulted in a decrease of the χ²/N.D.F to the value of 0.93. The solid line in Figure 7 indicates the best fit curve, the contribution of the two kind of dibaryonic de-excitation being 2.8% (for the direct ones) and 2.5% for step-by-step ones. The fit was made considering the full invariant mass spectra (60 beans) which could explain the small values of the above contributions. If we take into consideration the fact that the de-excitation signals affect only the first ten beans of the spectrum, then the improvement of the χ²/N.D.F estimator with about 0.5 indicates an integrated effect of approximately five standard deviations for those points.

The insufficient experimental statistics (due to the low pionic multiplicities of the investigated reactions did not allow us to introduce further hypothesis in order to improve the concordance between the spectrum and the simulated curve, but we may claim that the di-pionic signals of the dibaryonic orbital de-excitation were identified in our data.

The observed excess of pion pair production with low values of the invariant mass is equivalent to an enhancement of the production of pions with low relative momenta. This effect could be related with the observed angular correlation maxima at low relative angles in p+Au collisions at 4.9, 60, and 200 GeV, as reported in paper [Kampert et al., 92]. The explanation proposed in that article is based on the geometric properties of hadron-nucleus interaction at non-zero values of the impact parameter, but such an argument seems less convincing in the case of nearly symmetric nucleus-nucleus collisions.

6 Conclusions

The unusual behavior of some uniparticle distributions observed in the He+Li interaction at 4.5 AGeV/c is explained as the effects of an increased production of K⁻ mesons via dibaryonic de-excitation. Di-pionic invariant mass spectra are found to be in agreement with the expected signals of dibaryonic orbital de-excitation, thus supporting our interpretation of data.

The role played by the dibaryonic resonances in the relativistic nuclear collisions could be a significant one. The experimental data analyzed support the previous description of those exotic states as diquark-four quark cluster bags, as well as the predicted consequences concerning the behavior of such systems if produced inside compressed nuclear matter. The production of dibaryons during the high energy nuclear collisions could be responsible on the lack of observing till so far the creation of quark-gluon plasma in such processes. In fact, the apparition in the compressed nuclear matter of a bosonic phase, made of dibaryonic resonances, is expected to inhibit the deconfinement of quarks as supposed by the conventional picture of the relativistic nuclear physics.

We claim that the wealth of pion and kaon data accumulated in experiments at higher energies and multiplicities (CERN and BNL) could offer, if appropriately analyzed, very relevant insights on the role played by an intermediate bosonic phase in relativistic nuclear collisions.
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Figure 1: Schematic picture of the streamer chamber

Figure 2: The azimuthal distribution of the negative secondaries in He + Li central collisions at 4.5 AGeV/c

Figure 3: The rapidity distribution of the negative secondaries in He + Li central collisions at 4.5 AGeV/c

Figure 4: The $p_\perp$ distributions for the negative secondaries in He + Li collisions

Figure 5: Diagram describing the proposed $\Delta l = 1$ dibaryonic de-excitation

Figure 6: Diagram describing the proposed $\Delta l = 2$ dibaryonic de-excitation

Figure 7: The $(\pi^-\pi^-)$ invariant mass spectrum in He + Li central collisions at 4.5 AGeV/c. The curves are theoretical results obtained from different dibaryonic de-excitation (see the text for explanations)