The Invariant Mass Spectra Profile
Close to Pentaquark Mass Region
at 1.54 GeV/c^2.

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Abstract
Two possible reasons for the narrow peak observation in the invariant mass spectrum of the pK^0_s close to 1.54 GeV/c^2 are discussed.
# 1 Introduction

Five different experiments have reported the observation of a narrow peak in the invariant mass spectra close to 1.54GeV/$c^2$ with a width below 25MeV/$c^2$. These peaks are considered as a signature of a five quark resonance, the so-called $\theta^+$.

Three photo-production experiments 1, 2, 3 have observed the $\theta^+$ decay to $nK^+$ in three- or four- body final state. The neutron was reconstructed from the missing mass and energy.

The $\theta^+$ decay to $pK^0_s$ was observed in $\nu_{\mu^-}(\bar{\nu}_{\mu^-})$ collisions with nuclei 3. This analysis has combined data samples from different bubble chamber experiments with a large range of neutrino momenta.

Using a $K^+$ beam, the same $pK^0_s$ channel of the $\theta^+$ decay was observed by the DIANA collaboration 5. The Monte Carlo simulation for this experiment is rather simple for the following reason: first - the beam momentum spectrum is explicitly shown in the publication, second - all particles in the final state ($p$ and $K^0_s \rightarrow \pi^+\pi^-$) were reconstructed and identified.

The result of the simulation for the DIANA experiment are presented in the section below. One section further the result of the experiment “independent” simulation shows the possible source of the narrow peak in the invariant mass spectrum.

# 2 Monte Carlo simulation.

The experimental momentum spectrum of the incident beam particle $K^+$ (Fig.1) is shown for two cases: the momentum spectrum for all events with the identified $K^0_s$ (top) , and for events where both the $K^0_s$ and the proton were identified (bottom). The momentum spectra look very different, both in momentum range and in shape. For the events with $pK^0_s$ in the final state the momentum profile has an asymmetric “bell”-like shape with the average momentum close to 470MeV/$c$.

The $K^+$ momentum spectrum was simulated according to the experimental distribution shown in Fig.1b. The momenta of the outgoing particles are generated uniformly in the available Lorentz-invariant phase space. Two processes are simulated:

- three body final state - a nucleus play a role of the recoil particle:
  
  $K^+Xe \rightarrow pK^0_sXe'$

- two body final state - a charge-exchange reaction on the neutron of the Xe nucleus:
  
  $K^+n \rightarrow pK^0_s$

  The momentum is shared by two particles only.

The $pK^0_s$ invariant mass spectrum for three body final state simulation is shown in Fig.2b. The comparison with the experimental distribution ("red" histogram) shows a reasonable agreement in positions, widths and shapes of both spectra.

The invariant mass spectrum for the two body final state simulation is shown in Fig.2c. In contrast to the three body final state $pK^0_sXe'$ the mass distribution resembles narrow peak with a sharp maximum at 1.55GeV/$c^2$.

The simple MC test with the $K^+$ momentum spectrum of the gaussian shape (the mean at 450MeV/$c$ and the width 15MeV/$c$) shows that the narrow momentum range of the incident $K^+$ beam is the reason why the narrow peak is seen in the mass spectrum in case of two body final state (Fig.2d). The shift of the $K^+$ momentum distribution by 20MeV/$c$ gives the proportional shift by 10MeV/$c^2$ in the mass peak position (Fig.3d) and puts the maximum at 1.54GeV/$c^2$.

The simulation of the $pK^0_s$ kinematic disagree with the observed invariant mass spectrum only in one point - peaks are shifted by 10-15MeV/$c$. This shift may come from the fact that in the MC the binding energy of the nucleus was not included in the simulation. There is an explicit indication in reference 3 that the $K^+$ beam momentum was shifted by $\pm$15MeV/$c$ in different data sample, but there is no indication about the corresponding statistics, accumulated with a particular beam momenta. As result, the MC events were not weighted and that may also cause some kind of shift in the peak position. The difference in the width is not too important - the MC shows that with statistic of about 30 event, the narrow peak may be observed even if the original distribution is wide (Fig.4). The narrow two-bin peak distribution, when at least 50% of entries belongs to two bins only, was observed in 2% cases - a non-negligible number.
3 The kinematic “reflection” at 1.54GeV/c².

Since the mass region around 1.54GeV/c² has so much importance in the narrow peak search, another source of trouble must be pointed out. In a data sample of V⁰ candidates (V⁰ is used as a generic name for K⁰, Λ or Λ̅) the narrow peak in the mass spectrum may be created in the following way.

A V⁰ decays in two particles of opposite charge. Since the type of the particle is not known in the experiment the different mass hypothesis have to be assigned to each track to explore all combinations. With pion and proton/anti-proton masses assigned to corresponding tracks, each V⁰ may represent K⁰, Λ or Λ̅.

The most convenient way to present the kinematic of the V⁰ decays is an Armentero-Podolansky plot [6], shown in Fig. 5, where the three ellipses correspond to K⁰ → π⁺π⁻, Λ → p π⁻ and Λ̅ → pπ⁺ decays. The ellipses have two overlap regions where this V⁰ species are kinematically indistinguishable. Therefore, without an explicit cut on the corresponding mass hypothesis, there is always a cross contamination. For example K⁰ may be not a “true” K⁰ but a Λ or Λ̅ in these narrow kinematic regions.

In second step the V⁰ is then combined with the same physical track which was already used for the V⁰ itself. Two class of combination may be defined:

- True K⁰ and the π⁺ of the K⁰ but considered as a proton (class 1).
- True Λ but considered as a K⁰ and a positive track of the Λ which is a true proton (class 2).

Figures 3 and 4 show the invariant mass distributions for the two classes of combinations defined above.

The standard cut used in all experimental analysis is a cut on the invariant mass of the π⁺π⁻ combination around K⁰ mass (|m_{K⁰} ± m_{π⁺π⁻}| < 3·σ). The usual mass resolution for two track combinations is limited to σ=2-4MeV/c. For class 1 this cut does not change the invariant mass distribution (true K⁰), but for class 2 this cut removes combinations with small masses and retains combinations around 1.54GeV/c² (Fig. 5). Fig. 6 shows the combined (class 1 and class 2) mass spectrum.

It is hardly believable that a straightforward double track counting may happen in a real analysis. At least for DIANA this possibility is excluded by the nature of the experiment - in the bubble chamber all tracks are visible. The problem might be important for the electronic experiment if the cut on V⁰ masses is not tight enough, thus the K⁰ - Λ cross contamination is not removed completely, and the pool of reconstructed tracks is not free from “clones” or “ghosts” - de-facto the same track reconstructed twice due to, for example, some noise in the tracking detectors. The kinematic of such “clones” is very close to each other thus simulating the situation discussed above, naturally with a slight variation in the mass position and the width of the peak.

4 Conclusion.

The result of the simple MC shows that the invariant mass spectrum of the pK⁰ combinations has a narrow structure close to 1.54GeV/c² due to the narrow momentum range of the beam. If this is true, then further data analysis using the full momentum range of the beam (see Fig. 1a) will cause the broadening of the observed peak and yield the answer about its nature.

The artificial peaks in the invariant mass spectra due to kinematic reasons are well known. The only surprise is that such an artifact precisely coincides with the value of 1.54GeV/c².

The recent publication [7] shows that the nK⁺ channel is not free from the kinematic reflections.

Finally the question about the pentaquark signature will be found in a very classical way - increasing the statistic involved in the analysis and hopefully in a different experimental conditions.

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Figure 1: a) The range and equivalent momentum (upper scale) of the $K^+$ beam for the events with $K^0_s$ identification only. The arrows indicate the momentum region of the $p$ $K^0_s$ selection. b) The momentum of the $K^+$ beam for the events with $p$ $K^0_s$ identification. The momentum distributions were taken from [5].
Figure 2: The experimental beam momentum and MC mass spectra distribution corresponding to: b) reaction $K^+Xe \rightarrow K^0pXe'$; c) reaction $K^+n \rightarrow K^0p$; d) the summ of both b) and c); The histogram in red corresponds to the experimental mass distribution from [5].
Figure 3: The beam momentum simulated according to the gaussian shape and MC mass spectra distribution corresponding to: b) reaction $K^+ Xe \rightarrow K_0^0 p Xe'$; c) reaction $K^+ n \rightarrow K_0^0 p$; d) the summ of both b) and c); The histogram in red corresponds to the experimental mass distribution from [5].
Figure 4: The invariant mass distribution for pK⁰ combination in case, when at least 50% of entries were observed in two bins (red) and the “true” distribution shape (black) in case of big number of entries.
Figure 5: The Armenteros-Podolansky plot for the $V^0$ candidates. $p_L^+$ and $p_t$ are the laboratory longitudinal and transverse momenta, respectively, of the decay tracks with respect to the $V^0$ direction. At the crossing point of the two ellipses the $K_S^0$ and $\Lambda$ kinematically looks the same.
Figure 6: The invariant mass distribution for $pK_s^0$ combination of class 1.

Figure 7: The invariant mass distribution for $pK_s^0$ combination of class 2.
Figure 8: The invariant mass distribution for pK$_S^0$ combination of class 2 when the K$_S^0$ mass is limited within the K$_S^0$ mass region.

Figure 9: The combined invariant mass distribution for pK$_S^0$ combination of class 1 and class 2, when the K$_S^0$ mass is limited within the K$_S^0$ mass peak region.