Search for ppnK$^-$ deeply bound states with FOPI

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Deeply bound states such as $ppnK^-$ might be produced in heavy-ion reactions close to the strangeness production threshold. The status of reconstructing the 2-body decay channel of $ppnK^- \rightarrow \Lambda + d$ with the FOPI apparatus in the reaction Ni+Ni at 1.93 AGeV is described.

1 Introduction

Based on the properties of the $\bar{\mathrm{K}}$N - interaction Akaishi and Yamazaki predicted the existence of deeply bound kaonic states [1, 2]. Due to the strong $K^- - p$ attraction these states are expected to be enormously condensed systems with a central nucleon density as high as 1.5 fm^{-3} and are therefore called kaonic clusters. Due to their large binding energy the main decay channel to $\Sigma\pi$ is energetically forbidden and thus these states have a narrow width of $\Gamma < 20 MeV$.

Evidence for the existence of deeply bound kaonic states has been collected at KEK by stopping K$^-$ - mesons in liquid helium. In the reactions ^{4}He(stopped-K^-, n) [3] and ^{4}He(stopped-K^-, p) [4] narrow structures are observed in the missing mass spectra that are attributed to the $T = 0$ $ppnK^-$ and $T = 1$ $pnnK^-$ states [5].

The strong binding and the large central density of the kaonic clusters make it likely that they are producable also in heavy-ion collision and due to their reduced width they might survive until the freeze-out [6, 7, 8]. Due to the many body nature of the final state in an heavy-ion reaction only 2-body decays can be used for reconstructing short lived states. In the following the search for the decay channel $ppnK^- \rightarrow \Lambda + d$ will be described. For this state an invariant mass of M=3.137 MeV/c^2 and a width of Γ <20 MeV has been measured [3].

2 Experiment

In January 2003 the FOPI collaboration took a data sample of $1.2 \cdot 10^8$ central events of the reaction Ni+Ni at an incident energy of 1.93 AGeV delivered by the SIS at GSI. The events were triggered by the multiplicity of charged particles in the FOPI forward plastic wall [9, 10] that viewed a target displaced by 40 cm upstream with respect to the nominal target position. The most central 600 mb of the interaction cross section was recorded.

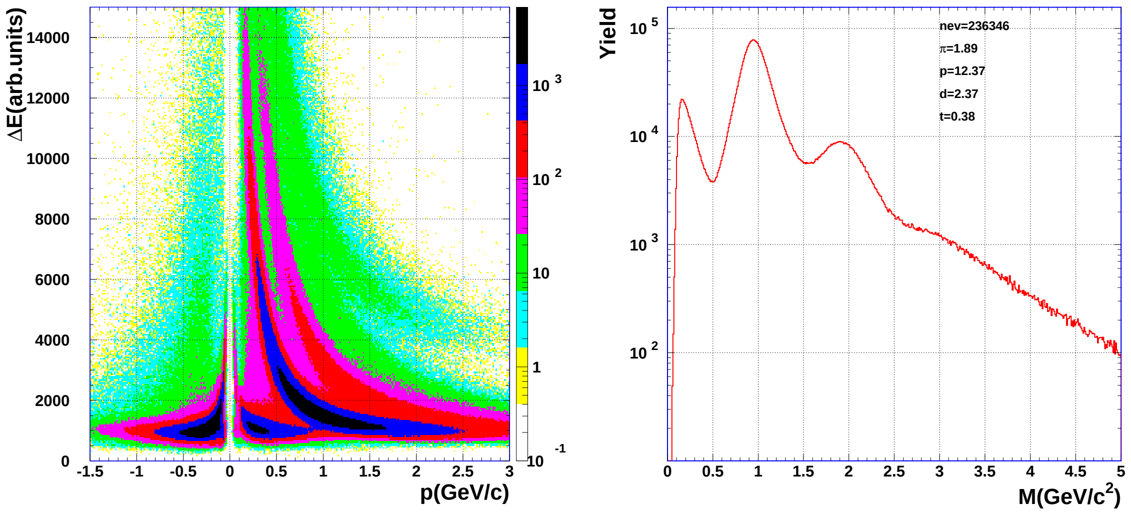

Figure 1: Correlation of the specific energy loss in the central drift chamber with the particle momentum determined from the track curvature (left). On the right side the mass distribution derived from linearizing the distribution with a Bethe-Bloch parametrisation for particles with a charge Z=1 is shown.

Within the event sample Λ particles are reconstructed by means of an invariant mass analysis of proton and pion tracks intersecting off the primary vertex. Particles were identified making use of the correlation of the energy loss in the central drift chamber the the particle momentum (Bethe-Bloch). The achieved resolution is shown in Fig. 1.
With the the PID capability in the CDC protons and negatively charged pions can be selected with the additional criteria that a) the tracks have a distance of closest approach to the primary vertex $|d_0^\pi| > 0.6$ cm and $|d_0^\pi| > 1.9$ cm, b) the intersection point (secondary vertex) has a transverse distance of 4 cm$<$r$_s$ $<$30 cm and c) the pointing angle $|\phi(\vec{p_t}) - \phi(\vec{x_{sec}})| < 2^o$. The resulting invariant mass distribution is shown in Fig. 2. All pairs fulfilling those selection criteria within a given event (red symbols) are compared to the background combining tracks fulfilling the same conditions o originating from different events (blue symbols, mixed event background). The mixed event background is normalized to the correlated event distribution in the range of $1.14 < M_{inv} < 1.25$ MeV. For the selection criteria employed in the following for investigating correlations with other particles 72k Λ - particles are reconstructed with a signal - to - background ratio of 5 and a width of $\sigma = 4.5$ MeV. The probability for observing a Λ - candidate under those conditions for the event sample under consideration (cross section σ=600 mb corresponding

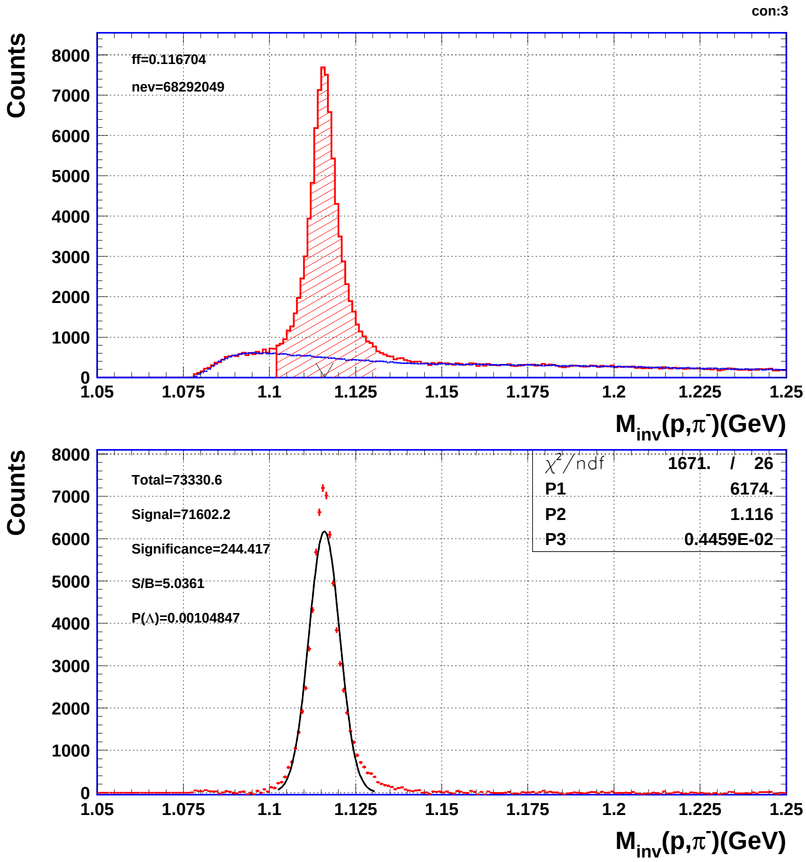

Figure 2: Invariant mass distribution of proton-π^-pairs under the selection criteria used for the $ppnK^-$ analysis

to an impact parameter b_{geo}=4.4 fm in a sharp cut-off approximation) is $P_\Lambda^{rec} = 1 \cdot 10^{-3}$, that can be decomposed into a primary yield of Λ of $P_\Lambda^{prod} \approx 1 \cdot 10^{-1}$ and a reconstruction efficiency in the order of of $\epsilon \approx 10^{-2}$. Details about the Λ phase space distributions and the reconstruction efficiencies can be found in [11, 12].

3 Reconstruction of Λ + d pairs

With an anticipated width of the $ppnK^-$ in the order of 10 MeV it is obvious that kaonic clusters are decaying inside the target. Their decay products are kinematically indistinguishable from all the other ejectiles emerging from a heavy-ion collision. Strongly decaying resonances can, however, be reconstructed by the analysis of the invariant mass distribution of their decay products. With the FOPI detector Δ-baryons [13] and Φ-mesons [14] have been found so far.

The sensitivity of the method can be estimated as follows: assuming that the analyzed decay branch of a resonance is populated with a probability P·BR, detected with an efficiency ϵ and a signal-to-background ratio of S/B, a certain number of events N is necessary in order to produce a statistically significant result (significance $\Sigma > 5$). From

$$\Sigma = S/\sqrt{S+B} \approx \sqrt{S} \cdot \sqrt{S/B}, S = \Sigma^2/(S/B) = P \cdot BR \cdot \epsilon \cdot N$$

the limit of the detectable production probability P·BR is obtained as

$$P \cdot BR = \Sigma^2/(S/B)/N/\epsilon.$$

For example, the available data from the Ni+Ni run in January 2003 with N=10^8, $\epsilon = 10^{-2}$, S/B=10^{-2} as typical numbers would allow for a significant results if the production probabilities of P·BR are larger than $3 \cdot 10^{-3}$. These dependences clearly call for large data samples.

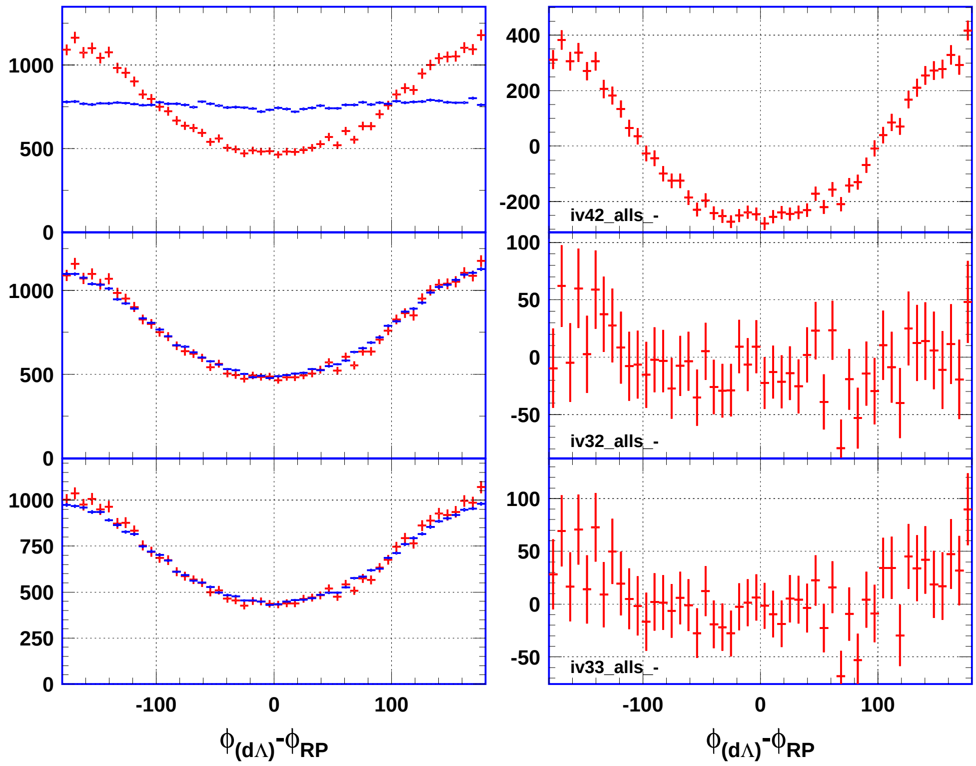

Figure 3: Azimuthal distribution of Λ candidates - deuteron pairs with respect to the reaction plane under different correlation criteria. In the left column correlated (mixed) pairs are shown by red (blue) crosses. In the right column the difference is plotted. For further details see text.

When trying to reconstruct the invariant mass distribution of Λ - candidates with some other particle special care has to be taken to be able to generate the corresponding mixed event distribution. This is essential since the shape of the background is determined by the acceptance of the experiment and cannot be calculated analytically. Two major effects have to be taken into account: a) the collective side flow of particles that focuses the

emission of baryons into a common reaction plane, b) the tracking efficiency for crossing and close-by tracks that is reduced with respect to independent tracks, i.e. when being taken from two different events.
For the case of Λ + d correlations the effect is shown for the azimuthal distributions with respect to the reaction plane in Fig. 3. The top row displays the raw distribution, demonstrating that Λ + d pairs are correlated with the reaction plane while mixed pairs are isotropically distributed with respect to the reaction plane. In order to eliminate effects due to the focusing of baryons into the sideflow direction all event were rotated to the common azimuthal reaction plane angle $\phi_{rp} = 0^o$. The resulting distributions after the rotation is shown in the middle part of Fig. 3. The lower row of Fig. 3 is obtained after further eliminating close - track pairs. This step does not affect the correlation with the reaction plane.

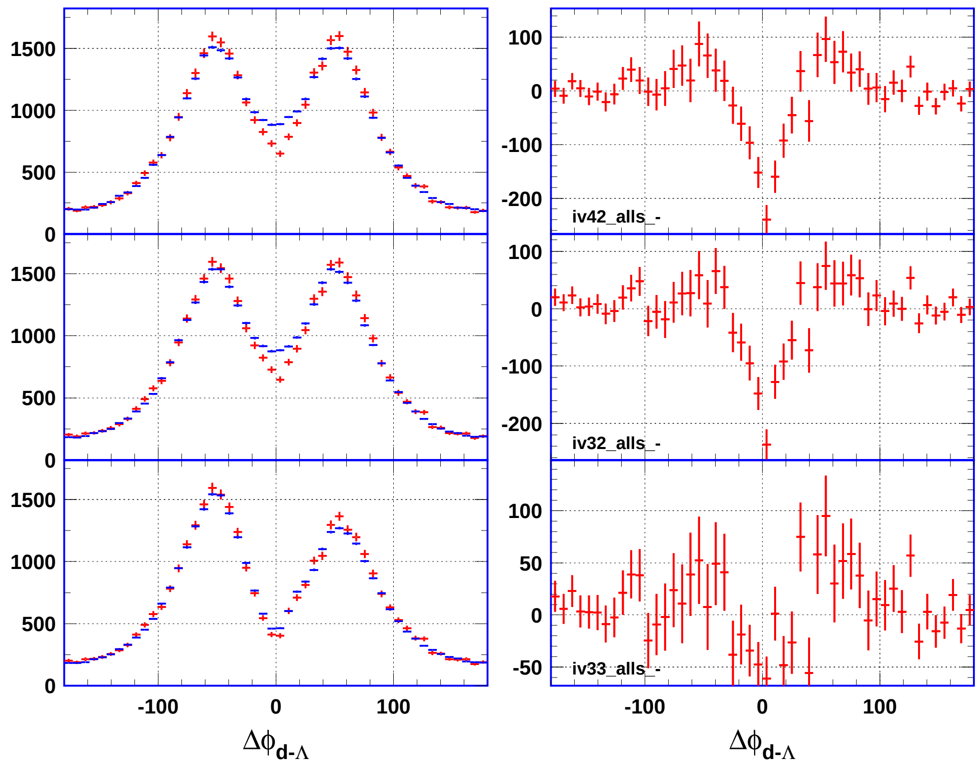

Figure 4: Difference of azimuthal angle distribution of Λ candidates and deuterons. The layout and conditions are the same as for Fig. 3.

That Λ - d pairs with a small difference in azimuthal angle have to be eliminated from the correlation analysis is derived from the upper two rows of Fig. 4: even after the rotation of the event to a common reaction plane (middle row) a deficit of correlated pairs with respect to the mixed event background is observed. This is attributed to a reduced tracking and detection efficiency for track pairs that are either crossing or close-by within the fiducial volume of the CDC. This argument is supported by the lower row of Fig. 4 where all pairs are eliminated from the comparison, that contain a deuteron track that is crossing any of the two Λ - daughter tracks within the geometrical boundaries of the CDC. The undershoot at $\Delta\phi_{\Lambda-d} = 0^o$. in the background subtracted distribution is removed almost completely. In order to avoid any biases for the following results all pairs are eliminated, that have an azimuthal difference angle of $|\Delta\phi_{\Lambda-d}| < 30^o$.

MC simulations

The effects described above are qualitatively reproduced by the FOPI GEANT3 based MC simulation where the response of the drift chamber is implemented on the raw data level. The simulation was tuned to reproduce the single track resolution parameters and is used in the following as reference in employing the same cuts to MC scenarios as used to examine the measured data.

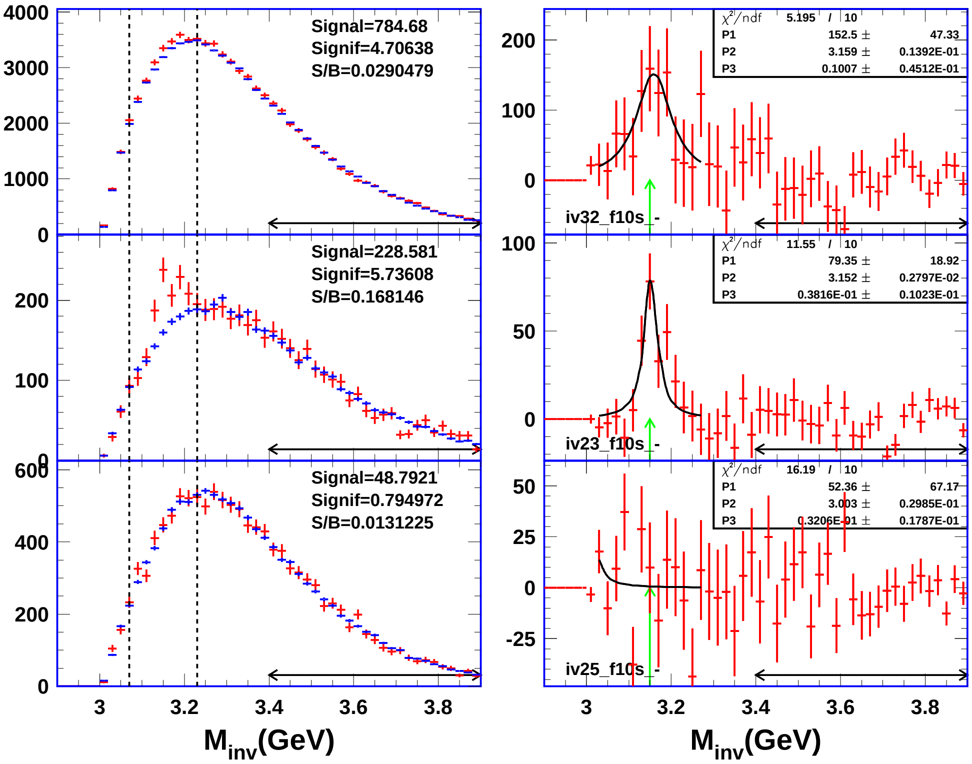

Figure 5: Invariant mass distributions of Λ-d pairs. On the left side combinatorial (red) and mixed event (blue) distributions are shown. They are normalized to each other within the range indicated by the horizontal arrow shown in the subpanels. The statistical information is evaluated in the interval defined by the vertical dashed lines.
On the right hand side the signal distribution as obtained from subtracting the mixed event background from the combinatorial distribution is displayed. The green arrows indicated the nominal center positions of the $ppnK^-$. In the first row data are plotted, the second row presents MC signal distributions, the bottom row represents the result for a MC background simulation. Further details are described in the text.

4 Results

After rotation of the event into a common reaction plane, applying the $\Delta\phi$ cuts and additionally restricting the rapidity of the Λ - d pairs to $y_{\Lambda-d} < 0.65$ the invariant mass distributions shown in Fig.5 are reconstructed. An excess is observed in the data (top row) at an invariant mass of $M_{inv} = 3.159 \pm 0.014\,\mathrm{GeV/c^2}$. The width of the observed structure is $\Gamma = 100 \pm 45\,\mathrm{MeV/c^2}$.

In Fig. 5 the data are compared to MC simulations where the invariant mass distribution of Λ-d pairs was analyzed for central Ni+Ni collision as calculated by means of IQMD transport simulations. In order to check that the reconstruction programs would allow for the detection of a resonance a signal with the properties reported in [3] was added to the IQMD events (middle row). Note that one decay of $ppnK^- \to \Lambda + d$ was added per event for the signal simulation. Clearly, with the methods and cuts employed to the data, the resonance could be reconstructed if existing. The reconstructed mean invariant mass is, however, shifted by about 10 MeV towards larger values. In the bottom row of Fig. 5 the biasing features of the selection cuts are inspected. One pair of Λ + K^0 particles was added to each IQMD event and the full events were analyzed with the same programs and cuts as used for the data. No significant excess is observed with the statistics currently available.

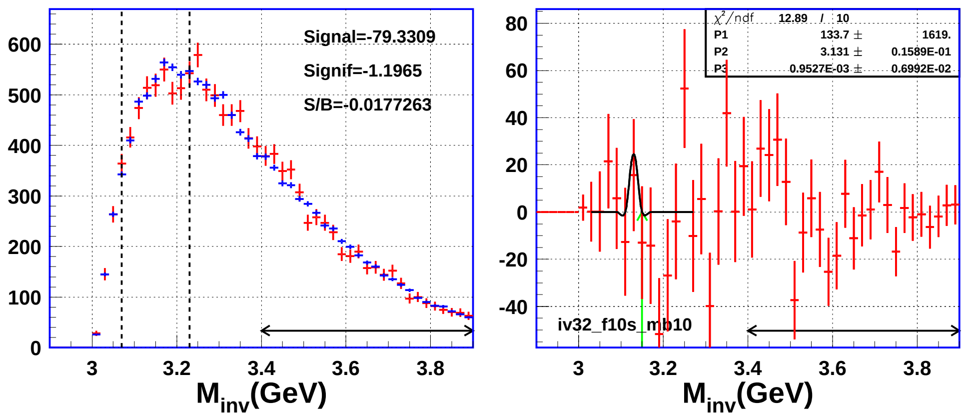

Figure 6: Invariant mass distributions of Λ-background - d pairs. Pairs of p-π^- tracks fulfilling the Λ-selection criteria with 10 MeV< $|M_{inv} - 1116\mathrm{MeV}|$ <20 MeV are combined with d-tracks. The layout of the figure is the same as in Fig. 5. Further details are described in the text.

As a further check, a sideband analysis was executed on the data sample. For the result presented in Fig. 5 Λ - candidates were selected within a mass window of ±10 MeV around the nominal mass. Taking pπ^--pairs that fulfill all the Λ - selection cuts used so far and e.g. employed in Figs. 2 and 5 but yielding an invariant mass in the range 10 MeV< $|M_{inv} - 1116\mathrm{MeV}|$ <20 MeV gives rise to the distributions presented in Fig. 6. Due to the reduced statistics off-peak the number of counts in the histograms is much less as compared to the data shown in Fig. 5. Anyhow, in the background data no significant structure or excess is visible confirming the conjecture that the excess observed in Fig. 5 is indeed caused by a real correlation among Λ - and d - particles.

5 Outlook

The structures observed in the Λ +d - invariant mass distributions shown up only under restrictive cuts on the phase space (rapidity $y_{\Lambda d}$ <0.65) and are statistically on the borderline at which one would declare the discovery of a new resonance. However, due to the complexity of the method combining Λ - candidates with tracks originating from the primary event vertex and employing strong selection cuts systematic distortions due to detector effects that are not implemented in the MC simulations cannot be ruled out completely at this moment. Nevertheless the possibility to produce these exotic states in heavy-ion collisions is very exciting since, if confirmed, heavy-ion collisions would provide a unique tool to produce a whole series of new states and one could get access to yet unexplored regions of the phase diagram of strongly interacting matter.
In order to progress it is mandatory to a) validate the analysis method by reconstructing known resonances. A candidate for this step is the $\Sigma^*(1385)$ - resonance that decays with a branching ratio of 99% in Λ +π - pairs. b) In order to improve the statistical significance the FOPI collaboration plans to run a new experiment with an upgraded data acquisition system. The experiment aims at a gain in the event statistics of a factor of 10 and correspondingly the significance of the measurement should be increased by at least a factor of 3. This gain factor is expected to be enlarged by the choice of the system Al+Al that has a smaller multiplicity and therefore the combinatorial background is reduced. c) As a third possibility the reconstruction of other deeply bound states would be very helpful to establish the picture. Especially the ppK^- is interesting since it should have a substantial branching ratio to Λ - p. The reconstruction in heavy - ion reactions is made more difficult due to the large associated multiplicity of protons (see Fig. 1). The analysis of this channel is in progress. d) The elementary reaction $p + d(liquid) \rightarrow ppK^-$ +K^0 +p will be studied to overcome the problem of the large combinatorial background. It further allows to combine missing mass techniques with the reconstruction of the invariant mass from the decay products of the resonance. Details of this experiment are given in [15].

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