Study of bound kaonic systems in nuclear matter with FINUDA at DAΦNE

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Abstract. The possible existence of deeply bound kaonic states has been studied with the FINUDA spectrometer at DAΦNE, exploting both the invariant mass specrtoscopy technique, and the missing mass one. A few indications for the existence of the strange dibaryon have been found; some indications for the existence of a tribaryon, confirming previous observations by other experiments, are, at the moment, questionable.

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DEEPLY BOUND $\overline{K}$-NUCLEUS STATES: INTRODUCTION

The possible existence of deeply bound (anti)kaon-nucleus states has raised considerable interest quite recently, with the publication of some first experimental observations [1, 2, 3] in rough agreement with a few theoretical expectations based on the calculations of Yamazaki and Akaishi [4].

These states consist of few-body strange (S=-1) systems composed by nucleons strongly bound to a $\overline{K}$. The strenght of the $\overline{K}N$ attractive interaction, in the $I = 0$ configuration, allows for the stability of the system, as well as for its compactness [5]. This feature is important as these aggregates could be possible constituents of high density forms of nuclear matter, such as the core of neutron stars.

Akaishi and Yamazaki predict for these states rather sizeable binding energies, as large as 100 MeV. In such a model the $\overline{K}N^{(I=0)}$ interaction is predicted to be so strong that the widths of these aggregates should be considerably narrow. Their main decay mode, $\Sigma\pi$, is in fact energetically closed, and moreover the $\Lambda\pi$ channel is forbidden because of isospin conservation; the predicted values are, for instance, 61 MeV for the strange dibaryon (ppK^- system), for which a mass 2322 MeV is expected, and $(13 \div 21)$ MeV for the tribaryon ($ppnK^-$ system), with a mass expected in the range

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$(3117 \div 3152)$ MeV, depending on the isospin configuration. In this framework, these states are expected to be formed with larger probabilities in lighter nuclei.

However, other models for the K^--nucleus interaction have been proposed, that require a shallower potential well ($50 \div 75$ MeV deep, mining existence of a bound system) [6], and comply as well to the description of K-atoms experimental results. At the moment, no experimental indication has been found to favour one of the two possibilities. Recently, however, a critical revision of the calculations of the deep-potential model have been made [7], and arguments were given in support of the shallower potential version.

FIRST EXPERIMENTAL OBSERVATIONS

The observations of a possible $\overline{K}$-nucleus state are based on two methods: by reconstructing the invariant mass of the system starting from its decay products, namely a hyperon and a nucleon (*invariant mass spectroscopy*), or by measuring the momentum of the monochromatic recoiling nucleon in a $A(K^-,NX)$ reaction (*missing mass spectroscopy*). The first method is of course more precise and allows for stricter selection criteria, such as cuts on angular correlations, but can be exploited only by performant apparatuses able to fully reconstruct the event topologies, as FINUDA [8] is. The second technique has been used so far for the first observations.

The experiment KEK-PS E471 studied the inclusive spectra of a proton [1] or a neutron [2] emitted in the $^4\mathrm{He}(K^-,NX)$ reaction. They quote the existence of two different states: $S^0(3115)$, with $I=1$, produced in the reaction $K^-_{stop} + ^4\mathrm{He} \rightarrow (K^-pnn) + p$ [1], and $S^+(1340)$, with $I=0$, produced in $K^-_{stop} + ^4\mathrm{He} \rightarrow (K^-ppn) + n$ [2]. The two masses are slightly different, while the widths are comparable, with a quoted upper limit of 21 MeV/c^2. The preferred decay channel, for both, is suggested to be Σ^-NN, since in both the cases the peak in the inclusive spectrum becomes clearer when a high momentum π^- in coincidence with the nucleon is required. The two structures are suggested [9] to be compatible with a deeply bound kaon-nucleus state with a binding energy of about 170 MeV; their masses are remarkably in agreement with the expectations of the model by Akaishi and Yamazaki, suitably modified [9].

A third observation was performed by the BNL-AGS E930 Experiment, which measured the missing mass spectrum in the $^{16}\mathrm{O}(K^-,n)$ reaction, with 930 MeV/c kaons. The distribution shows two slight enhancements, corresponding to a binding energy of the kaon of about 90 MeV (which can be referred to the formation of the kaonic oxygen $^{16}_{\overline{K}}\mathrm{O}$ with the kaon in p-shell), and of 130 MeV ($^{16}_{\overline{K}}\mathrm{O}$ with the kaon in s-shell).

OBSERVATIONS WITH FINUDA

FINUDA is a multi-purpose magnetic spectrometer installed the DAΦNE e^+e^- accelerator at Laboratori Nazionali di Frascati, Italy. Details of its set-up and performances may be found elsewhere [8]; its most peculiar features are a very good momentum resolution (from 0.5 to 1.5% FWHM depending on the mass and momentum of the particle), an angular acceptance close to 2π sr and an excellent particle identification. Moreover, the apparatus is equipped with targets of five nuclear species, in order to provide measurements of the same observables in several nuclear media at the same time.

Thanks to these features, the apparatus can be used not only to perform high resolution studies on hypernuclear spectroscopy and decay modes, but can also deliver interesting by-products results –like, for instance, hints on the existence of deeply bound kaonic states, obtained using effectively both the invariant mass and the missing mass spectroscopy methods.

The invariant mass method. Some indications of the existence of a strange dibaryon decaying into Λp have been found with FINUDA [10], thanks to its ability to fully reconstruct the particles produced in a K^-A interaction. When a K^- coming from the decay of the ϕ meson stops in a nuclear target, it can interact with one or more nucleons, forming deeply bound states or undergoing absorption processes. If a kaonic bound state is formed, one should be able to reconstruct its mass by the measurement of a YN pair from its decay. Moreover, in the hypothesis of a bound state decaying at rest, a back-to-back correlation of these two particles can be required.

The Λ particle can be reconstructed in FINUDA by its decay products, a proton and a π^-. Because of the 1.1 T magnetic field, the requirement of high quality tracks (built by the maximum number of hits in the spectrometer) imposes an acceptance cut on the Λ momentum, which can be detected only if exceeding 300 MeV/c, since the reconstruction of the pion is possible only down to $\sim$ 180 MeV/c. In a typical "deeply $\overline{K}$-bound" event, the back-to-back Λ and the proton have a momentum of about 500 MeV/c, while the pion from the Λ decay has a 200 MeV/c momentum. The event may therefore be fully reconstructed. By allowing tracks to be reconstructed using three points only, including therefore short tracks also in the analysis, one can increase the available statistics, losing however in momentum resolution. The analysis including short tracks is currently underway [11]; the preliminary issues confirm the results obtained with high resolution tracks, allowing a reduction of the statistical errors and giving the possibility to study different behaviors depending on the target material.

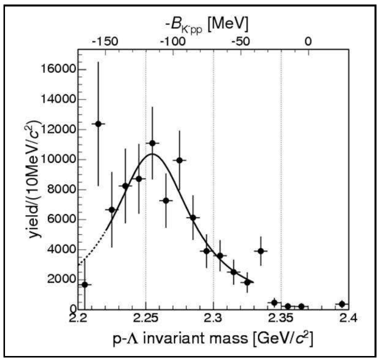

FIGURE 1. Acceptance corrected invariant mass of the (Λp) system (back-to-back particles). The peak has been fitted with a Lorenzian function smeared with the apparatus resolution (gaussian function with $\sigma = 4$ MeV).

Independently on the target, a clear back-to-back correlation is found for the events in which a Λ, reconstructed with a resolution of 6 MeV/c^2 FWHM, is produced in coincidence with a second proton (amounting to about the 5% of all events with a reconstructed Λ).

In case of a two nucleon absorption reaction $K^- + (pp) \to Y^\star N \to \Lambda p$ with the production of a $Y^\star$ intermediate state, one would expect the invariant mass of the $(K^- pp)$ system to be peaked at 2.37 GeV. On the contrary, the invariant mass of the back-to-back Λp system (selecting events from the lightest available targets only, ^{6}Li, ^{7}Li and ^{12}C), exhibits a much lower peak, shown in Fig. 1.

It cannot simply be explained as due to the contribution of the $\Sigma^0 p$ channel, with the following electromagnetic decay $\Sigma^0 \to \Lambda\gamma$, since in this case the peak would be just 74 MeV/c^2 lower, and moreover Doppler broadened. The observed peak is rather narrow, and with proper acceptance corrections (which are mass dependent), shifts further downwards. After background subtraction, which eliminates the contributions of quasi-free YN production of a kaon against two nucleons, one gets a peak at about 2250 MeV/c^2. Fitting it with a lorentzian function the binding energy and width of such a state can be obtained: $B = 115^{+6}_{-5}(\mathrm{stat})^{+3}_{-4}(\mathrm{sys})$ MeV, $\Gamma = 67^{+14}_{-11}(\mathrm{stat})^{+2}_{-3}(\mathrm{sys})$ MeV. Its tentative production yield is about 0.1%/(stopped K^-).

This is the first observation of a dibaryonic strange system; recently, a similar behaviour has been observed by the FOPI Experiment at GSI, studying the (Λp) invariant mass system in Ni+Ni collision events at 1.093 GeV/A [12].

The missing mass method. The inclusive momentum distribution of a proton emitted after the capture at rest of a K^- on ^{6}Li is shown in Fig. 2.

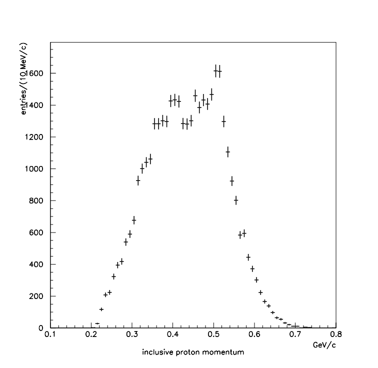

FIGURE 2. Inclusive momentum spectrum of a proton produced in a K^{-6}Li absorption process in FINUDA.

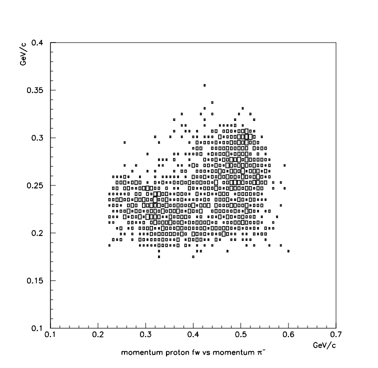

FIGURE 3. Scatter plot of semi-inclusive momenta spectra (p and π^- in coincidence: along the x axis, the distribution of the p momentum is plotted, along y, the distribution of the π^-. A clear correlation between the two can be observed, for higher π^- and p momenta.

While the structure of the left side of the spectrum can be explained as due to the contribution of non mesonic decays of hyperfragments, the peak at about 500 MeV/c is similar to the signal observed by E471. The events in this peak are characterized by the simultaneous presence of a high momentum π^-, as shown in the scatter plot of the two momenta reported in Fig. 3. When a selection on the pion momentum is made ($p_\pi > 260$ MeV/c), a clear peak in the proton momentum spectrum shows up. This enhancement could have a few possible explanations.
Following the analysis by E471, and accounting on the experimental observation that in several reactions a ^{6}Li nucleus behaves like a $(d+\alpha)$ cluster, with the two nuclei in relative s-wave [14], one might try to explain it as due to the formation of a tribaryon on a “quasi”-^{4}He substructure of ^{6}Li. In this hypothesis, a fit of the missing mass spectrum, with proper background subtraction, delivers a mass and a width thoroughly compatible with the results from E471.
However, the momentum of the negative pion seems to be too high for it to be produced in the decay of the Σ^- produced in the $\Sigma^- NN$ or $\Sigma^- d$ decay channels of the tri-baryon, since both are at the very limit of the available phase space. Therefore, this explanations seems questionable. Following the analysis of E930 [3], the production of a $(K^- ppnnn)$ cluster (corresponding to a $^{5}_{K^-}$He kaonic nucleus) recoiling against the measured proton can be suggested. The binding energy of the kaon in this hypothesis has a distribution peaked at about 160 MeV, value in reasonable agreement with the predictions of Mareš *et al.* [13], and of the same scale of those found by E930 for $^{16}_{K^-}$O.

A physical process producing 508 MeV/c protons is the "rare" decay of the ${}^{4}_{\Lambda}$He hypernucleus in two body: ${}^{4}_{\Lambda}\mathrm{He} \rightarrow p+t$. This hyperfragment is produced from a ^{6}Li nucleus with the emission of a 255 MeV/c π^{-}. The authors on Ref. [1] discard this possibility studying the behaviour of the fast pions by means of scintillators light output. In FINUDA the specific energy-loss measurement provided by the vertex detector could help to identify the presence of tritons emitted from the ^{6}Li targets. No indications for the production of these nuclei with a rate such as to justify the strenght of the observed peak (which suggests a production rate of the order of 10^{-2}/(stopped K^{-}), to be compared with the expected rate for the rare decay, tentatively two orders of magnitude lower) has been obtained.

Without invoking the production of K^{-}-nucleons aggregates, a simple explanation complying with the observed features could be the interaction of a K^{-} on a deuteron, or two nucleons, as in $K^{-}+d \rightarrow \Sigma^{-}p$. In this case, the momentum of the recoiling proton is 515 MeV/c, while the π^{-} momentum (from the Σ^{-} decay) is in the range $(200 \div 300)$ MeV/c. The expected production rate of this reaction is compatible with the observed yield, even taking into account that in the ^{6}Li nucleus, as previously mentioned, a sizeable content of d clusters is present.

Conclusions and future prospects

With FINUDA, clear indications for the existence of a $(K^{-}pp)$ aggregate decaying in Λp have been found, using the invariant mass spectroscopy technique, while, from the analysis of the features of the inclusive and semi-inclusive proton spectra, the existence of the $\overline{K}$-bound tribaryon as emerges in the first observations performed at KEK seems to be less sound.

A new huge FINUDA data taking is expected in 2006, which will make possible the study, with large statistics, of the esistence of new possible deeply bound states like $(K^{-}pn)$ and $(K^{-}ppn)$, and of many-body deeply bound states decaying in Λd and Λt, to clarify, if possible, the tribaryon matter.

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