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A novel approach to the measurement of the hyperon nucleon/s interaction by AMADEUS

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Abstract. The AMADEUS collaboration is investigating the low-energy antikaon interactions with nucleons and nuclei, taking advantage of the low-momentum antikaons beam provided by the DAΦNE collider at LNF-INFN.
In this work a novel technique is outlined for the measurement of the hyperon-nucleon two and three body scattering cross sections. The method consists in producing hyperons by antikaons atomic captures in light nuclear targets, and extrapolating the cross sections from the measurement of the yields of the corresponding elastic final state interactions of the hyperons.
The feasibility of this kind of analyses is shown by comparison of calculated Σ^0 production in ^{4}He by K^- absorption on three nucleons, with a sample of K^{-12}C absorption measured by AMADEUS in collaboration with KLOE. The feasibility of a dedicated high statistics measurement is discussed.

1 Introduction

The AMADEUS collaboration is investigating the low-energy antikaon interaction with nucleons and nuclei, exploiting the unique low-momentum beam of kaons ($p_K \sim 127$ MeV/c)

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produced by the DAΦNE collider at LNF-INFN [1], to constrain hadronic nuclear physics models in the strangeness -1 sector.

As a first step, the data collected in 2004/2005 by the KLOE collaboration [2] (corresponding to an integrated luminosity of about 1.74 fb^{-1}) consisting in a complex of K^- absorptions in H, ^{4}He, ^{9}Be and ^{12}C, was analyzed, with the aim to measure e.g. K^- multi-nucleon absorption branching fractions and cross sections [3–5], yields and spectral shapes of the non-resonant antikaon-nucleon absorption transition amplitudes below the $\overline{K}N$ threshold [6] and to perform for the first time invariant mass spectroscopic studies with very low momentum (about 100 MeV/c) in-flight K^- captures [7].

A second dedicated measurement was performed in 2012, with a high purity carbon (graphite) target, which was installed between the beam pipe and the KLOE DC inner wall. Aim of this measurement was to collect a reference sample of pure K^- absorption at-rest in ^{12}C. The geometry of the target was optimized to maximize the kaon stopping power (technical details can be found in Ref. [8]). The total reconstructed integrated luminosity amounts to about 37 pb^{-1}. Details of the event selection and particle identification procedure are reported in Ref. [8].

The investigation of the hyperons dynamics in nuclear matter and of the hyperon-nucleon/multi-nucleons interaction is a subject of utmost interest, with profound implications on the features of possible strange phases in compact astrophysical objects, such as Neutron Stars (NSs) (see e.g. Ref. [9] for a recent review). NSs are among the most compact objects in the Universe, thus providing a perfect testbed for the investigation of the matter properties in extreme conditions of density, isospin asymmetry and temperature.

The study of strange baryons behavior in nuclear matter was pursued by exploiting several techniques: via scattering experiments with secondary hyperon beams [10–12] interacting with a hydrogen target, through the analysis of exotic nuclei containing hyperons (the so called hypernuclei, see Refs. [13–15] and references therein) and, more recently, using femtoscopic techniques [16–21].

In this work we describe a novel approach, which could supply the measurement of the hyperon-1N (interaction with one nucleon) and hyperon-2N (interaction with two nucleons) cross sections, also for channels which are not accessible in scattering experiments (as in the case of Σ^0-1/2N), in a hyperon momentum range which is still unexplored. The idea consists in producing hyperons, as a consequence of K^--multi nucleon interaction processes, through K^- induced reactions on light nuclear targets, and extract the hyperon-1/2N cross sections from the measurement of the yields of the elastic Final State Interaction (FSI) processes. The explicative example of Σ^0 production due to K^--3NA (absorption on three nucleons) in ^{4}He is discussed in Sections 2 and 3.

2 Measurement of the Σ^0-N two and three body interactions

In the following Sections the aim of the proposed measurement will be outlined using the example of the Σ^0-N two and three body interaction cross section. The idea consists in exploiting the K^- three nucleon absorption at rest, in a ^{4}He gaseous target, to produce a primary Σ^0d pair, and then to disentangle and measure the absolute yields of the Σ^0 elastic FSI reactions with the deuteron or with the residual neutron to obtain the Σ^0-1/2N interaction cross sections. ^{4}He is the most appropriate nuclear target, since the abovementioned *signal reaction* can not involve fragmentation of the residual nucleus, which reduces in this case to a neutron. Moreover, an exclusive analysis, with the identification of the Σ^0, d and n, would allow to close the kinematics, for a clean discrimination of the involved background processes, and to get rid of the dominant inelastic FSI conversion processes. The signal reaction under study is initiated by the atomic capture of a negatively charged kaon followed by the nuclear K^--3NA capture at-rest:

$$K^- \, {}^4\text{He} \rightarrow (K^- \, ppn) + n \rightarrow \Sigma^0 \, d + n. \quad (1)$$

The K^--3NA can be followed by two kinds of elastic FSIs:

- $n\, d \rightarrow n\, d$, – to disentangle this effect on the deformation of the final state kinematic distributions we can take advantage of the well known scattering cross sections,
- $\Sigma^0\, n/d \rightarrow \Sigma^0\, n/d$, – from which we aim to extract information on the $\Sigma^0 - 1/2$N interaction cross section.

The AMADEUS collaboration has a track record experience in the investigation of K^- induced reactions on light nuclear targets (both at rest and in-flight) aimed to study the K^- single- [6, 7] and multi-Nucleon capture processes [3–5]. In particular in Refs. [3–5] the branching ratios and the low-energy cross sections (for a K^- momentum of about 100 MeV/c) were measured for the K^--2/3NA, in the $\Lambda\, p$ and $\Sigma^0 p$ channels. It was shown that the Quasi-Free (QF) K^--multiN absorption (without FSI) can be well disentangled from the same K^--multiN reaction, when this is followed by elastic FSI, namely the re-scattering of the hyperon or the nucleon, which are produced in the primary hadronic interaction, with the residual nucleus. For the generic multi-nucleon capture

$$K^- \, AN \rightarrow Y\,(A-1)N, \quad (2)$$

which occurs in the field of the residual nucleus, the hyperon-nucleon(s) pair ($Y\,(A-1)$), which emerges from the primary interaction, always populate the most energetic part of the invariant mass distribution (just below the kinematc threshold) and is characterized by the strongest angular correlation. A clear example is shown in Figure 1 (adapted from Ref. [4]), where the invariant mass (panel a) and angular correlation (panel b) distributions are shown for the $\Lambda\, p$ channel, produced in K^--multiN captures on a ^{12}C target. The elastic FSI degrades such sharp correlation, shifting the corresponding invariant mass to lower values. This is among the major kinematical properties which will be exploited in the analysis we aim to perform.

The proposal for the realization of a dedicated high statistics measurement at the DAΦNE collider, which would fulfill all the requirements of this method, was recently put forward (see Ref. [24])

The carbon target is not ideal for the purpose of our measurement, since many processes can contribute to form the final state under study, such as fragmentation of the residual nucleus and charge exchange reactions which greatly complicate the data interpretation. A dedicated measurement with a high density gaseous ^{4}He target is necessary to pin down the searched signal, and maximizes the probability of K^- nuclear captures at rest, with respect to the in-flight competitor reactions. Nevertheless, to demonstrate the potentiality of the proposed measurement, in Section 3 the calculated distributions of the signal channel are compared to the measured distributions from a sample of $\Sigma^0\, d$ events, reconstructed by using partial statistics from the 2012 data taking campaign. The data correspond to K^- absorption events on a solid ^{12}C target, almost purely at rest.

3 Kinematics of the K^--3NA

In Figure 2 the calculated invariant mass (left) of the $\Sigma^0\, d$ pairs produced in the reaction Eq. (1) is compared with the measured invariant mass (right), of the $\Sigma^0\, d$ events reconstructed by using partial statistics from the 2012 data taking campaign. Calculations are performed

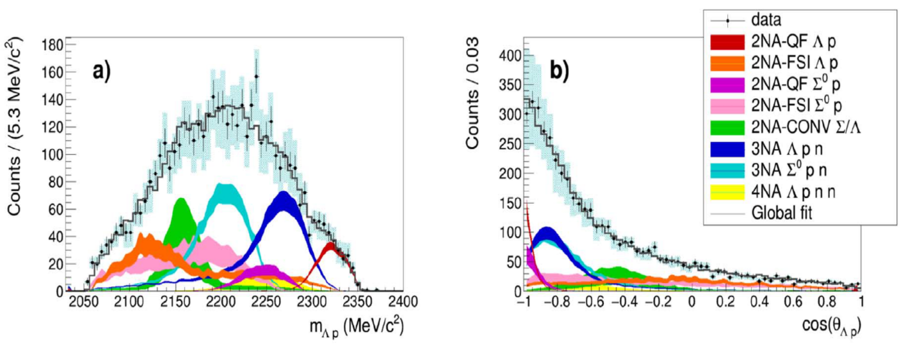

Figure 1. The $\Lambda\, p$ invariant mass (panel a), $\Lambda\, p$ angular correlation (panel b) distributions are shown for K^- absorption on ^{12}C. Black points represent the data, black error bars correspond to the statistical errors, cyan error bars correspond to the systematic errors. The grey line distributions represent the global fit function, the coloured distributions represent the contributing processes according to the colour code reported in the legend and the widths correspond to the statistical error. The figure is adapted from Ref. [4].

according to a phenomelogical model of the K^- capture (see Refs. [4, 6, 22, 23]). The figure evidences that the QF $\Sigma^0\, d$ events, produced in the K^--3NA reaction, populate a narrow invariant mass distribution at the higher edge of the invariant mass spectrum, limited by the kinematical threshold which is located at about 3290 MeV/c^2. The few events in the measured spectrum which exceed the threshold are due the experimental resolution. The invariant mass region lying immediately below the QF distribution is expected to be populated by the K^--3NA reaction, followed by elastic FSI of the primary products of the hadronic interaction, namely the $\Sigma^0\, n/d \rightarrow \Sigma^0\, n/d$ two and three body interactions. The goal of our proposal is to measure the yields of these reactions, from which we aim to extract the corresponding cross sections.

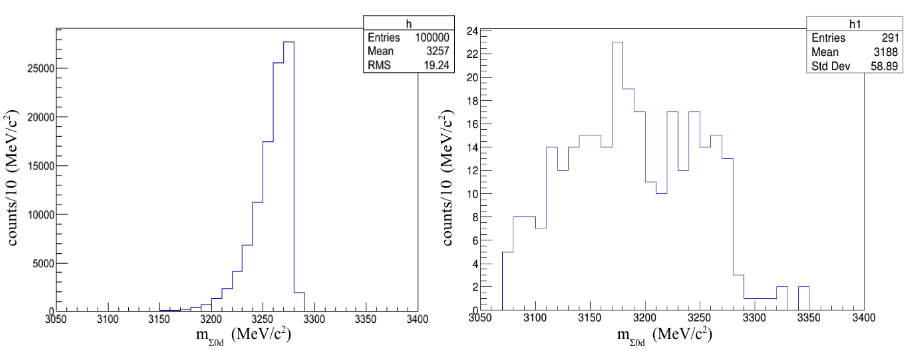

Figure 2. The panel on the left shows the calculated $\Sigma^0\, d$ invariant mass spectrum for the process in Eq. (1). This is compared with the measured invariant mass (right), of the $\Sigma^0\, d$ events reconstructed by using partial statistics from the 2012 data taking campaign.

The calculated Σ^0 momentum (p_{Σ^0}), for the reaction in Eq. (1), is shown in Figure 3 (left) and compared with the corresponding measured distribution (right). The QF K$^-$-3NA process corresponds to the higher part of the hyperon momentum spectrum. Moreover the narrow p_{Σ^0} distribution allows to pin down the cross sections of the $\Sigma^0 - 1/2$N interactions at a Σ^0 momentum of about $p_{\Sigma^0} = 550 \pm 50$ MeV/c.

The main background process is represented by the K$^-$-2NA nuclear capture at-rest:

$$\mathrm{K}^-\,{}^4\mathrm{He} \rightarrow (\mathrm{K}^-\,pn) + d \rightarrow \Sigma^0\,n + d, \tag{3}$$

which can, as well, be followed by elastic FSIs of Σ^0, neutron and deuteron. It is straightforward to shown that the $\Sigma^0\,d$ invariant mass spectrum pertaining to the reaction in Eq. (3) is much broader than the distribution in Figure 2 and centered at about 3180 MeV/c^2. Moreover, the detection of the neutron would allow a clean distinction of the K$^-$-3NA signal from the K$^-$-2NA. Energetic neutrons emerging from the latter process, whose momentum distribution is peaked at about 450 MeV/c, could indeed be well disentangled from the Fermi neutrons produced in a K$^-$-3NA reaction, whose momentum distribution is centered at about 170 MeV/c.

To conclude the discussion of the involved background processes, the copious contribution of K$^-$-1NA reactions should be easily discriminated, as the production of a pion would necessarily lead to uncorrelated and low-energy $\Sigma^0\,d$ pairs (see also Refs. [3–5]).

It is worth noticing that the measurement proposed in this work depends, as a fundamental ingredient, on a reliable calculation of the elastic final state interaction reactions of the hyperon with the residual nucleus. Presently, the phenomenological model adopted in our calculation does not involve energy dependence of the scattering amplitude for this process, which requires further investigation.

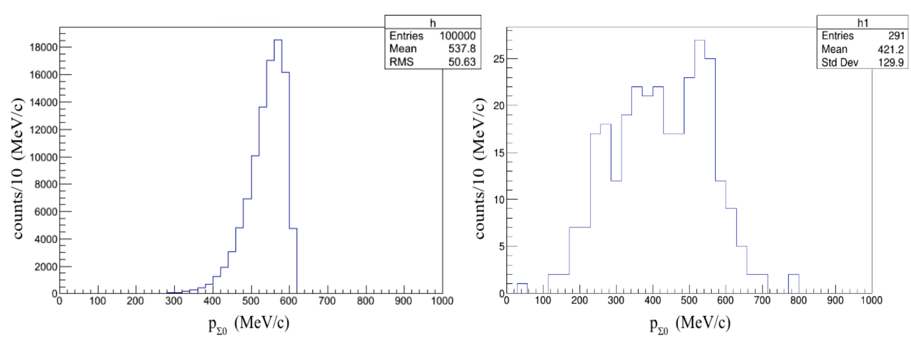

Figure 3. The figure shows comparison among the calculated Σ^0 momentum spectrum (left) for the process in Eq. (1) and the measured distribution (right) for the $\Sigma^0\,d$ events reconstructed by using partial statistics from the 2012 data taking campaign.

4 Discussion

In this work a novel approach is presented which could provide experimental information on the cross section of hyperon-1/2N interaction (hyperon interaction with one/two nucleons) also for channels which are not accessible in scattering experiments (as in the case of Σ^0-1/2N). The idea consists in producing hyperons in K$^-$ multi-nucleon interaction processes, through K^- atomic captures on light nuclear targets, and then evaluate the cross sections from the corresponding yields of the elastic final state interaction processes.

The feasibility of the proposed measurement is demonstrated by comparing the calculated spectra for the $K^-\,{}^4He \to \Sigma^0\, d + n$ atomic absorption with a preliminarily analyzed sample of $K^-\,{}^{12}C \to \Sigma^0\, d$ + Residual events collected by AMADEUS in collaboration with KLOE.

High statistics samples could be collected in the optimal experimental conditions, by stopping antikaons in high-density light nuclear gaseous targets, exploiting a future dedicated apparatus working on the DAΦNE collider (see Ref. [24]).

Refined calculations are demanded, for a precise discrimination of the hyperons final state interactions, accounting for the eventual energy dependence of the corresponding scattering amplitudes.

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