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Experimental study of the (K^+, K^0) interactions on ^{7}Li close to threshold

FINUDA Collaboration

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Abstract

The inelastic charge exchange reaction (K^+, K^0) on ^{7}Li has been experimentally investigated close to threshold with the FINUDA spectrometer at the e^+e^- collider DAΦNE by searching for K^0_S decays. It is the first time that this process has been studied at such low momentum. An upper limit of 2.0 mb (at 95% confidence level) has been measured for the total cross section.

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Keywords: Low momentum kaon–nucleus interactions; Charge exchange reactions; Positive kaons

1. Introduction

The charge exchange reaction induced by low energy K^+ was intensively studied in the fifties and early sixties using emulsions, bubble chambers and finally counter experiments [1–5], while, in subsequent years, this subject attracted only sporadic interest [6,7]. The reason was that, contrary to K^-, a low momentum K^+ has no access to states containing hyperons with their interesting and rich dynamics (see, for instance, [8,9]), and its interaction was hence thought to simply be smoothly decreasing at low momenta. Therefore, later, more refined experiments focused only on higher energies to search for possible $S = +1$ resonances [10–12]. When it was understood that the relative *weakness* of the K^+ strong interaction with nucleons could probe the interior of nuclei [13], an intense phase of studies devoted to this item started at intermediate energies to compare K^+–nucleus interactions with those on deuterons [14–22], and to look for possible evidence of strange quark content in nucleons. Later on, however, the interest in K^+ interactions on nucleons and nuclei again subsided, until the very recent upsurge of activity related to the *pentaquark* search [23–25] (and references therein).

Taking advantage of the FINUDA spectrometer installed on the DAΦNE collider at LNF, we studied whether FINUDA could explore the K^+ charge exchange reaction on medium-light nuclei from ≈ 100 MeV/c down to the threshold of the reaction, in order to provide experimental information on the scattering amplitude $\frac{1}{2}(f_1 - f_0)$ of the process. Here f_0 and f_1 are, respectively, the isospin $I = 0$ and isospin $I = 1$ amplitudes.

2. The FINUDA experiment at DAΦNE

The DAΦNE collider, described in detail in Ref. [26], is a source of K^+K^- pairs via the decay of $\Phi(1020)$ mesons created in the collision of 510 MeV e^+, e^-. The charged kaons are created (almost) back-to-back and with a momentum of 127 MeV/c, slightly modulated in the radial plane by the tiny outward *boost* (≈ 13 MeV/c) of the decaying Φ due to the small crossing angle (≈ 25 mrad) of the e^+, e^- beams.

FINUDA is a high acceptance, high resolution, non-focusing magnetic spectrometer consisting of a superconducting solenoid ($B = 1$ T) located around the thin (500 μm) Be beam pipe of DAΦNE, and instrumented with several tracking detectors and two scintillator barrels for triggering, t.o.f. measurements and neutron detection. The momentum resolution, optimized for detecting the prompt π^- from Λ hypernuclear formation (260–270 MeV/c), is at present $< 0.6\%$ (FWHM). The apparatus is also able to detect the hypernuclear decay products. A full description of FINUDA is given in Ref. [27]. In the FINUDA detector, up to eight different thin (≈ 200 mg/cm^2) targets can be installed. The FINUDA vertex-target region is shown in Fig. 1. The two arrays of bi-dimensional Si-microstrips, ISIM placed before and OSIM after the nuclear targets, allow precise tracking of the K^+, K^- and of the charged particles originating from their interactions. Moreover they provide a dE/dx measurement.

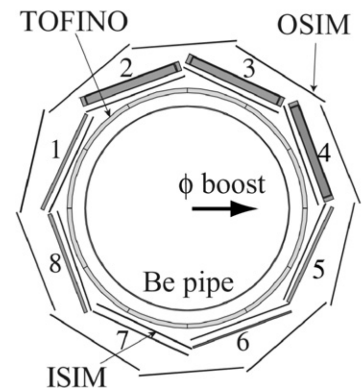

Fig. 1. The FINUDA vertex-target region. The Be pipe, the inner thin scintillator barrel (tofino), the ISIM and OSIM Si-microstrip detectors and the eight targets (numbered from 1 to 8) between them are shown. The bold arrow indicates the direction of Φ boost.

For the first round of data taking three natural C (slots 1, 5, 8), two ^{6}Li (enriched to 90%) (slots 2, 3), and one each of ^{7}Li (slot 4), ^{27}Al (slot 6), and natural V (slot 7) were used as targets.

In the following, we report the result obtained for the (K^+, K^0) charge exchange reactions on the ^{7}Li target mounted in the first FINUDA run, never measured before in this low K^+ momentum range.

3. Data taking and data analysis

The data were collected in the 2003/04 FINUDA run devoted to the study of Λ-hypernuclei [27] and kaon-nuclear bound systems [28,29]. The experimental details (trigger selection and data taking procedures) can be found in the mentioned papers. In this analysis, we selected events originating from K^+ interactions. Such events are collected in FINUDA using the same trigger as in hypernuclear data taking; hence no dedicated trigger was needed to study this process. The majority of the K^+ entering the FINUDA targets are brought to rest and then decay. The $K_{\mu 2}$ and $K_{\pi 2}$ decays of the stopped K^+, producing 235 MeV/c μ^+, and 205 MeV/c π^+, allowed a continuous check of the performance of both the detector and the reconstruction-analysis code [27,30]. The events of the present analysis have been selected by looking for a pair of positive and negative charged particles coming out from the K^+ interaction in the selected targets. Proton tracks have been excluded by checking the energy loss in the Si microstrips with a rejection power of better than 96% in the momentum region of interest [31]. The events selected by the reconstruction program were subject to topology and invariant mass analysis to test the hypothesis of pions produced in the decay:

$$K_S^0 \to \pi^+\pi^-, \qquad \text{B.R.} = 0.69. \tag{1}$$

Due to the very low momenta of the produced K_S^0 (≈10–90 MeV/c), a nearly back-to-back topology of the $\pi^+\pi^-$ pairs (both of momentum ≈ 205 MeV/c) is expected.

It is very important, before continuing the discussion, to recall that the reaction (K^+, K^0) occurs inside a nucleus. Indeed, even the elementary process,

$$K^+ + n \to K_S^0 + p \tag{2}$$

cannot be studied experimentally on free neutrons and, in fact, existing data were obtained mainly on deuterium targets. This means that the actual threshold of the reaction increases with respect to that of the elementary one (63.8 MeV/c), depending on the selected nucleus. In the case of ^{7}Li, for instance, the threshold is 68.9 MeV/c. This is a very important point for FINUDA. The K^+ produced by DAΦNE have a maximum momentum of ≈ 133 MeV/c but, after crossing the beam pipe and the inner detectors, they reach the targets with momenta not higher than ≈ 100 MeV/c. This reaction, therefore, turns out to be below threshold on several nuclei. Moreover, due to the low momentum of the involved K^+, the Coulomb barrier plays a role in its interaction on nuclei, increasing with the Z of the target nucleus. Fig. 2 shows the K^+ momentum thresholds Q of the (K^+, K^0) reaction for a selection of different nuclei. In the first FINUDA run, the experimental conditions allowed exploration of the (K^+, K^0) reaction only for the ^{7}Li target.

In Fig. 3 (top), as an example, one of the candidate events detected in the first FINUDA run is displayed. This candidate event appears, however, quite surprising: in fact, it originates from a target nucleus (^{12}C, slot 5) whose threshold is well above the maximum momentum of the incident K^+ (Fig. 2). This indicates that background processes exist, simulating a $K_S^0 \to \pi^+\pi^-$ decay from a K^+ interacting in a FINUDA target. Among all the possible background sources, (π^+, e^-) pairs originating from the K^+ decays at rest in the targets are by far the largest. The K^+ decays produce, with the B.R. of ≈ 21%, $\pi^+\pi^0$ pairs whose topology and momentum are similar to that of the $\pi^+\pi^-$ pairs from K_S^0 decay at rest.

The π^0 decays in ≈ 10^{-16} s mainly into $\gamma\gamma$. One of the γs can be emitted in the same direction as the decaying π^0, and can create an e^+e^- pair within the same target. If the e^-

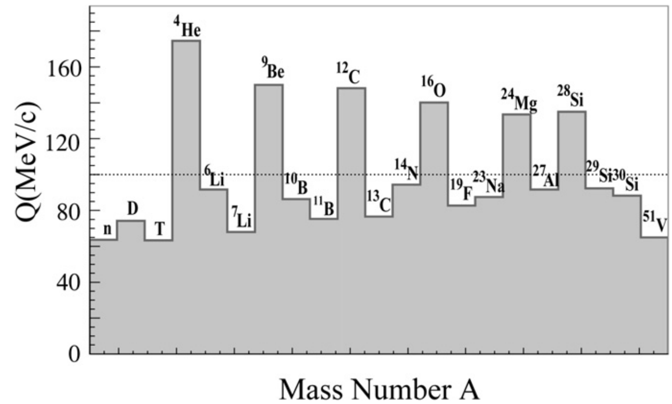

Fig. 2. The threshold momentum Q of the reaction (K^+, K^0) for several nuclei as a function of their mass number A. The horizontal line indicates the maximum K^+ momentum reachable (in the Φ boost direction) on the FINUDA targets.

is also forward emitted, it keeps the topology and momentum of the parent π^0, similar to the π^- from the decay at rest, $K_S^0 \to \pi^+\pi^-$. At the momenta involved, FINUDA cannot discriminate between an e^- and a π^-, hence this background is very insidious. In Fig. 3 (bottom), a background event of the type described above, picked up by the FINUDA Monte Carlo simulating the decay of stopped K^+ in FINUDA, is shown.

An experimental signature of the presence of such a background can be seen by looking at the invariant mass distribution of two positive charged tracks, assumed to be both π^+, emitted following a K^+ interaction in any of the FINUDA targets. Such events can only occur from pair creation in which the e^+, instead of the e^-, is forward emitted.

Fig. 4 shows the invariant mass distribution of the measured $(+,+)$ tracks (assumed to be π^+ and with relative angles larger than 145°) occurring in K^+ interactions in any FINUDA target. A wide peak, close to the K_S^0 mass, can be seen. This is also found in the equivalent distribution obtained using $(+,-)$ tracks. The peak due to $(+,+)$ tracks is depressed simply due to the lower acceptance of FINUDA for $(+,+)$ tracks with respect to $(+,-)$ tracks of momenta ≈ 200 MeV/c. A simple inspection of the figure shows that the peak around the K_S^0 mass is too wide to be due to K_S^0 decays, since FINUDA has a resolution in this energy interval of better than 2 MeV/c^2 [32], i.e. well within the bin width (10 MeV/c^2) in the histograms of Fig. 4. The conclusion is that events occurring in the decay $K_S^0 \to \pi^+\pi^-$ cannot be selected simply looking at distributions of the type shown in Fig. 4.

We studied the contamination of the above reaction by using the FINUDA Monte Carlo. We generated a number of $K^+ \to \pi^+\pi^0$ decays comparable with those expected from the experimentally measured number of stopped K^+, and then we examined the distributions in relative angle and invariant mass of the resulting π^+e^- events with the hypothesis that these are $\pi^+\pi^-$ pairs. With further simulation, events due to the decay $K_S^0 \to \pi^+\pi^-$ were also generated and their relative angle and invariant mass reconstructed. The high resolution of FINUDA on the K_S^0 mass (better than ±2 MeV/c^2) and on the relative angle of the $(+,-)$ or $(+,+)$ tracks (≈ 1°) should allow one

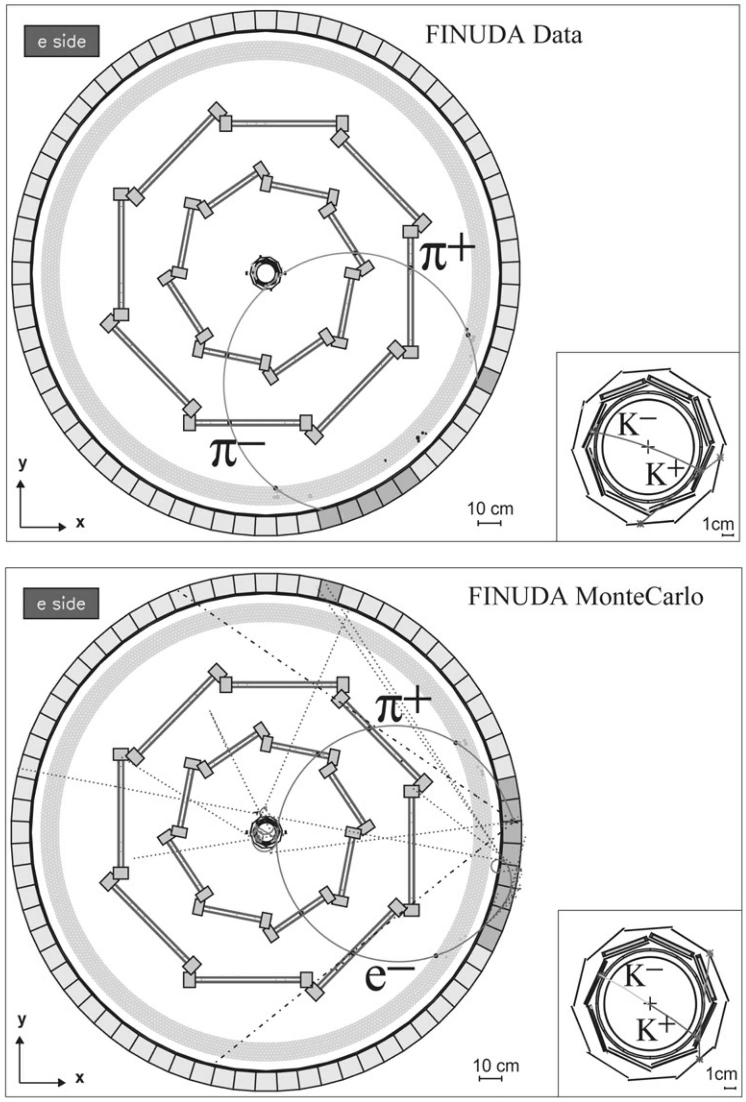

Fig. 3. Top: Display of a candidate $K^0_S \to \pi^+\pi^-$ event from a K^+ interaction on the FINUDA target #5. The curved tracks cross all the tracking detectors; the vertex Si-microstrips, the two octagonal layers of drift chambers, the six circular straw tube layers, and hit the external scintillator barrel. The inset shows the vertex-target region with the highly ionizing K^+ and K^- hitting target #5 and the one opposite, respectively. Bottom: Display of one Monte Carlo event in which the decay: $K^+ \to \pi^+\pi^0$ of a K^+ stopped on the FINUDA target #5, is followed by the reactions, $\pi^0 \to \gamma\gamma$; $\gamma + A \to A'e^+e^-$. The e^- can be misidentified as a π^-, simulating an event topologically very similar to that shown at the top.

to distinguish the difference (if any) between the topologies of the two processes. From this study it was indeed possible to define, at a 95% confidence level, a background free, signal region of 494–502 MeV/c^2 and 176°–180°, in the (π^+, π^-) invariant mass and relative angle, respectively.

4. Results and discussion

In the first FINUDA run only the ^{7}Li target was effectively accessible to the reaction (K^+, K^0) with a reasonable flux of K^+ above threshold. The momentum distribution of K^+ entering in the ^{7}Li target had the shape expected from the Landau distribution of the momentum losses, with a peak at 95 MeV/c and FWHM 15.0 MeV/c. The topological analysis of the experimental data showed that for the ^{7}Li target we could observe 5 candidate (π^+, π^-) pairs, all of which, when displayed on an invariant mass versus relative angle scatter plot, lay outside the signal region expected for (π^+, π^-) pairs from K^0_S decay almost at rest, as can be seen in Fig. 5.

In conclusion, no good event has been detected.

Using the FINUDA Monte Carlo, that takes into account the threshold of the reaction and the K^+ flux and momentum distribution, we obtained the experimental integrated luminosity for the ^{7}Li target: 16.15×10^{27} cm^{-2}. With the same Monte Carlo, the FINUDA global efficiency (geometrical acceptance × trigger efficiency × detectors efficiency) to detect (π^+, π^-) pairs from K^0_S decay almost at rest has been also calculated. We verified that in the limited range of the involved K^0_S momenta (10–90 MeV/c) the efficiency remains constant and equal to 0.099 ± 0.005. With the experimental integrated luminosity and the FINUDA global efficiency to detect (π^+, π^-) pairs from K^0_S decay almost at rest, we achieved a sensitivity

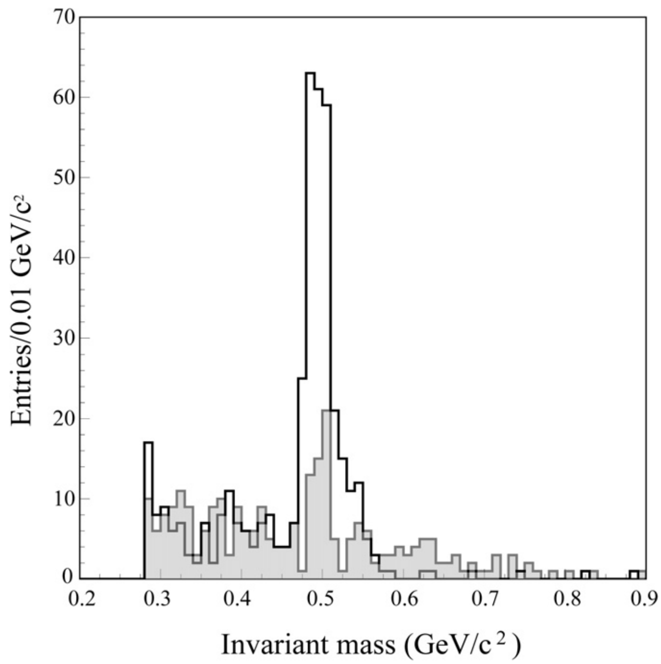

Fig. 4. Invariant mass distributions of the measured $(+,-)$ and $(+,+)$ (open and filled histogram, respectively) tracks (assumed to be $\pi^{\pm}$) with relative angles greater than 145°, following K^+ interactions in all FINUDA targets. Protons have been rejected using dE/dx information provided by the Si microstrips.

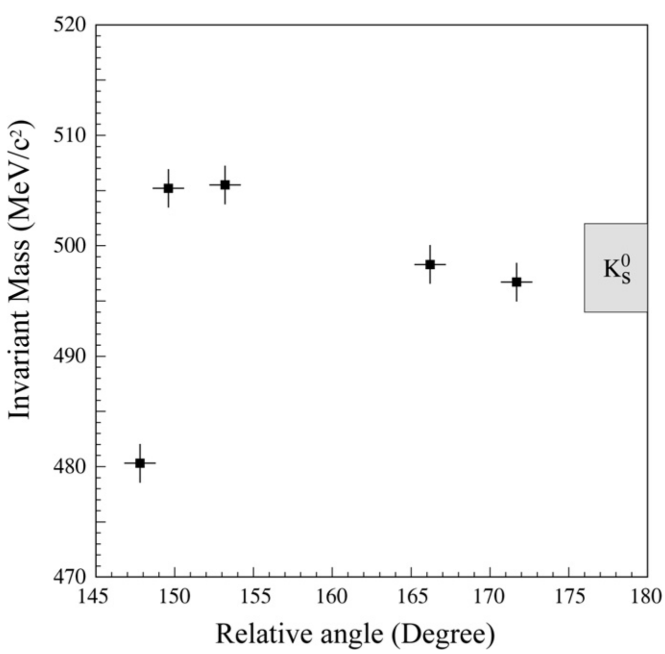

Fig. 5. Scatter plot of the invariant mass versus relative angle for the $(+,-)$ measured tracks, which were assumed to be $\pi^{\pm}$, following K^+ interactions in the ^{7}Li target. Protons have been rejected using dE/dx information provided by the Si microstrips. The signal region expected (at 95% C.L.) for events from $K^0_S \to \pi^+\pi^-$ is indicated by the grey area.

of ≈ 0.62 mb per event with the collected statistics. Having found no good event, and no background, within the overall integrated luminosity, the result indicates, following standard

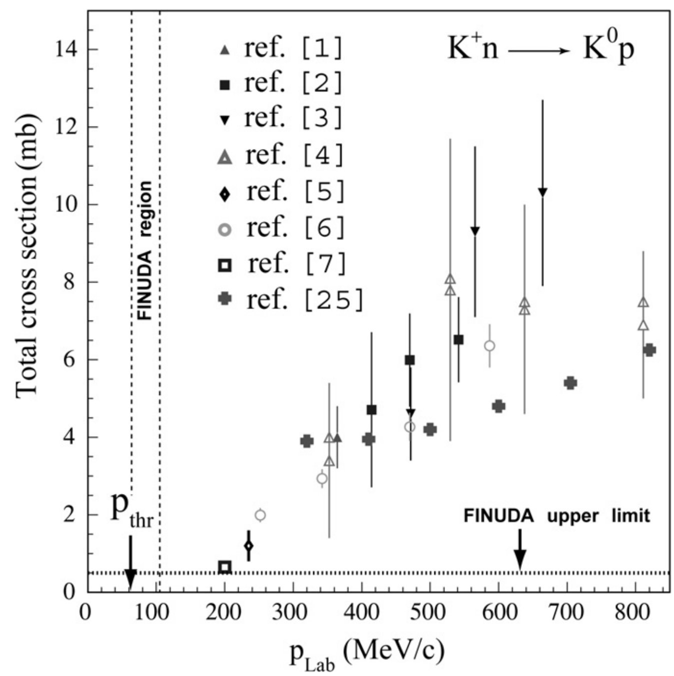

Fig. 6. Existing data and calculations on the total cross section of the elementary charge exchange reaction $K^+ + n \to K^0 + p$ below 800 MeV/c K^+ laboratory momentum p_{Lab} (the calculations from [7] and [25] are adapted). The threshold momentum p_{thr} and the region explored by FINUDA are also indicated, as well as the 0.5 mb level (horizontal dotted line). The 0.5 mb level is equal to the value obtained dividing the FINUDA result (< 2.0 mb) by the number of neutrons in ^{7}Li.

statistical analysis methods, that the near threshold cross section for $^7\text{Li}(K^+, K^0)^7\text{Be}$ is less than 2.0 mb at 95% C.L.

There are no previous measurements of the (K^+, K^0) cross section on nuclei close to threshold, deuteron included. Moreover, theoretical calculations are also lacking in this energy region. The charge exchange reaction of a K^+ on a nucleus is, of course, related to the elementary process (2). A compilation of the existing experimental data and theoretical calculations for the elementary cross section from 200 MeV/c up to 800 MeV/c K^+ laboratory momenta is shown in Fig. 6. The experimental data were extracted from measurements on deuterium or from heavier nuclei. As one can see, in the low momentum region, the data or calculations available are very old and go down to a minimum momentum twice as high as that accessible by FINUDA. The data are reasonably consistent (within the experimental errors) and show a rather smooth decreasing trend in the low momentum tail. In the region accessible by FINUDA, indicated in the same figure, a prediction of less than 0.5 mb for the elementary charge exchange cross section seems quite a reasonable upper bound. The 0.5 mb upper limit corresponds to the FINUDA result for ^{7}Li divided by the number of neutrons in the nucleus.

The relationship of the (K^+, K^0) cross section on nuclei to that for the elementary process is not trivial at low momenta. The most relevant effect is the Pauli exclusion principle, as the created proton is below the Fermi momentum, and the cross section would be heavily damped. At higher laboratory momenta (from 300 MeV/c up to and above the threshold for pion emission) Pauli blocking becomes progressively less effective. In such a momentum region, it is known that the interaction cross section of K^+ with nuclei tends to become proportional to *volume*, i.e. rather accurately (within 10%) proportional to the number of nucleons in the nucleus [33].

It is difficult without an explicit calculation to predict the actual near threshold value, but we can try to put two limiting expectations for the possible value of the cross section of (K^+, K^0) on ^{7}Li close to threshold; (1) an upper bound equal to that of the corresponding cross section for the elementary process times the number of neutrons in the target (i.e. no Pauli damping); (2) a lower bound equal to, or less than, the cross section of the corresponding elementary process (i.e. complete Pauli damping). Taking ≈ 0.5 mb as the estimate for the near threshold elementary cross section (Fig. 6) and assuming the *volume* approximation, we get for the $^7\mathrm{Li}(K^+, K^0)^7\mathrm{Be}$ cross section an upper bound value of ≈ 2 mb.

In conclusion, the estimated cross section window ($\leqslant 0.5$–2.0 mb) is compatible with the FINUDA measured upper limit, confirming, for the first time experimentally, a smooth and decreasing cross section on ^{7}Li in this momentum region. In the FINUDA data run of 2006/07, the following targets will be available: ^{6}Li, ^{7}Li, ^{9}Be, ^{13}C and ^2H_2O [34]. It will therefore be possible to repeat the measurement on the (K^+, K^0) reaction on ^{7}Li, with a scheduled tenfold increase in integrated luminosity respect the present measurement. It will also be possible to study simultaneously the (K^+, K^0) reaction on ^{13}C and D in the K^+ momentum region from their respective thresholds to ≈ 100 MeV/c.

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