Proposal and Beam request

For Lab. use

Exp. No.: #	Session No.

Title of Experiment

Investigation of final state interactions

in the $pd \rightarrow {}^3HeK^+K^-$ / ${}^3HK^+\bar{K}^0$ reactions near threshold

Collaborators: ANKE Collaboration

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Total number of particles and type of beam (p,d,polarization)	Momentum range (MeV/c)	Intensity or internal reaction rate (particles per second)	
unpolarized protons	2554	minimum needed $\geq 10^{31}$	maximum useful
Type of target	Safety aspects (if any)	Earliest date of installation	Total beam time (weeks)
ANKE deuteron cluster target		January , 2010	2 weeks

Summary of experiment:

We propose to measure non-resonant $K\bar{K}$ pair production in the reactions $pd \to {}^3\mathrm{He}K^+K^-$ and $pd \to {}^3\mathrm{H}K^+\bar{K}^0$ in order to study the ${}^3\mathrm{A}\bar{K}$ final state interactions (FSI). The experiment would be carried out at the ANKE facility at a beam energy of 1.783 GeV, corresponding to an excess energy of 25MeV with respect to the ${}^3\mathrm{He}K^+K^-$ threshold. This is two half widths below the nominal threshold so that the influence of this meson is minimized. This study is a natural extension of our work that has shown the importance of the FSI in the K^-pp, $\bar{K}^0d$ and K^-d systems and which has led to evaluations of the K^-p and $\bar{K}d$ effective scattering lengths. The beam time needed to collect a few thousand ${}^3\mathrm{A}\bar{K}$ coincidences as well as approximately 300 ${}^3\mathrm{He}K^+K^-$ correlations is estimated to be **two weeks**. Under the proposed conditions theoretical analysis is simple.

COSY proposal/beam request

Investigation of final state interactions in the pd $\rightarrow$ ^{3}He K$^+$K$^-$/^{3}H K$^+\bar{K}^0$ reactions near threshold

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(for the ANKE collaboration)

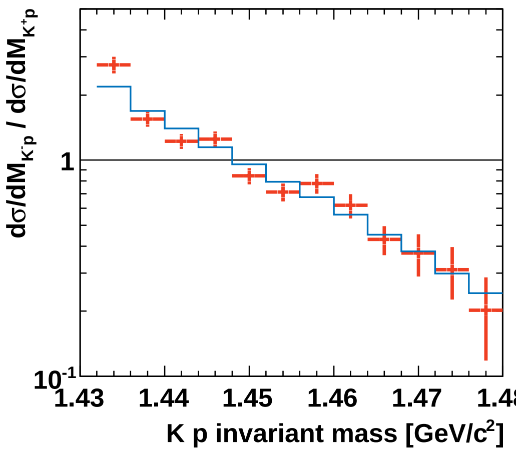
July 24, 2009

Abstract

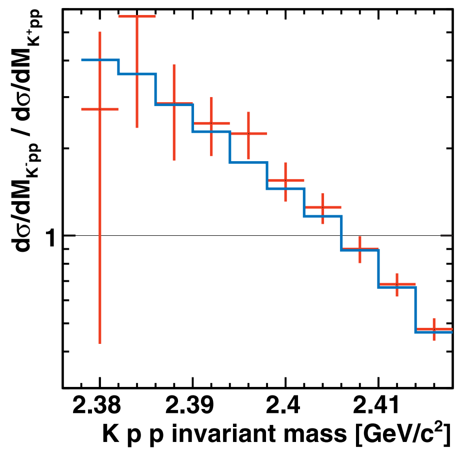
We propose to measure non-resonant $K\bar{K}$ pair production in the reactions $pd \rightarrow {}^3\mathrm{He}\,K^+K^-$ and $pd \rightarrow {}^3\mathrm{H}\,K^+\bar{K}^0$ in order to study the ${}^3\mathrm{A}\,\bar{K}$ final state interactions (*FSI*). The experiment would be carried out at the ANKE facility at a beam energy of 1.783 GeV, corresponding to an excess energy of 25 MeV with respect to the ${}^3\mathrm{He}\,K^+K^-$ threshold. This is two half widths below the nominal ϕ threshold so that the influence of this meson is minimized. This study is a natural extension of our work that has shown the importance of the *FSI* in the K^-pp, $\bar{K}^0d$ and K^-d systems and which has led to evaluations of the K^-p and $\bar{K}d$ effective scattering lengths. The beam time needed to collect a few thousand ${}^3\mathrm{A}K^+$ coincidences as well as approximately 300 ${}^3\mathrm{He}K^+K^-$ correlations is estimated to be **two weeks**. Under the proposed conditions theoretical analysis is simple.

1 Overview

In order to continue the ANKE studies of the final state interactions of antikaons with nucleons and nuclei, we are now proposing to investigate the $pd \rightarrow {}^3\mathrm{He}\,K^+K^-$ reaction a little below the ϕ threshold. The choice of energy is such as to have the largest range in excitation energy that is consistent with there being little influence from ϕ production. The results should also permit the investigation of the final state interaction between



(a) Data in terms of the K^-p and K^+p invariant masses.



(b) Data in terms of the K^-pp and K^+pp invariant masses.

Figure 1: Ratios of the differential cross sections for the $pp \to ppK^+K^-$ reaction at $Q_{K\bar{K}} = 51\,\text{MeV}$ away from the ϕ region. Experimental data (red) are compared to a Monte Carlo simulation (blue).

kaon pairs when these are produced in reactions other than nucleon-nucleon collisions. Data will be obtained in parallel on the $pd \to {}^3\text{H}\,K^+\bar{K}^0$ reaction, which will be sensitive to the isospin dependence of the final state interaction of the antikaon with the three-nucleon system.

2 Physics case

Measurements of the $pp \to ppK^+K^-$ reaction at both COSY-11 [1] and ANKE [2,3] have shown that the interaction of the K^- with the final protons is much stronger than that of the K^+. Thus, if we define the ratio of the acceptance–corrected distributions in the Kp invariant masses

$$R_{Kp} = \frac{d\sigma/dM(K^-p)}{d\sigma/dM(K^+p)}\,, \tag{1}$$

then this shows a very strong preference for low values of $M(Kp)$ provided that the invariant mass of the K^+K^- is chosen to be away from the region of the ϕ peak. This behaviour was noted for all the measured excess energies ($Q_{K\bar{K}} = 51,\ 67$, and $108\,\text{MeV}$) and an example at 51 MeV is shown in Fig. 1(a).

Equally striking is the variation of the three-particle invariant-mass dis-

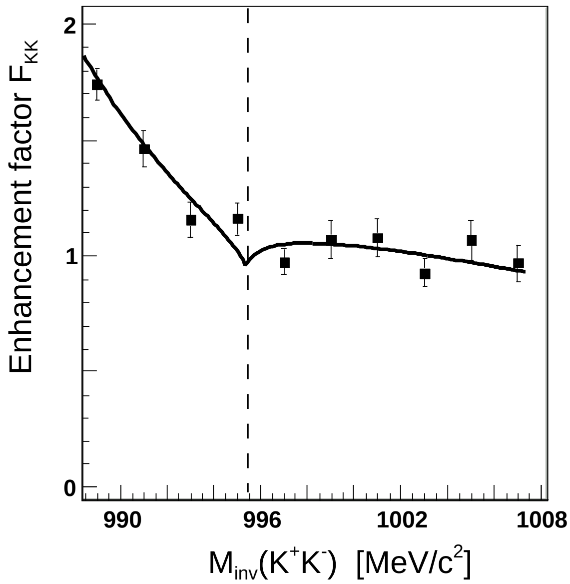


Figure 2: Ratio of the K^+K^- invariant mass spectra from the $pp \to ppK^+K^-$ reaction to the simulation presented in Ref. [3]. The experimental points correspond to the weighted average of ANKE data taken at 2.65, 2.70, and 2.83 GeV. The curve includes both K^+K^- *FSI* and charge exchange $K^0\bar{K}^0 \to K^+K^-$ contributions. The dashed line indicates the $K^0\bar{K}^0$ threshold.

tribution, where the ratio

$$R_{Kpp} = \frac{d\sigma/dM(K^-pp)}{d\sigma/dM(K^+pp)}\,, \tag{2}$$

shown in Fig. 1(b) presents a similar strong bias towards low masses of the Kpp system.

The magnitude and mass dependence of both the R_{Kp} and R_{Kpp} ratios can be described quantitatively at all the COSY-11 and ANKE energies by assuming that there are overlapping final state interactions (*FSI*) between the pp and both K^-p pairs. This approach has been successfully pioneered for the $pp \to pp\eta$ reaction [4] and, within the framework of this simple *ansatz* [3], the only free parameter is an effective K^-p scattering length.

Although the above *ansatz* describes the vast bulk of all the available data, there is evidence of a $K\bar{K}$ *FSI* at very low K^+K^- invariant masses for all beam energies. This is shown clearly in Fig. 2. The average of the ratio of the experimental data to the simulation involving just the K^-p and pp *FSI* is compared to fits that include both an elastic K^+K^- *FSI* plus a charge-exchange contribution, where a $K^0\bar{K}^0$ pair is converted into K^+K^-

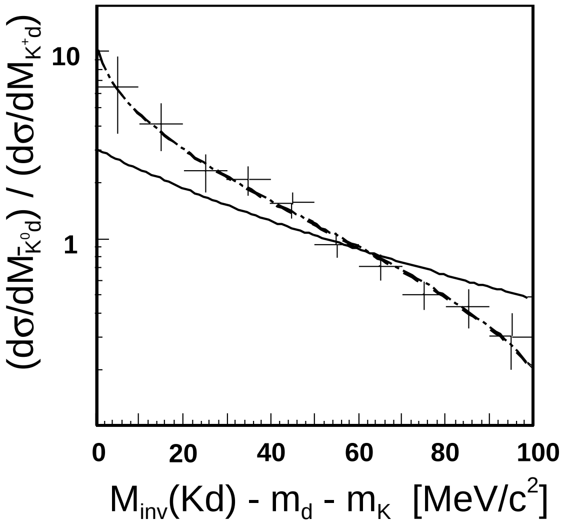


Figure 3: Ratio of the differential cross section for the $pp \to dK^+\bar{K}^0$ reaction at an excess energy of 104.7 MeV in terms of the $\bar{K}^0d$ and K^+d invariant masses. The dashed curve represents the best fit to the data [9], whereas the solid one represents the constant amplitude approach [8].

through a *FSI* [5]. It is important to stress that this $K\bar{K}$ *FSI* is a much smaller effect than the *FSI* in the K^-pp system and therefore it does not influence the precision with which the K^-p effective scattering length will be determined.

A further three weeks of beam time were taken in Spring 2009 to study the effects of the final state interactions between the K^-p and K^+K^- pairs in the $pp \to ppK^+K^-$ reaction [6]. The run was very successful in terms of count rates *etc.* but it is unfortunately still too early to provide detailed results.

Since the antikaon is so strongly attracted to the proton, it is interesting to investigate its interaction with nuclei. For the simplest nucleus, this is possible by using the $pp \to dK^+\bar{K}^0$ reaction, which has been measured at ANKE at excess energies of 48 [7] and 105 MeV [8], and recently reanalysed in greater depth [9]. Effects similar to those observed in the $pp \to ppK^+K^-$ case are also seen here, with the strong tendency for the $\bar{K}^0d$ invariant mass to be lower than that of the K^+d system, as illustrated in Fig. 3.

Although there is about a factor of 25 difference in the ratio between low and high invariant masses, this analysis is complicated by the spin-parity requirement that even near threshold one of the final particles must be in a P-wave. The data show that this is overwhelmingly the K^+, with the $\bar{K}^0d$

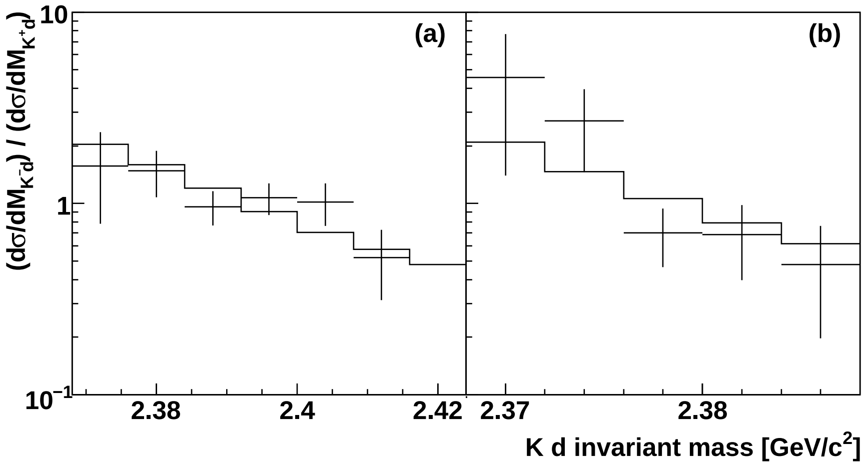
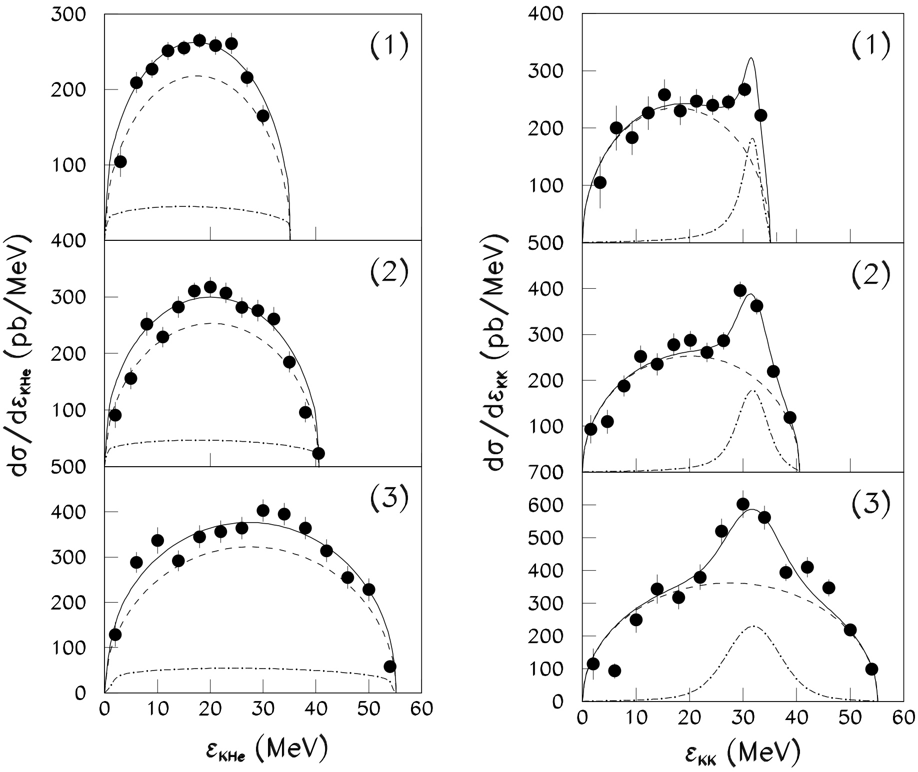


Figure 4: Ratios of the differential cross section for $pn \to dK^+K^-$ reaction for two ranges of excess energy (a): $42 < Q < 52\,\mathrm{MeV}$, (b): $12 < Q < 22\,\mathrm{MeV}$. The histograms are the simulations in the scattering length approximation with $a = (1.0 + i1.2)\,\mathrm{fm}$.

being in an S-wave. Such a difference would come about naturally through a strong $\bar{K}d$ attraction.

The strong $\bar{K}d$ *FSI* has been confirmed by the measuremnts of $pn \to dK^+K^-$ reaction, where an overall S-wave for particles in the final state is not forbiden by selection rules [10]. This investigation was carried using a 2.65 GeV proton beam and a deuteron as an effective neutron target. Due to the Fermi motion, a wide excess energy range was covered. Ratios of the differential $K^{\pm}d$ cross sections for this reaction also shows $\bar{K}d$ attraction, as illustrated in Fig. 4.

One possible continuation of the ANKE programme to study the antikaon-nucleon/nucleus interaction would be to measure the cross section for $dd \to {}^4\mathrm{He}\,K^+K^-$ in order to investigate the ${}^4\mathrm{He}K^-$ system. However, it has been shown that the production rate in this channel is extremely small [11]. The more realistic path followed here is to propose a measurement of the $pd \to {}^3\mathrm{He}\,K^+K^-$ reaction, which will be sensitive to the ${}^3\mathrm{He}K^-$ *FSI.* Data on this process were obtained by the COSY-MOMO collaboration at three energies above the ϕ threshold, viz. $Q_{K\bar{K}} = 35$, 41, and 55 MeV [12]. Although the identification of the ^{3}He was carried out in Big Karl and the momentum well measured, the signs of the charges on the two kaons were not determined in the MOMO vertex detector. As a consequence, it is impossible from these data to construct ${}^3\mathrm{He}K^-/{}^3\mathrm{He}K^+$ ratios and any *FSI* effect is averaged over the two charge states with a resulting diminution of



(a) Data in terms of the excitation energy in the KHe system.

(b) Data in terms of the excitation energy in the K^+K^- system.

Figure 5: MOMO [12] data on the $pd \rightarrow {}^3\mathrm{He}\,K^+K^-$ reaction at (1) $Q_{K\bar{K}} = 35.1\,\mathrm{MeV}$, (2) $40.6\,\mathrm{MeV}$, and (3) $55.2\,\mathrm{MeV}$. The dot-dashed curves are simulations of the ϕ-contributions and the broken ones those for the non-ϕ. The solid curves represent their sums.

signal [15]. In order to advance the understanding of the ${}^3\mathrm{He}K^-$ *FSI*, measurements have to be carried out with an unambiguous identification of all three final state particles. This is the subject of the present proposal.

The MOMO results provide a very robust basis upon which to make estimates of the expected counting rates and we show here some of their results. The ${}^3\mathrm{He}\,K$ distributions of Fig. 5(a) look rather similar to phase space but this is largely a reflection of the fact that MOMO could not distinguish the K^+ from the K^-. It is seen from Fig. 5(b) that the non-ϕ contribution represents a larger fraction of the total than is the case for the $pp \rightarrow ppK^+K^-$ reaction [3].

In order to fix the parameters of the ${}^3\mathrm{He}K^-$ *FSI*, one should have as large a range of $Q_{K\bar{K}}$ as possible though, to avoid contamination from the production of the ϕ meson, the measurement should preferably be carried out at least two half-widths below the nominal ϕ mass. We therefore propose to the PAC to carry out a measurement at $Q_{K\bar{K}} = 25\,\text{MeV}$. At such a low excess energy, corrections to the scattering length description due to effective range terms will be less of a danger than for our $pp \to ppK^+K^-$ data that were obtained above the ϕ threshold [3]. The theoretical analysis is also simplified by having a ^{3}He rather than a proton-proton pair in the final state.

It should be noted that there exist no experimental determinations of the $K^-{}^3$He scattering length, though values could be extracted from measurements of the shifts and widths of the $K^-{}^3$He atom, for which experiments are in preparation at both J-PARC and DAPHNE [13, 14].

3 Simulation of the pd → ^{3}He K$^+$K$^-$ reaction

In order to estimate the detection rates and optimise the ANKE detector setup, the $pd \to {}^3\text{He}\,K^+K^-$ reaction was simulated using the GEANT4 package [16]. The input distribution was generated at an excess energy of 25 MeV using a phase-space description. The MOMO non-ϕ total cross section seems to behave like phase space,

$$\sigma_{\text{tot}}(pd \to {}^3\text{He}\,\{K^+K^-\}_s) \approx 5\,(Q_{K\bar{K}}/\text{MeV})^2\ \text{pb}\,, \tag{3}$$

which leads to a value of 3.1 nb for $Q_{K\bar{K}} = 25\,\text{MeV}$. The results of the simulation were therefore normalised to this value. Using the simulation results together with a luminosity of $1.5 \times 10^{31}\,\text{cm}^{-2}\text{s}^{-1}$, the estimated count rate of the ANKE detector is given by

$$n = L\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\,\Delta\Omega\,\varepsilon_{\text{eff}} = L \times \sigma_{\text{tot}} \times \varepsilon_{\text{total}}, \tag{4}$$

The estimated total efficiency needed to evaluate the above, $\varepsilon_{\text{total}} = 3.6\%$, is made up of the following partial efficiencies:

- The ANKE detector acceptance $\varepsilon_{\text{acceptance}} = 8.6\%$ for the phase space input distribution at 25 MeV in the $^3\text{He}K^+$ coincidence trigger case;
- Considering the COSY duty time between the cycles, the time for regeneration of the hydrogen cluster-jet target, as well as possible downtimes of the COSY accelerator, we take $\varepsilon_{\text{COSY}} = 70\%$;
- The detection efficiency $\varepsilon_{\text{detector}} = 75\%$ is given mainly by the overall efficiency of the multi-wire chambers for positively charged (ANKE side and forward systems) and negatively charged particles;

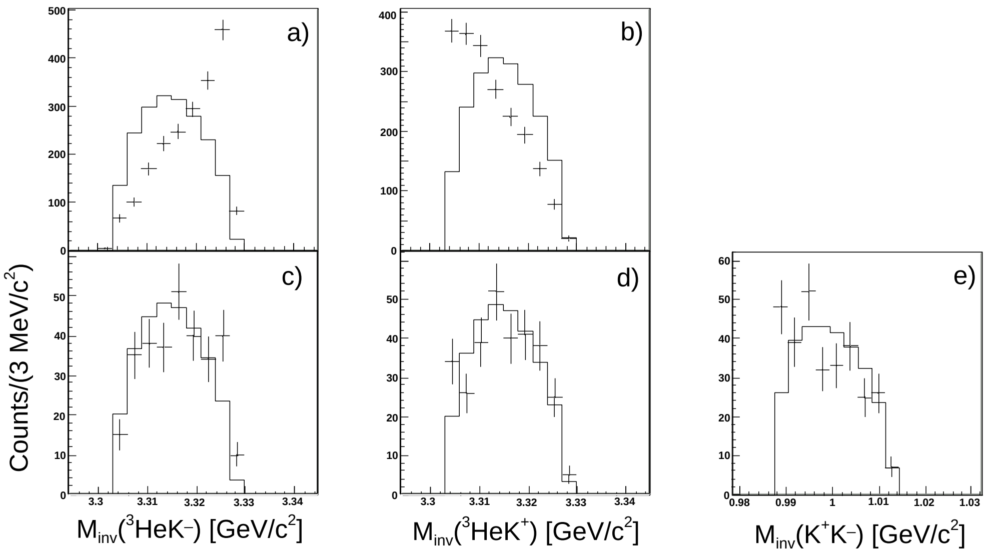


Figure 6: Monte Carlo simulation of the $pd \to {}^3\mathrm{He}\,K^+K^-$ reaction at $T_p = 1.783\,\mathrm{GeV}$. The input distributions have been generated using three-body phase space. The crosses indicate the statistics expected for two weeks of data-taking: 2000 events for the $^3\mathrm{He}K^+$ trigger (panels a and b) 300 events for the $^3\mathrm{He}K^+K^-$ trigger (panels c, d, and e). The histograms represent the initial distributions, scaled to the same numbers of events.

- The data-taking efficiency of the ANKE data acquisition system $\varepsilon_{\mathrm{daq}} = 80\%$.

After taking into account these efficiencies, the numbers of detected $^3\mathrm{He}K^+$ correlations expected from two weeks of data-taking are about 2000. Figure 6 shows the simulated invariant mass distributions. The typical ANKE momentum resolution of $\Delta p/p \approx 2\%$ (FWHM) provides a $3\,\mathrm{MeV/c^2}$ resolution for the $M_{\mathrm{inv}}(^3\mathrm{He}K)$ spectrum when a $^3\mathrm{He}K$ correlation is detected. The $M_{\mathrm{inv}}(K^+K^-)$ spectrum is equal to $M_{\mathrm{missing\ mass}}(pd,^3\mathrm{He})$ in this scheme but the corresponding mass resolution is around $10\,\mathrm{MeV/c^2}$. This same bin width is used in the case of the $^3\mathrm{He}K^+K^-$ identification due to the low statistics.

The background for collected $^3\mathrm{He}K^+$ correlations is estimated on a level of 10%. Such estimations are based on our previous measurement of the $pp \to dK^+\bar{K}^0$ reaction [7, 8] where the same type of trigger has been used. The background conditions could be even better because energy losses of ^{3}He are higher than for deuterons and this criterion will suppress background stronger.

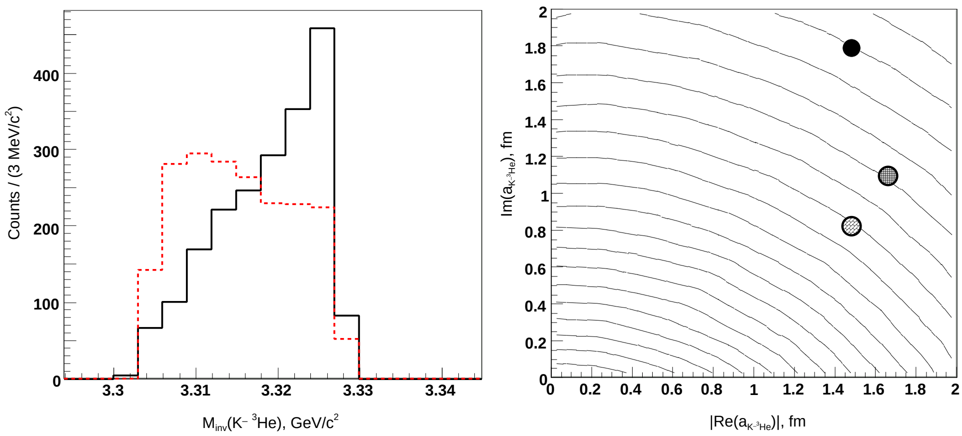


Figure 7: Left: Simulated invariant ^{3}HeK^- mass distribution using three-body phase space (black solid lines) and including the ^{3}HeK^- *FSI* with a scattering length of 1.5 fm (red dashed lines). Right: Contours of expected correlations between the determinations of the real and imaginary parts of the $K^-{}^3$He scattering lengths. It is expected that the typical statistical precision attainable on $|a_{K^-{}^3\mathrm{He}}|$ should be better than about 0.2 fm. The points correspond to multiple scattering estimates [15] using K^-N input from Conboy [17], Oller and Meißner [18], and Barret and Deloff [19].

Figure 7 shows the invariant ^{3}HeK^- mass distribution expected without and with the ^{3}HeK^- *FSI* switched on. It is seen that the data will be sensitive to the magnitude of the ^{3}HeK^- scattering length. The main spectrum which will provide information on the ^{3}HeK^- *FSI* is the ratio:

$$R_{HeK} = \frac{d\sigma/dM(K^-{}^3\mathrm{He})}{d\sigma/dM(K^+{}^3\mathrm{He})}\,. \qquad (5)$$

Monte Carlo simulations show that over the two weeks of measurements ANKE will collect data that will allow the ^{3}HeK^- effective scattering length to be determined on the 0.2 fm level or better (see Fig. 7).

4 Measurement of the pd → ^{3}H K$^+\bar{\mathrm{K}}^0$ reaction

Another important result of the experiment would be the simultaneous measurement of the cross section for the $pd \to {}^3\mathrm{H}\,K^+\bar{K}^0$ reaction. For this the ^{3}HK^+ trigger can be used, with the $\bar{K}^0$ being reconstructed as a peak in the $M_{\text{missing mass}}(pd,{}^3\mathrm{H}K^+)$ distribution. The ANKE detector acceptance

$\varepsilon_{\text{acceptance}} = 6.6\%$ was estimated by using a phase space input at a beam energy of 1.783 GeV in the $^3\text{He}K^+$ coincidence trigger case. This would lead to about 1000 events over the two weeks under the assumption that total cross section for the $pd \to {}^3\text{H}\,K^+\bar{K}^0$ reaction has the same energy dependence as $pd \to {}^3\text{He}\,K^+K^-$. Due to the mass differences, this reaction is at the slightly lower excess energy of $Q_{K\bar{K}} = 20.5$ MeV. Accidental background is estimated to be on a level of less than 15%.

It should be also noted that the $^3\text{H}\bar{K}^0$ and $^3\text{He}K^-$ *FSI* do not have to be the same unless they are dominated by a single isospin state driven, for example, by the $\Lambda(1405)$. The comparison of the $^3\text{H}\bar{K}$ and $^3\text{He}\bar{K}$ distributions could therefore provide a measure of the different $I_{\text{He}\bar{K}}$ isospin contributions. Furthermore, in the $pd \to {}^3\text{H}\,K^+\bar{K}^0$ case the kaon pairs must be in isospin $I_{KK} = 1$ and so the comparison of the results here and in the $pd \to {}^3\text{He}\,K^+K^-$ reaction could lead to the isolation of the $I_{KK} = 0$ contribution.

5 Study of the K$\bar{\text{K}}$ *FSI*

There is little evidence for the influence of the scalar mesons at low K^+K^- invariant masses in the $pd \to {}^3\text{He}\,K^+K^-$ reaction, though it must be stressed that this region was poorly covered in the Big Karl spectrometer settings, especially at 35.1 MeV [15]. Nevertheless it is possible that the structure seen at 40.6 and 55.2 MeV is genuine and arises from the elastic and charge-exchange *FSI*, similar to that observed in the $pp \to ppK^+K^-$ reaction [5] and illustrated in Fig. 2. Since the statistical accuracy and mass resolution in the $pd \to {}^3\text{He}\,K^+K^-$ reaction at low $m_{K^+K^-}$ is comparable to that achieved for $pp \to ppK^+K^-$, this is also a promising line of research.

It is evident that for a study of the cusp effect shown in Fig. 2, a high K^+K^- mass resolution of 1–2 MeV/c^2 is required. This can only be achieved at ANKE when all three final particles are detected. Due to the lower acceptance we will then reconstruct roughly 300 events during two weeks of beam time (see Fig. 6). This would lead to a statistical accuracy that is only slightly worse than that achieved for the *pp* data in Fig. 2. This was based on about 1000 events but at an excitation energy that was twice as large. The K^+K^- mass resolution improves with decreasing Q, which is another advantage of making measurements at a low excitation energy.

6 Beam-time request

For this experiment we request **two weeks** of beam time to measure the ^{3}HeK^- *FSI* in the $pd \to {}^3\mathrm{He}\,K^+K^-$ reaction at a beam energy of 1.783 GeV. This corresponds to an excess energy of 25.0 MeV above the kaon pair production threshold. During this time we expect to collect about 2000 ^{3}HeK^+, 300 ^{3}HeK^+K^-, and 1000 ^{3}HK^+ correlations. The ANKE spectrometer is the optimal instrument for this purpose. The measurement would be ready to start from January 2010.

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