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ASSOCIATED PRODUCTION OF HYPERNUCLEI

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The characteristics of the (π^+, k^+) reaction, a new experimental tool to produce hypernuclei, are discussed. Results from a recent (π^+, k^+) experiment are presented. Some future prospects of the (π^+, k^+) reaction are discussed.

1. INTRODUCTION

The (k^-, π^+) reaction has been the most important experimental tool^{1,2} to produce hypernuclei. In this strangeness-exchange reaction, the strange quark is brought in by the kaon beam and subsequently transferred to the target nucleus to form a hypernucleus, as illustrated in Fig. 1. One of the most important features of the (k^-, π) reaction is the selective excitation of low spin "substitution states" due to the small amount of momentum transfer. Identification of such states in p-shell Λ -hypernuclei has provided the first evidence of a small spin-orbit potential.³ On the other hand, the meager kaon flux available in existing accelerators has limited the usefulness of the (k^-, π) reaction. In particular, high-spin hypernuclear states, which are expected to be weakly populated in the (k^-, π) reaction, have never been identified.

It is evident that hypernuclei can be produced by reactions other than the (k^-, π) . These reactions usually fall into the category of associated productions, in which a pair of s and $\bar{s}$ quarks are produced. One example of such reactions is the $n(\pi^+, k^+)\Lambda$ reaction, shown schematically in Fig. 1. Intense proton and photon beam can also be employed to produce hypernuclei through the $p(p, p'k^+)\Lambda$ and the $p(\gamma, k^+)\Lambda$ reactions.^{4,5} A more exotic reaction $p(\bar{p}, \bar{\Lambda})\Lambda$ has also been contemplated.^{6,7} In this paper we focus on the (π^+, k^+) experiment⁸ recently investigated at the AGS accelerator at Brookhaven. This experiment demonstrates, for the first time, that hypernuclei can be produced with the mechanism of associated production.

In Section 2 we will discuss some important features of the (π^+, k^+) reaction. Comparisons of the (π^+, k^+) reaction with the more familiar (k^-, π) reaction will be frequently made. The (π^+, k^+) experiment at AGS and the interpretation of the experimental results are the subjects of Section 3, followed by a discussion of the future prospects of the (π^+, k^+) reaction in Section 4.

FIGURE 1
Quark line diagrams for the $n(K^-, \pi^-)\Lambda$ and the $n(\pi^+, K^+)\Lambda$ reactions

2. THE (π^+, K^+) REACTION

The theoretical aspects of the (π^+, K^+) reaction as a spectroscopic tool for hypernuclear physics have been investigated in detail by Dover, Ludeking and Walker.⁹ Before discussing the (π^+, K^+) experimental results, it is useful to review some pertinent features of the (π^+, K^+) reaction.

2.1. Momentum transfer

Since it requires a considerable amount of energy to produce a massive pair of strange quarks, a common feature in all associated production of hyperons is that the reaction is endothermic. The $n(\pi^+, K^+)\Lambda$ reaction has a Q-value about 655 MeV more negative than in the $n(K^-, \pi^-)\Lambda$ reaction. This leads to a large amount of momentum transfer (>300 MeV/c) in the (π^+, K^+) reaction, as shown in Fig. 2. This situation is in contrast to the strangeness-exchange (K^-, π^-) reaction using kaons in flight, where the momentum transfer is relatively small (<100 MeV/c). It is interesting to note, however, that the $n(K^-, \pi^-)\Lambda$ reaction with stopped kaons has a momentum transfer comparable to the $n(\pi^+, K^+)\Lambda$ reaction.

The large momentum transfer in the (π^+, K^+) reaction implies that hypernuclear states with high spin are favorably excited in this reaction.⁹ This contrasts with the (K^-, π^-) reaction which selectively excites low spin states at small reaction angles. It should not be concluded, however, that high spin

FIGURE 2
Momentum transfer for various reactions at 0° reaction angle

hypernuclear states cannot be studied with the (k^-, π^-) reaction. Figure 3 shows that the momentum transfer in the $^{12}\text{C}(k^-, \pi^-)$ reaction measured at 25° is comparable to that in the $^{12}\text{C}(\pi^+, k^+)$ reaction at 0° . In practice, reaction has never been measured at such large angles due to the rapid drop of the (k^-, π^-)

FIGURE 3
Momentum transfer for the (π^+, k^+) and (k^-, π^-) reactions as a function of laboratory angle

counting rate. In this sense, the (π^+, k^+) reaction complements the (k^-, π^-) reaction for exploring a different variety of hypernuclear states.

2.2. Elementary cross section

The threshold of the $n(\pi^+, k^+)\Lambda$ reaction occurs at 888 MeV/c. On a nuclear target, this threshold is significantly lowered. Typical of all endothermic binary reactions, the $n(\pi^+, k^+)\Lambda$ cross section peaks at an energy slightly above the threshold. Figure 4 shows the 0° cross sections of the $p(\pi^-, k^0)\Lambda$ reaction¹⁰ (equivalent to $n(\pi^+, k^+)\Lambda$ by isospin invariance). The peak (π^+, k^+) cross section of 0.9 mb/sr, occurring around 1050 MeV/c pion momentum, is roughly five times smaller than the peak cross section of the (k^-, π^-) reaction. Nevertheless, the much higher pion flux more than compensates this difference and makes the (π^+, k^+) reaction even more efficient than the (k^-, π^-) reaction for producing high-spin hypernuclear states.

FIGURE 4
 0° cross section for the $\pi^-p \rightarrow k^0\Lambda$ reaction as a function of beam momentum

2.3. Penetrability

The mean-free-path of hadrons in nuclei is usually taken as $1/\rho\sigma$. Since the total cross section σ of k^+ meson is much smaller than the k^- meson, the (π^+, k^+) reaction is expected to probe the nuclear interior somewhat better than the (k^-, π^-) reaction. This implies that deeply bound hypernuclear states, especially for medium and heavy hypernuclei, are more accessible by the (π^+, k^+) re-

action. An even better reaction to probe the nuclear interior is the (γ, k^+) reaction.

2.4. (π^+, k^+) versus (k^-, π^-) reactions

Comparisons between the (π^+, k^+) reaction and the (k^-, π^-) reaction as a tool for Λ -hypernuclei spectroscopy are shown in Table I. In addition to the characteristics discussed earlier, we note that the experimental environment for these two reactions is significantly different. The available pion flux in a typical beam line is at least two orders of magnitude greater than the kaon flux. The purity of pion beam is also superior to the kaon beam, making the beam particle identification in the (π^+, k^+) reaction somewhat less critical. The $k^- \rightarrow \mu^- \nu$, $k^- \rightarrow 2\pi$ and $k^- \rightarrow 3\pi$ decays, sources of background for the (k^-, π^-) reaction, do not contribute to the background in the (π^+, k^+) reaction. More discussions of the experimental aspects of the (π^+, k^+) reaction will be given in the next section.

TABLE I
Comparison between the $n(k^-, \pi^-)\Lambda$ and the $n(\pi^+, k^+)\Lambda$ reactions

	$n(k^-, \pi^-)\Lambda$	$n(\pi^+, k^+)\Lambda$
momentum transfer	$<100 \text{ MeV}/c$	$\sim 300 \text{ MeV}/c$
selectivity	low spin states	high spin states
mean free path	$\pi^- = 1.9 \text{ fm}$ $k^- = 2.0 \text{ fm}$	$\pi^+ = 1.6 \text{ fm}$ $k^+ = 4.6 \text{ fm}$
cross section	$\sigma_{\text{max}}(0^\circ) = 5 \text{ mb/sr}$	$\sigma_{\text{max}}(0^\circ) = 0.9 \text{ mb/sr}$
beam intensity (purity)	$<10^5/\text{beam spill}$ ($k/\text{all} \approx 7\%$)	$\sim 10^7/\text{beam spill}$ ($\pi/\text{all} \approx 80\%$)

3. THE $^{12}\text{C}(\pi^+, k^+)\Lambda^{12}\text{C}$ REACTION

3.1. Experimental setup

The feasibility of the (π^+, k^+) reaction for populating Λ -hypernuclei was investigated¹¹ at AGS using the Low Energy Separated Beam (LESB-I) and the hypernuclear spectrometer "Mohy-Dick." Figure 5 shows the layout of the beam line and the two spectrometers. The beam momentum was chosen at $1054 \text{ MeV}/c$, which is near the peak of the $n(\pi^+, k^+)\Lambda$ elementary cross section. The mass separator in the beam line, together with the time-of-flight measurement, provides good π^+ separation from k^+ and p . However, the e^+ contamination, not separable by the TOF technique, is estimated to be about 15%.

C2 BEAM LINE AND SPECTROMETERS

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FIGURE 5
Experimental setup for the $^{12}\text{C}(\pi^+, k^+)^{12}\text{C}$ experiment at AGS

The pion beam momentum was measured by drift chambers placed near the mass slit and the reaction target. High rate drift chambers¹² were constructed to handle the high beam flux near the mass slit region. The pion flux on target was about $3 \times 10^6/\text{spill}$. This flux was limited not by the drift chambers, rather by the scintillation counters S1 and S2. For future (π, k) experiments, segmented S1, S2 counters would allow a higher pion flux to be used.

The energy deposited in the target was measured by using an active scintillation target. Reaction products were detected by the kaon spectrometer sitting on a rotatable platform. Identification of kaons was achieved by the liquid nitrogen Cherenkov counters vetoing the fast pions and by the TOF information. Note that only 25% of the kaons emerging from the target survive the flight path of 7.9 meters. A shorter kaon spectrometer would be quite desirable for future (π^+, k^+) experiments.

3.2. Experimental results

The $^{12}\text{C}(\pi^+, k^+)$ spectra at $\theta_{\text{lab}} = 5^\circ$, 10° and 15° are shown in Fig. 6. The number of pions on target are 2.4×10^{10} , 1.1×10^{11} , and 1.8×10^{10} , respectively, for $\theta_{\text{lab}} = 5^\circ$, 10° , 15° . This corresponds to a total beam time of 70 hours. The spectra are plotted as a function of missing mass, with ^{12}C ground state corresponding to zero missing mass. Two peaks clearly stand out on the

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FIGURE 6
Spectra of the $^{12}\text{C}(\pi^+, k^+)$ reaction at three detection angles

$^{12}\text{C}(\pi^+, k^+)$ spectra. The peak with smaller missing mass is assigned as the ^{12}C ground state, even though the location of this peak is 4 MeV more negative than expected. This slight discrepancy is attributed to the difficulty of calibrating the central momenta of the pion and kaon spectrometers, a task complicated by the large mismatch of the two spectrometers (pion spectrometer at 1054 MeV/c, kaon spectrometer at 716 MeV/c) and by the lack of any reference reaction.

Figure 6 shows that the (π^+, k^+) spectra are not completely free from experimental background. This background most likely originates from a pion beam entering the kaon spectrometer and producing slow moving particles (π^+, k^+, p)

which simulate the flight time of a good (π^+, k^+) event.¹³ Despite this background, the $^{12}_\Lambda\text{C}$ ground state peak and the peak at $E_x = 11$ MeV are clearly visible. The spectra have not been corrected for the spectrometer acceptance, which accounts for the spectra shape at higher excitation energy.

It is instructive to compare the $^{12}\text{C}(\pi^+, k^+)^{12}_\Lambda\text{C}$ spectra with the $^{12}\text{C}(k^-, \pi^-)^{12}_\Lambda\text{C}$ spectra. Figure 7 shows $^{12}\text{C}(k^-, \pi^-)$ spectra measured with kaon in flight^{2,14} and with stopped kaons.¹⁵ The gross features of the $^{12}\text{C}(k^-, \pi^-)$ spectra are similar to those of the $^{12}\text{C}(\pi^+, k^+)$ spectra. However, the relative intensity of the g.s. versus the 11 MeV state depends on the reaction and the angle of detection. As will be shown in a later section, the 11 MeV state observed in the (k^-, π^-) reaction at 0° is different from the state observed in the (π^+, k^+) reaction.

FIGURE 7
Spectra of the $^{12}\text{C}(k^-, \pi^-)$ reaction with kaons^{2,14} in flight and stopped kaons¹⁵

The angular distributions of the two peaks populated in the $^{12}\text{C}(\pi^+, k^+)^{12}_{\Lambda}\text{C}$ reaction and in the $^{12}\text{C}(k^-, \pi^-)^{12}_{\Lambda}\text{C}$ reaction are shown in Fig. 8. The two states in the $^{12}\text{C}(\pi^+, k^+)^{12}_{\Lambda}\text{C}$ reaction both have angular distributions peaking at forward angle and falling gradually at larger angles. Similar angular distribution shape is also observed for the 11 MeV peak in the (k^-, π^-) reaction. In contrast, the ground state populated in the (k^-, π^-) reaction has a bell shaped angular distribution peaking at $\theta = 10^\circ$.

FIGURE 8
Angular distributions for the $^{12}\text{C}(\pi^+, k^+)^{12}_{\Lambda}\text{C}$ and the $^{12}\text{C}(k^-, \pi^-)^{12}_{\Lambda}\text{C}$ reactions

3.3. DWBA analysis

DWBA (Distorted Wave Born Approximation) calculation has been employed in the past to describe successfully the (k^-, π^-) reaction populating p-shell Λ -hypernuclei.¹⁶ A simple one-step reaction mechanism, in which a neutron in the target nucleus is turned into a Λ -particle, is assumed in this calculation. The spectroscopic amplitude for each neutron-hole Λ -particle configuration is obtained by shell model calculations. In the analysis of the (π^+, k^+) data, we follow closely the steps used in the previous (k^-, π^-) analysis.¹⁶ Two ingredients entering the (π^+, k^+) calculation are different from those in the (k^-, π^-) calculations. First, the optical model potentials for describing the distortion of the π^+ , k^+ waves are obtained by fitting the elastic scattering

data of π^+ , k^+ on ^{12}C at 800 MeV/c.¹⁷ The fits to the scattering data and the sets of optical model parameters are shown in Fig. 9. Note that the real potential for $k^+ + ^{12}\text{C}$ is repulsive. Second, the cross section of the elementary reaction $n(\pi^+, k^+)\Lambda$, required in the DWBA calculation, is obtained with a Fermi-averaging procedure. As shown in Fig. 4, the $n(\pi^+, k^+)\Lambda$ cross section is

FIGURE 9

Elastic scattering data¹⁷ of π^+ and k^+ on ^{12}C at 800 MeV/c. The solid curves are optical model fits. The optical model parameters are $(V, W, Y_0, a) = (24.83 \text{ MeV}, -38.84 \text{ MeV}, 0.857 \text{ fm}, 0.473 \text{ fm})$ for k^+ and $(-47.3 \text{ MeV}, -44.6 \text{ MeV}, 0.944 \text{ fm}, 0.529 \text{ fm})$ for π^+ .

strongly energy dependent, making it important to consider the Fermi motion of the target nucleons. Ideally, the amplitude of the $n(\pi^+, k^+)\Lambda$ reaction is Fermi-averaged.¹⁶ However, such amplitudes are not available and instead the cross sections are Fermi-averaged. Three different momentum distributions have been assumed: (1) uniform sphere with $k_F = 220$ MeV/c; (2) diffuse Fermi-gas model, $\rho(k) = \rho_0(1 + \exp(k - k_0)/\Delta k)^{-1}$, with $k_0 = 100$ MeV/c, $\Delta k = 50$ MeV/c; and (3) harmonic oscillator model, $\rho(k) = \rho_0(kb)^2 \exp(-k^2 b^2)$, with $b = 1.64$ fm. The Fermi-averaged cross section $\bar{\sigma}(\pi^+ n \rightarrow k^+ \Lambda)$ is 0.49 mb/sr, 0.50 mb/sr, 0.47 mb/sr, respectively, for the three different momentum distributions. The effect of Fermi-averaging is a reduction of 50% from the peak cross section.

The results of the DWBA calculations using the code CHUCK¹⁸ are shown in Fig. 10. The spectroscopic amplitudes for various transitions are taken from

FIGURE 10

Solid curves are DWBA predictions for the ^{12}C ground state and the ^{12}C 11 MeV state

Ref. 16. The calculation for the $^{12}_{\Lambda}\text{C}$ ground state, with a weak-coupling configuration of $(P_{3/2,1/2})^{-1}_n(S_{1/2})_{\Lambda}$, underestimates the data by about 30%. This is acceptable considering the 30% systematic error in the data and the uncertainty in the optical model parameters. The 11 MeV state has a particle-hole configuration of $(P_{3/2,1/2})^{-1}_n(P_{3/2,1/2})_{\Lambda}$ coupling to either 2^+ or 0^+ . The calculations, which describe the data well, show that the 0^+ state is about a factor of 50 more weakly excited than the 2^+ state. Furthermore, the 0^+ state has an angular distribution shape different from the data. Therefore, it can be concluded that the 11 MeV state observed in the $^{12}\text{C}(\pi^+, k^+)^{12}_{\Lambda}\text{C}$ reaction is dominantly a 2^+ state. This is different from the situation in the $^{12}\text{C}(k^-, \pi^-)^{12}_{\Lambda}\text{C}$ reaction, where both the 0^+ and 2^+ states contribute to the observed cross sections.¹⁹

There is an indication that a third peak, about 10 MeV higher than the $E_x = 11$ MeV state, might be excited in the 5° spectrum. Unfortunately, this state is close to the edge of spectrometer acceptance. Nevertheless, the location of this state coincides with the expected position of the $[(P_{3/2})^{-1}_n(d_{5/2})_{\Lambda}]3^-$ state and the $[(S_{1/2})^{-1}_n(S_{1/2})_{\Lambda}]0^+$ state. In fact, a previous (k^-, π^-) experiment²⁰ reported the observation of the $[(S_{1/2})^{-1}_n(S_{1/2})_{\Lambda}]0^+$ state. For the (π^+, k^+) reaction, the $[(P_{3/2})^{-1}_n(d_{5/2})_{\Lambda}]3^-$ state is expected to be more strongly excited, as shown in Fig. 11. In any event, both states are expected to be rather broad, and further experiments are needed for clarification.

4. FUTURE PROSPECTS

The success of the $^{12}\text{C}(\pi^+, k^+)^{12}_{\Lambda}\text{C}$ experiments has clearly demonstrated the feasibility of the (π^+, k^+) reaction as a tool for hypernuclear spectroscopy. From the good DWBA description of the data, the reaction mechanism appears to be well understood. This allows us to concentrate on the structure information of the hypernuclei. Two future (π^+, k^+) experiments have been proposed at KEK and at AGS.^{21,22} In this section, the proposed measurements and the physics motivations of the AGS experiment are discussed.

4.1. (π^+, k^+) reaction on heavy nuclei

There are two major reasons for measuring the (π^+, k^+) reaction on heavy nuclei. First, the knowledge of Λ -hypernuclei, obtained from emulsion experiments and the (k^-, π^-) experiments, is largely on light s-shell and p-shell hypernuclei. Properties of heavy hypernuclei are very poorly known. As an example, the ground state mass of Λ -hypernuclei is only known²³ accurately up to $^{15}_{\Lambda}\text{N}$. Second, the (π^+, k^+) reaction is most suitable for populating high-spin states, expected to occur more frequently in heavier hypernuclei.

FIGURE 11

DWBA predictions for the cross sections of the $[(p_{3/2})_n^{-1} (d_{5/2})_{\Lambda}] 3^-$ and $[(s_{1/2})_n^{-1} (s_{1/2})_{\Lambda}] 0^+$ states in the $^{12}\text{C}(\pi^+, k^+)_{\Lambda}^{12}\text{C}$ reaction

Measurements of the (π^+, k^+) reaction on ^{28}Si and ^{40}Ca nuclei have been proposed.²² A 4^+ state with the configuration $(d_{3/2, 5/2})_n^{-1} (d_{3/2, 5/2})_{\Lambda}$ is expected to be strongly excited in both cases. A 5^- state in $^{40}_{\Lambda}\text{Ca}$ with the configuration $(d_{3/2})_n^{-1} (f_{7/2})_{\Lambda}$ should also be observable if its width is not too broad. Although such high-spin hypernuclear states are predicted to exist, they have never been identified experimentally. The main physics interest of the high-spin hypernuclear states is that the configuration of these states is expected to be very simple. Unlike the situation for low-spin substitution states, not many particle-hole configurations can couple to high spin states. Clear identifications of such high-spin states provide direct measurement of the location of different Λ -orbitals. In particular, this would allow us to check the strength of spin-orbit interaction for d-shell Λ -hypernuclei.

The ground states of medium or heavy hypernuclei usually fall into the category of high spin states. For example, the $^{28}_{\Lambda}\text{Si}$ ground state is expected to be a 2^+ state with the configuration of $(d_{5/2})^{-1}_n (s_{1/2})_{\Lambda}$. Figure 12 shows the DWBA predictions of the (π^+, k^+) cross sections for $^{28}_{\Lambda}\text{Si}$ ground state and the 4^+ state. Although the ground state is not as strongly excited as the 4^+ state, the fact that the ground state is well separated from the quasi-free peak should make it easily identifiable. We recall that the $^{12}_{\Lambda}\text{C}$ ground state was strongly excited and well identified in the (π^+, k^+) reaction. A similar situation is expected for the $^{28}_{\Lambda}\text{Si}$ and $^{40}_{\Lambda}\text{Ca}$ ground states.

FIGURE 12
DWBA predictions for the $[(d_{5/2})^{-1}_n (d_{5/2})_{\Lambda}]4^+$ and $[(d_{5/2})^{-1}_n (s_{1/2})_{\Lambda}]2^+$ states in the $^{28}_{\Lambda}\text{Si}(\pi^+, k^+)^{28}_{\Lambda}\text{Si}$ reaction

An accurate measurement of the mass of $^{28}_{\Lambda}\text{Si}$ and $^{40}_{\Lambda}\text{Ca}$ could shed some light on the problem²⁴ of overbinding for $^5_{\Lambda}\text{He}$. A recent work by Biedenharn and Hungerford²⁵ considered the possibility of deconfinement for the s-shell Λ particle, causing the up and down quarks to be Pauli blocked and hence a smaller binding energy for $^5_{\Lambda}\text{He}$. One expects that the effects of deconfinement and

quark blocking should be more striking for Λ particles deeply bound in heavy nuclei. One possible manifestation of such effects could be an anomalous binding energy for heavy hypernuclei.

4.2. Λ -hypernucleus in the continuum and Σ -hypernucleus

We propose to extend the $^{12}\text{C}(\pi^+, k^+)$ measurement to cover more highly excited $^{12}_{\Lambda}\text{C}$ states all the way up to the region of $^{12}_{\Sigma}\text{C}$ states. In addition to obtaining better information on the possible existence of the third peak at $E_x = 20$ MeV, this measurement would allow us to investigate the region of quasi-free Λ -production and the production of Σ -hypernuclei.

The quasi-free Λ -production in the (k^-, π^-) reaction has been clearly observed and the data have been interpreted by Dalitz and Gal.²⁶ Due to the larger momentum transfer, the quasi-free peak is expected to be much broader in the (π^+, k^+) reaction.⁹ The fact that the quasi-free peak in the (k^-, π^-) reaction has a narrow width and large strength makes it difficult to study the Λ -hypernuclear states in the continuum. In contrast, the situation is much more favorable for the (π^+, k^+) reaction.

The predicted cross section²² for the $^{12}\text{C}(\pi^+, k^+)^{12}_{\Sigma}\text{C}$ cross section is rather small, on the order of a few tenths of $\mu\text{b}/\text{sr}$. Whether these Σ -hypernuclear states could be observed depends on the strength of the Λ quasi-free background.

4.3. The $d(\pi^+, k^+)\text{H}$ reaction

The theoretical and experimental situation on the $S = -1$ dibaryon, has been discussed at this conference by Dover²⁷ and by Piekarz.²⁸ Among all the $S = -1$ dibaryons predicted by Mulders et al.,²⁹ the 2.6 GeV, $L^P = 1^-$, spin triplet state is of particular interest. This state has the same spin as deuteron and could be produced in the $d(k^-, \pi^-)$ or the $d(\pi^+, k^+)$ reaction with $\Delta L = 1$. Intriguing results on the $d(k^-, \pi^-)$ reaction have been obtained in a recent AGS experiment²⁸ and a CERN experiment.³⁰

In order to shed more light on the important issue of the existence of strange dibaryons, we plan to measure²² the $d(\pi^+, k^+)$ reaction using the same multiplicity hodoscope previously used²⁸ in the $d(k^-, \pi^-)$ reaction. Since it requires $\Delta L = 1$ to produce the strange dibaryon, the large momentum transfer in the (π^+, k^+) reaction is rather favorable. The cusp at the ΣN threshold is formed via a $\Delta L = 0$ process and should not be strongly populated. We expect the separation between the dibaryon peak and the cusp background to be adequate in the $d(\pi^+, k^+)$ reaction. A prediction on the zero degree $d(\pi^+, k^+)\text{H}$ cross section at 1.05 GeV/c was given by Aerts and Dover³¹ as 0.7 $\mu\text{b}/\text{sr}$, roughly a factor of three lower than the peak cross section of the $d(k^-, \pi^-)\text{H}$ reaction.

This is rather encouraging considering the available pion flux is about two orders of magnitude higher than kaon flux.

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