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TITLE HYPERNUCLEAR PHYSICS WITH A NEUTRAL MESON SPECTROMETER

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Hypernuclear Physics with a Neutral Meson Spectrometer

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Abstract

The (K^-, π^0) reaction, which complements the (K^-, π^-) and the (π^+, K^+) reactions, offers another means to study hypernuclear physics. The physics motivation for measuring the (K^-, π^0) reaction is discussed. The feasibility for detecting π^0 using the LAMPF Neutral Meson Spectrometer is studied with Monte-Carlo simulations. We conclude that the (K^-, π^0) reaction can be well measured at existing kaon beam lines.

I. Introduction

The (K^-, π^-) and the (π^+, K^+) reactions have been the major experimental tools for studying Λ-hypernuclei. In these reactions, a neutron in the target nucleus is converted into a lambda hyperon and hypernuclear states with a neutron-hole coupled to a lambda-particle are populated predominantly. Other elementary processes, including $p(\gamma, K^+)\Lambda$, $p(p, K^+p)\Lambda$, $p(\pi^-, K^0)\Lambda$, and $p(K^-, \pi^0)\Lambda$, have been considered[1-4] as complementary methods to produce hypernuclei. All of these reactions share a common feature that a proton, rather than a neutron, is changed into a lambda particle. None of these reactions has been used as a tool for hypernuclear studies yet, although there are plans to study the (γ, K^+) and the (p, K^+) reactions at the CEBAF[1] and COSY[2] facilities. In this paper, we examine the physics motivations and experimental feasibility for studying the (K^-, π^0) reaction. The absence of a high-resolution, large-acceptance detector for π^0 has been a major hindrance for pursuing this study. Nevertheless, with the successful operation of the π^0-spectrometer[5] and the recent construction of a high-performance Neutral Meson Spectrometer (NMS)[6] at LAMPF, the prospect for studying the (K^-, π^0) reaction at existing facilities deserves serious considerations.

II. Physics Motivations

1. Λ-Hypernuclei with the (K^-, π^0) Reaction

What are the interesting issues in Λ hypernuclei that can be addressed in the (K^-, π^0) reaction? First of all, on a zero isospin (T=0) target, the (K^-, π^0) reaction together with the (K^-, π^-) reaction, excite mirror hypernuclear pairs. Table I lists the binding energies of all the known mirror-hypernuclear pairs. These binding energies were determined from emulsion experiments[7] and they were limited to hypernuclear ground states. The binding energy difference in ${}^4_\Lambda H$ ${}^4_\Lambda He$ pair was interpreted as evidence of Charge Symmetry Breaking (CSB) effect resulting from Σ^0-Λ mixing[8]. A high resolution study of the (K^-, π^0) and the (K^-, π^-) reactions offer the opportunity to produce mirror hypernuclear pairs not only for ground states, but also for excited states. A precision measurement of the γ ray energies from the (K^-, π^-_γ) and the (K^-, π^0_γ) reactions allows a sensitive test of the presumably very small CSB effects. Of particular interest are the transitions in which a Λ changes its single particle orbitals, for example, from p-shell to s-shell.

On a neutron rich (T=0) target, the (K^-, π^0) reaction will selectively excite hypernuclear states with isospin T+1/2. In contrast, the (K^-, π^-) reaction will populate both the T+1/2 and the

Table I. Λ Binding Energies for Mirror-Hypernuclear Pairs

Hypernucleus	B_Λ (MeV)
${}^{4}_{\Lambda}H$	2.04 ± 0.04
${}^{4}_{\Lambda}He$	2.39 ± 0.03
${}^{8}_{\Lambda}Li$	6.80 ± 0.03
${}^{8}_{\Lambda}Be$	6.84 ± 0.05
${}^{9}_{\Lambda}Li$	8.50 ± 0.12
${}^{9}_{\Lambda}B$	8.29 ± 0.18
${}^{10}_{\Lambda}Be$	9.11 ± 0.22
${}^{10}_{\Lambda}B$	8.89 ± 0.12
${}^{12}_{\Lambda}B$	11.37 ± 0.06
${}^{12}_{\Lambda}C$	10.76 ± 0.19

T = 1/2 hypernuclear states. A comparison between the (K^-, π^0) and the (K^-, π^+) spectra will therefore help to determine the isospin of the hypernuclear states.

It is clear that the (K^-, π^0) reaction can lead to neutron-rich hypernuclei not reachable by the (K^-, π^+) reaction. Certain light Λ-hypernuclei can only be produced by the (K^-, π^0) reaction. Examples are the ${}^{3}He(K^-, \pi^0)\,{}^{3}_{\Lambda}H$ and the ${}^{4}He(K^-, \pi^0){}^{4}_{\Lambda}H$ reactions, which provide means to study interesting decay properties of the ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ ground states[9].

2. The $d(K^-, \pi^0)$ Reaction

The $d(K^-, \pi^+)\Lambda p$ and the $d(\pi^+, K^+)\Lambda p$ reactions have been studied in several experiments at a number of beam energies[10-12]. In these experiments a peak in the Λp mass spectrum was clearly observed. The location of this peak (M = 2129.0 ± 0.4 MeV) is near the thresholds of $\Sigma^+ n$ (2128.9 MeV) and $\Sigma^0 p$ (2130.8 MeV), suggesting the presence of a threshold-cusp effect. However, this peak could also correspond to an S = -1 dibaryon resonance. The $d(K^-, \pi^+)\Lambda n$ reaction could shed some light on the nature of this peak. We note that the thresholds for $\Sigma^0 n$ and $\Sigma^- p$, the two channels which can couple to Λn, are 2132.1 and 2135.7 MeV, respectively. These threshold energies are at least 3 MeV higher than the mass of the peak observed in the $d(K^-, \pi^+)\Lambda p$ reaction. An accurate measurement of the masses of any peaks in the $d(K^-, \pi^0)\Lambda n$ reaction will help to disentangle the threshold-cusp from the S = -1 dibaryon resonance effects.

3. Σ-Hypernuclei with the (K^-, π^0) Reaction

Despite much experimental efforts, evidences for the existence of Σ hypernuclear states are not conclusive. Nevertheless, a recent study[13] at KEK on the ^{4}He(stopped K^-, π^+) reactions found a peak in the (K^-, π^+) spectrum, corresponding to a ${}^{4}_{\Sigma}He$ bound state with a binding energy of 3.2 MeV. It is intriguing, however, that no evidence of Σ hypernuclear states was seen in the (K^-, π^+) spectrum. Qualitatively similar results were also obtained in a recent ${}^{4}He(K^-, \pi^+)$ experiment at AGS using kaons in flight[14]. To understand the difference between the (K^-, π^0) and the (K^-, π^+) reaction, we note that the ${}^{4}He(K^-, \pi^0)$ reaction can excite both isospin 1/2 and isospin 3/2 Σ hypernuclear states, while the ${}^{4}He(K^-, \pi^+)$ reaction can only reach isospin 3/2 state. Therefore, the absence of peaks in the (K^-, π^+) spectrum suggests that the Σ hypernuclear state observed in

the $^4He(K^-,\pi^-)$ reaction has isospin 1/2. It should be noted that Dalitz et al.[15] have presented a different interpretation of these data.

The (K^-,π^0) reaction will provide valuable information to clarify the nature of the peak observed in the $^4He(K^-,\pi^-)$ reaction. Since both isospin 3/2 and isospin 1/2 Σ-hypernuclear states can be excited in the $^4He(K^-,\pi^0)$ reaction, one expects observing a peak corresponding to $^4_\Sigma H$ with isospin 1/2 in this reaction.

4. H-dibaryon Search with π^0 Detection

An experiment is currently underway at AGS to search for the S = -2 H-dibaryon[16]. In this experiment a two-step process, $K^-p \to K^+\Xi^-$ followed by $\Xi^- d \to nH$, is used. Evidence of H would show up as a peak in the neutron energy spectrum. It is conceivable that one can also search for H-dibaryon via another two-step process, namely, $K^-p \to K^+\Xi^-$ followed by $\Xi^- p \to \pi^0 H$. The signature of H-dibaryon would be a peak in the π^0 energy spectrum. The advantage of this approach is the simplification of target design, since the same liquid hydrogen target is used in both reactions. However, only tightly bound H-dibaryon can be reached in this method.

III. Monte-Carlo Simulation of the (K^-,π^0) Reaction

To evaluate the technical feasibility to detect the (K^-,π^0) reaction, several important issues, such as the expected energy resolution, solid-angle acceptance, and estimated count rate, need to be addressed. In this section, we present results from a Monte-Carlo study on the performance of the NMS at existing kaon beam lines at AGS.

1. Neutral Meson Spectrometer

The design principles for the NMS[6] are very similar to those for the LAMPF π^0-spectrometer. The NMS consists of two identical arms, each of which contains a 6 x 10 array of CsI crystals and four planes of active BGO converters. The thickness of each BGO converter plane is 0.6 cm (0.5 radiation length). Each BGO converter plane is followed by wire chambers to measure electrons and positrons originating from the conversion point. The total energy of the photons from the $\pi^0 \to 2\gamma$ decay is measured by summing the energies deposited in the active BGO converters and the CsI counter array. Each CsI counter is 30 cm long, with a 7.5 cm x 10 cm cross section tapered to 10 cm x 10 cm. The design goals for the NMS are to achieve an energy resolution of 3% (FWHM) for 100 MeV γ and a conversion point resolution of $\sim 250\mu m$ (FWHM).

From the measured conversion point and energy of each photon, one must assume a certain interaction point in the target to reconstruct the π^0 energy. The π^0 energy resolution therefore depends on the uncertainties of the interaction point and the photon conversion point, and the energy resolution of photons. All of these uncertainties, as well as the beam momentum resolution and the energy loss of kaon beam in the target, contribute to the missing mass resolution. To reduce the uncertainties of the interaction point, a thin target together with a position measurement of the kaon beam are needed. The uncertainty in the interaction point has less effect on the π^0 energy resolution as the distance (R) between the target and the spectrometer is increased. However, the solid angle acceptance drops rapidly at large R. A careful Monte Carlo study is required to find a setting of the spectrometer that optimizes solid angle acceptance and energy resolution simultaneously.

We have considered two reactions in our Monte Carlo study. The first is the $^{12}C(K^-,\pi^0)^{12}_\Lambda B$ reaction at 700 MeV/c, a typical beam momentum for studying Λ hypernuclei. Another reaction is the $^4He(K^-,\pi^0)^4_\Sigma H$ using stopped kaon beam in a liquid ^{4}He target. These two reactions represent

quite different conditions in beam energy, target configuration, π^0-energy, and the background situation. In the first reaction, the energy of π^0 emitted at 0° is $\sim$530 MeV with the minimal opening angle, η, $\sim$ 23.5°. For the second reaction, the π^0 energy is $\sim$90 MeV with $\eta \sim 75^\circ$.

2. Detection of the $^{12}C(K^-,\pi^0)^{12}_{\Lambda}B$ Reaction

For simulating the performance of NMS, we use a modified version of the code PIANG[5] originally written for the LAMPF π^0-spectrometer. We assume a beam momentum uncertainty of 1.5 MeV/c (FWHM) at 700 MeV/c and a 1 cm-thick carbon target. The spectrometer is set at an opening angle of 35°, and the distance between the target and the mean location of the converters is 100 cm. Figure 1 shows the missing-mass resolution as a function of Xcut for two different assumptions for the γ-ray energy resolution and the conversion point resolution of NMS. The solid curve is obtained by using the design specifications of the NMS, whereas the dashed curve assumes resolutions three times worse than the designed values. Xcut represents a cut on the γ-ray energy asymmetry parameter X, defined as

$$X = |(E(\gamma_1) - E(\gamma_2))/(E(\gamma_1) + E(\gamma_2))|$$

Figure 1 shows that a missing-mass resolution of $\sim$1.5–2.0 MeV can be readily achieved in the (K^-,π^0) reaction at existing kaon beam line using the NMS. This missing-mass resolution is very similar to what has been obtained in the (K^-,π^-) and the (π^+,K^+) experiments. Figure 1 also demonstrates the importance of achieving the best possible energy and position resolution for NMS, since one could then cut on a larger value of X (which gives larger solid-angle acceptance) without deteriorating the missing-mass resolution significantly.

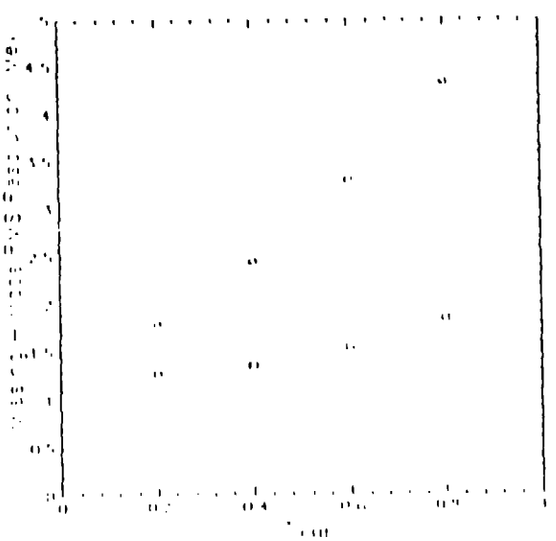

Fig. 1. Monte Carlo simulation of the missing mass resolutions for the NMS detecting the $^{12}C(K^-,\pi^0)^{12}_{\Lambda}B$ reaction at 700 MeV/c. The solid curve uses the designed values of the NMS position and energy resolutions. The dashed curve assumes resolutions three times worse than the designed values. The spectrometer is set at R = 100 cm, η = 35°.

Figure 2(a) shows the solid angle acceptance of NMS as a function of the θ_{lab} of the π^0. We assume the following settings for the NMS: R = 100 cm, Xcut = 0.4, and opening angle = 35°. The integrated solid angle angle acceptance is 33 msr, which is larger than the typical acceptance

of ~15 msr for charged-particle spectrometer. Since the angular distributions of the (K^-, π^0) reaction are expected to be forward-peaked, we will only consider the solid-angle acceptance for $0° \leq \theta_{lab} \leq 10°$. In Figure 2(b) we plot the NMS solid-angle acceptance as a function of Xcut for various values of R and η. Even at a setting of R = 200 cm, which gives excellent missing-mass resolution, the solid-angle acceptance, ~10 msr, is still quite adequate.

We are now ready to make a count-rate estimate for this reaction. Assuming $10^5 K^-$/spill, a 1 cm-long carbon target, an average cross section $d\sigma/d\Omega = 0.5$ mb for $\theta_{lab} < 10°$, a 20 msr solid-angle acceptance for NMS, and a 50% overall efficiency for π^0 conversion probability and other detector efficiencies, we estimate ~70 events/hour. This count rate is very favorable when compared with the (K^-, π^-) reaction.

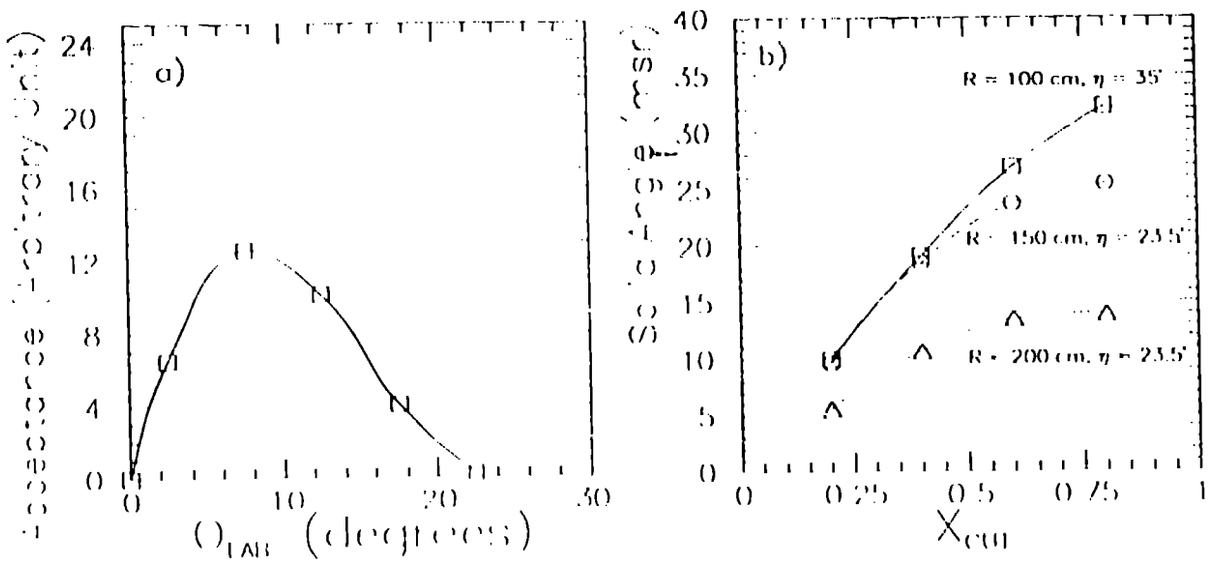

Fig. 2. (a) Acceptance as a function of θ_{lab} of the NMS for detecting the $^{12}C(K^-, \pi^0)^{12}_{\Lambda}B$ reaction at 700 MeV/c. The NMS is set at R = 100 cm, η = 35°, and Xcut = 0.4. (b) Solid angles of the NMS for detecting the $^{12}C(K^-, \pi^0)^{12}_{\Lambda}B$ reaction at 700 MeV/c over the range $\theta_{lab} < 10°$. Various curves correspond to different NMS settings.

3. Detection of the ^4He(stopped $K^-, \pi^0)^4_{\Sigma}H$ Reaction

There are several important differences between this reaction and the reaction just considered. First, the π^0 energy is relatively low (~90 MeV) and the minimal opening angle is ~75°. Second, the beam momentum spread and the energy loss in the target will no longer contribute to the missing mass resolution. Third, the large dimension of the target implies a big uncertainty in the interaction point, which gives the major contribution to the opening angle resolution. Finally, the angular distribution of the emitted π^0 is isotropic.

To simulate the performance of the NMS for detecting this reaction, we assume a liquid ^{4}He target of the dimension 10 cm x 10 cm x 10 cm, with kaons stopped uniformly along the beam direction.

We also assume that the position of the stopped kaons in the direction transverse to the beam axis can be determined to an accuracy of 1 cm (FWHM), presumably via chambers placed near the front surface of the ^{4}He target. Since the dominant contribution to the π^0 energy resolution comes from the uncertainty in the interaction point, it is important to set the spectrometer at a configuration which minimizes this contribution. This is illustrated in Figure 3(a). The solid curve corresponds to the setting for $\theta_{lab} = 0°$, namely, the bisector of the two arms of the NMS is along the beam axis. The dashed curve was obtained with the NMS centered at $\theta_{lab} = 90°$. The missing-mass resolution is much improved in the latter setting, since the opening angle determination is less sensitive to the uncertainty of the interaction point in this case. Figure 3(b) shows the solid-angle acceptance as a function of R. A missing-mass resolution of ~1 MeV and a solid-angle acceptance of ~20 msr can be achieved.

As for the expected count rate for the $^4He(K^-,\pi^0)^4_{\Lambda}H$ reaction, we assume 500 stopped K^- per beam spill at the AGS beam line, a 6 x 10^{-3} probability for each stopped K^- to form the $^4_{\Lambda}H$ bound state, a 20 msr solid angle acceptance, and a 50% overall efficiency for π^0 conversion and detector efficiencies. We estimate a total of ~1450 events for 500 hours of running time. This rate is comparable to that in the $^4He(K^-,\pi^-)^4_{\Lambda}He$ reaction.

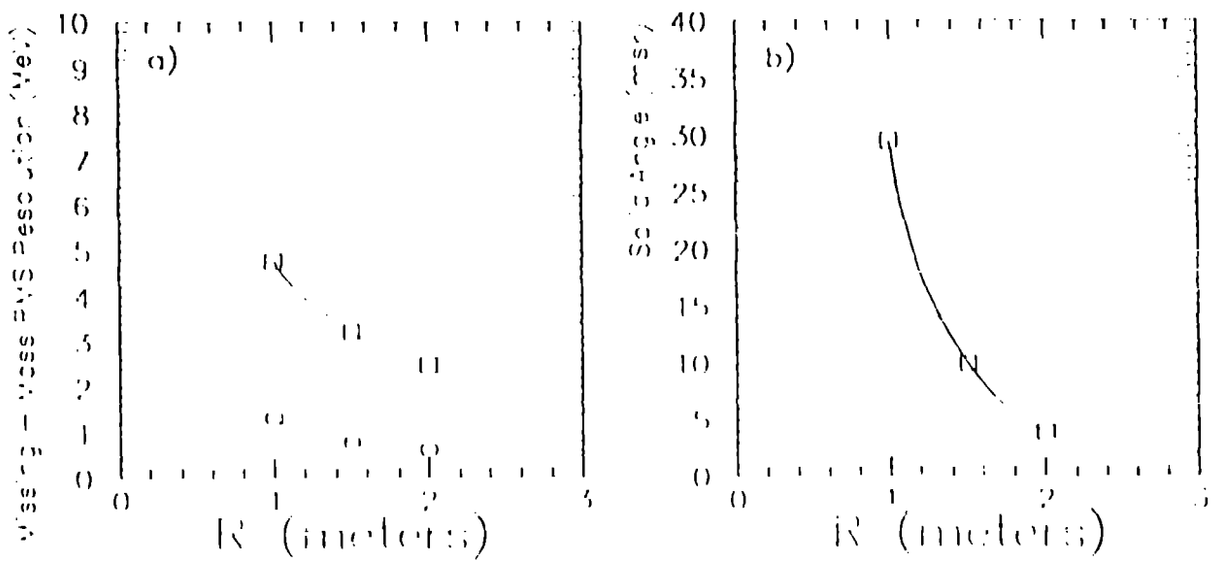

Fig. 3. (a) Monte Carlo simulation of missing mass resolution for the NMS detecting the ^4He(stopped $K^-,\pi^0)^4_{\Lambda}H$ reaction. The solid and dashed curves correspond to the setting at $\theta_{lab} = 0°$ and $\theta_{lab} = 90°$, respectively. R = 100 cm, $\eta = 75°$, and Xcut = 0.4. (b) Solid angle of NMS as a function of R. Xcut = 0.4.

IV. Summary

The (K^-,π^0) reaction is complementary to the (K^-,π^-) reaction for studying hypernuclear physics. We discuss a number of issues in hypernuclear physics which can be well addressed by the (K^-,π^0)

reaction. Based on the results of Monte-Carlo simulations for the performance of the NMS to detect the $^{12}C(K^-,\pi^0)^{12}_{\Lambda}B$ and $^4He(\text{stopped}K^-,\pi^0)^4_{\Sigma}H$ reactions, we conclude that the (K^-,π^0) reaction can be well pursued at existing kaon beam facilities.

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