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# Prospects for Studying the $(\pi^-, K^\circ)$ Reaction at PILAC

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## ABSTRACT

The $(\pi^-, K^\circ)$ reaction, which complements the $(\pi^+, K^+)$ reaction, offers another means to study $\Lambda$-hypernulei at PILAC. The physics motivation for measuring the $(\pi^-, K^\circ)$ reaction is discussed. The feasibility for detecting $K^\circ$ at PILAC using the LAMPF Neutral Meson Spectrometer and a simple dipole spectrometer is studied with Monte-Carlo simulations. We conclude that the $(\pi^-, K^\circ)$ reaction can be well pursued at PILAC.

## I. INTRODUCTION

The recent finding[1] that the $(\pi^+, K^+)$ associate production reaction can populate deep-bound $\Lambda$ single-particle states in heavy hypernuclei has opened up an entirely new approach to the study of hypernuclei. In this workshop, the opportunity offerd by the proposed high intensity pion beam facility, PILAC[2], to study the $(\pi^+, K^+)$ reaction has been discussed by several speakers. The $(\pi^-, K^\circ)$ reaction, which in many ways complements the $(\pi^+, K^+)$ reaction, provides another means to produce hypernuclei. In this paper, the feasibility to study the $(\pi^-, K^\circ)$ reaction at PILAC is examined. Some of the physics motivation for measuring the $(\pi^-, K^\circ)$ reaction are first discussed, followed by consideration on the $K^\circ$ detection. Finally, results from Monte-Carlo simulation of $K^\circ$ detection with a simple magnetic spectrometer and the LAMPF Neutral Meson Spectrometer are presented.

## II. PHYSICS MOTIVATIONS

### 1. The $p(\pi^-, K^\circ)\Lambda$ Reaction

The elementary process for $A(\pi^+, K^+)_\Lambda A$ is the $n(\pi^+, K^+)\Lambda$ reaction. This reaction, however, is not readily accessible experimentally. Isospin invariance implies that the $p(\pi^-, K^\circ)\Lambda$ and the $n(\pi^+, K^+)\Lambda$ reactions have identical cross sections. Figure 1 shows the existing data[3] on the $p(\pi^-, K^\circ)\Lambda$ total cross sections.

We mention three energy regions where more precise data on the $p(\pi^-, K^\circ)\Lambda$ reaction are of interest. First, precise measurements of the $p(\pi^-, K^\circ)\Lambda$ differential cross sections and polarization data around $P_{lab} = 1050\ MeV/c$ will allow us to choose the most optimal beam energy for measuring the $A(\pi^+, K^+)_\Lambda A$ reaction, and to provide inputs to theoretical calculations describing the cross sections, energy dependence, and selectivity of the $A(\pi^+, K^+)_\Lambda A$ reaction. This is especially important since the existing measurements[3] of the $p(\pi^-, K^\circ)\Lambda$ cross sections around 1050 $MeV/c$ differ by ~ 50%.

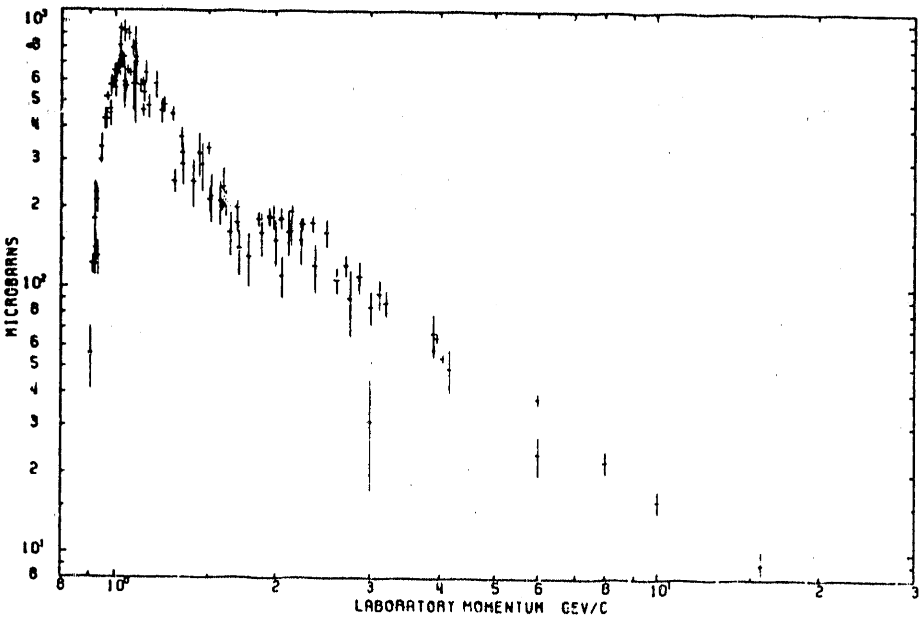

**Fig. 1.** $\pi^- p \to K^\circ \Lambda$ total cross sections[3] as a function of pion momentum.

Another interesting energy region is around 900 $MeV/c$, near the threshold of the $p(\pi^-, K^\circ)\Lambda$ reaction. A recent LEAR experiment[4] measuring the $\bar{p}p \to \bar{\Lambda}\Lambda$ cross sections near threshold energy showed that the observed energy dependence is in agreement with a P-wave production. The $\pi^- p \to K^\circ \Lambda$ reaction is closely related to the $\bar{p}p \to \bar{\Lambda}\Lambda$ reaction. In both reactions, a pair of $u, \bar{u}$ quarks are annihilated and a pair of $s, \bar{s}$ quarks created. A good measurement of the threshold behavior of the $\pi^- p \to K^\circ \Lambda$ cross sections, poorly known at present, would allow an interesting comparison between these two reactions and shed more light on the mechanism of $s, \bar{s}$ threshold production.

The $(\pi^-, K^\circ)$ reaction near the $p(\pi^-, K^\circ)\Sigma^\circ$ threshold is also of some interest. Previous data[5] on the $p(\pi^-, K^\circ)\Lambda$ cross sections showed a threshold-cusp effect due to the opening of the $p(\pi^-, K^\circ)\Sigma^\circ$ channel. It would be interesting to measure accurately both the $p(\pi^-, K^\circ)\Lambda$ and the $p(\pi^-, K^\circ)\Sigma^\circ$ reactions near this energy region for a good determination of the threshold-cusp effect and also to deduce the coupling between the $\Lambda N$ and $\Sigma N$ channels.

## 2. Λ- Hypernuclei with the $(\pi^-, K^\circ)$ Reaction

Table I lists some elementary processes which could produce Λ- hypernuclei. Only the $(K^-, \pi^-)$ and the $(\pi^+, K^+)$ reactions have so far been explored experimentally. These two reactions are similar, because they both convert a neutron into a lambda and the resulting hypernuclei have the configurations of a lambda particle coupled to a neutron hole. The $(\pi^-, K^\circ)$ reaction, on the other hand, converts a proton into a lambda particle. This is similar to the $(K^-, \pi^\circ)$ reaction which can be measured at future KAON facility[6]. It is interesting to compare the $(\pi^-, K^\circ)$ with the $(\gamma, K^+)$ reaction which will be pursued[7] at the CEBAF facility, since the $(\pi^-, K^\circ)$ reaction excites natural-parity states while the $(\gamma, K^+)$ reaction populates unnatural parity states.

**Table I. Elementary Processes for Λ- Hypernuclei Production**

| Reaction | Q- value (MeV) |
|---|---|
| $n(K^-, \pi^-)\Lambda$ | 178.0 |
| $n(\pi^+, K^+)\Lambda$ | -530.1 |
| $p(K^-, \pi^\circ)\Lambda$ | 181.3 |
| $p(\gamma, K^+)\Lambda$ | -671.0 |
| $p(p, K^+p)\Lambda$ | -671.0 |
| $p(\pi^-, K^\circ)\Lambda$ | -535.5 |

What are the interesting topics in Λ-hypernuclei that can be addressed in the $(\pi^-, K^\circ)$ reaction? First of all, on a zero isospin (T=0) target, the $(\pi^-, K^\circ)$ reaction, together with the $(\pi^+, K^+)$ reaction, excite mirror-hypernuclear pairs. Table II compares the binding energies of several mirror hypernuclear pairs. These binding energies are determined from emulsion data[8] and are limited to hypernuclear ground states. The observed binding energy difference in ${}^4_\Lambda H$ - ${}^4_\Lambda He$ pair was interpreted[9] as evidence of Charge-Symmetry-Breaking (CSB). The $(\pi^-, K^\circ)$ reaction offers the opportunity to produce mirror hypernuclei for excited states. This can be accomplished by comparing the $\gamma$- ray energies from the $(\pi^+, K^+\gamma)$ and the $(\pi^-, K^\circ\gamma)$ reactions. Of particular interest are the transitions in which a $\Lambda$ changes its single-particle orbitals, for example, from p-shell to s-shell ground state. Good energy resolution of the $\gamma$-ray detection allows a sensitive measurement of the presumably very small CSB effects.

**Table II. $\Lambda$ Binding Energies for Mirror Hypernuclei**

| Hypernucleus | $B_\Lambda$ (MeV) |
|---|---|
| ${}^4_\Lambda H$ | $2.04 \pm 0.04$ |
| ${}^4_\Lambda He$ | $2.39 \pm 0.03$ |
| ${}^8_\Lambda Li$ | $6.68 \pm 0.03$ |
| ${}^8_\Lambda Be$ | $6.84 \pm 0.05$ |
| ${}^{10}_\Lambda Be$ | $9.11 \pm 0.22$ |
| ${}^{10}_\Lambda B$ | $8.89 \pm 0.12$ |
| ${}^{12}_\Lambda B$ | $11.37 \pm 0.06$ |
| ${}^{12}_\Lambda C$ | $10.76 \pm 0.19$ |

On a neutron rich $(T > 0)$ target, the $(\pi^-, K^\circ)$ reaction will selectively excite hypernuclear states with isospin $T + 1/2$. In contrast, the $(\pi^+, K^+)$ reaction will populate both the $T + 1/2$ and $T - 1/2$ hypernuclear states. A comparison between the $(\pi^-, K^\circ)$ and the $(\pi^+, K^+)$ spectra will therefore determine the isospin of the hypernuclear states.

It is clear that the $(\pi^-, K^\circ)$ reaction can lead to very neutron-rich hypernuclei, such as in the reaction ${}^{14}C(\pi^-, K^\circ){}^{14}_\Lambda B$. Certain light $\Lambda$- hypernuclei can also be produced by the $(\pi^-, K^\circ)$ reaction. In particular, Barnes discussed[10] in this workshop that some interesting decay properties of the ${}^3_\Lambda H$ and ${}^4_\Lambda H$ can be studied via the ${}^3He(\pi^-, K^\circ){}^3_\Lambda H$ and the ${}^4He(\pi^-, K^\circ){}^4_\Lambda H$ reactions.

### 3. The $d(\pi^-, K^\circ)$ Reaction

The $d(K^-, \pi^-)\Lambda p$ and the $d(\pi^+, K^+)\Lambda p$ reactions have been studied in several experiments[11–13] at a number of beam energies. In these experiments a striking peak in the $\Lambda p$ mass spectrum was observed. The location of this peak[12] ($M = 2129.0 \pm 0.4$ MeV) coincides with the thresholds of $\Sigma^+ n$ (2128.9 MeV) and $\Sigma^0 p$ (2130.7 MeV). This suggests the presence of a threshold-cusp effect. However, there is also the possibility that this peak corresponds to an $S = -1$ dibaryon resonance[14]. The $d(\pi^-, K^\circ)\Lambda n$ reaction can shed some light on the origin of this peak. We note that the thresholds for $\Sigma^0 n$ and $\Sigma^- p$, the two channels which can couple to $\Lambda n$, are located at 2132.0 and 2135.6 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 peaks observed in the $d(\pi^-, K^\circ)\Lambda n$ reaction could disentangle the threshold-cusp from the $S = -1$ dibaryon resonance effect.

### 4. $\Sigma$- Hypernuclei with the $(\pi^+, K^\circ)$ Reaction

The $(\pi^+, K^+)$ and the $(\pi^-, K^\circ)$ reactions are not suitable for studying $\Sigma$-hypernuclei because of the large background from $\Lambda$ quasi-free production[15]. The $p(\pi^-, K^+)\Sigma^-$ and $n(\pi^+, K^\circ)\Sigma^+$ reactions are free from the $\Lambda$ quasi-free background and can be studied at PILAC. The energy dependence of the $n(\pi^+, K^\circ)\Sigma^+$ cross sections has a broad peak centered around 1200 MeV/c. The $(\pi^+, K^\circ)$ reaction has some advantage since the more intense $\pi^+$ beam can be used.

## III. MONTE-CARLO SIMULATION OF THE $K^\circ$ DETECTION

In this section we present results from Monte-Carlo simulation of the $K^\circ$ detection at PILAC. In particular, we discuss the detection of $K_S \to \pi^+\pi^-$ and $K_S \to \pi^\circ\pi^\circ$, respectively, with a magnetic spectrometer and the LAMPF Neutral Meson Spectrometer (NMS)[16] currently under construction. As a specific example, we consider the reaction ${}^{12}C(\pi^-, K^\circ){}^{12}_{\Lambda}B(g.s.)$. The cross section and angular distribution of the analogous reaction, ${}^{12}C(\pi^+, K^+){}^{12}_{\Lambda}C(g.s.)$, have already been measured[17].

With 1050 MeV/c $\pi^-$ beam, the $K^\circ$ emitted from the ${}^{12}C(\pi^-, K^\circ){}^{12}_{\Lambda}B(g.s.)$ reaction at forward angles has a momentum around 720 MeV/c. Half of the time, $K^\circ$ will decay as $K_S$, which has an average decay length of $\sim 4cm$ at this momentum. $K_S$ decays into $\pi^+\pi^-$ with $\sim 68\%$ probability, and into $\pi^\circ\pi^\circ$ with $\sim 31\%$ probability. This implies that only $\sim 34\%$ of $K^\circ$ will emerge as $\pi^+\pi^-$, and

$\sim 16\%$ as $\pi^\circ\pi^\circ$. This loss of efficiency is, in fact, not as large as in the $(\pi^+, K^+)$ reaction, in which only $\sim 10\%$ of $K^+$ will survive a spectrometer of $\sim$ 12-meter length.

The cross section of the ${}^{12}C(\pi^+, K^+){}^{12}_{\Lambda}C$ reaction is known to peak at forward angles. In the $(\pi^-, K^\circ)$ reaction one can readily measure the cross section at forward angles, since the pions from the $K_S \rightarrow \pi^+\pi^-$ decays are emitted at large angles. The minimal opening angles, $\eta_{min}$, between the $\pi^+\pi^-$ is given by the expression

$$sin^2(\eta_{min}/2) = (m^2_{K_S} - 4m^2_{\pi^\circ})/(E^2_{K_S} - 4m^2_{\pi^\circ}) \tag{1}$$

where $E_{K_S}$ is the $K_S$ total energy. $\eta_{min}$ is $\sim 60^\circ$ for $K_S$ of 720 MeV/c.

1. $K_S \rightarrow \pi^+\pi^-$ Detection

We simulate the performance of a simple spectrometer shown schematically in Figure 2. The goal of this simulation is to study the solid angle acceptance and energy resolution of this rather modest detection system. This spectrometer consists of an existing LAMPF dipole magnet of 119 cm(length) × 213 cm(width) with an adjustable vertical gap. The magnetic field is 10 KG at a vertical gap of 63 cm. This magnet was also considered by Ransome in his simulation[18] of the $\Lambda p$ scattering at PILAC. Fig. 2 shows that the $\pi^+, \pi^-$ tracks will be measured by four sets of drift chambers, two of them located upstream and the other two downstream of the magnet. A scintillator hodoscope placed downstream of the drift chambers provides the fast trigger. An aerogel Cherenkov detector is used for particle identification. A 10-cm gap in each detector plane will allow the beam to pass through, at the expense of solid angle acceptance.

To obtain good missing-mass resolution, dispersed beam from PILAC is required. The beam profile on the target is 40 cm(vertical) × 4 cm(horizontal) with a vertical dispersion[2] of 25 cm/%. By reconstructing the momenta of the $\pi^+\pi^-$ pair, the $K^\circ$ decay vertex, the interaction point in target, and the beam momentum can be deduced.

The target thickness sets an important limitation on the achievable energy resolution in the $(\pi, K^\circ)$ reaction, since the $K^\circ$, unlike the $\pi^-$ beam, does not lose energy in the target. With a 1 gm/cm$^2$ carbon target, the uncertainty of the distance traversed by the pion beam in target corresponds to an uncertainty of the effective beam energy of ± 0.9 MeV.

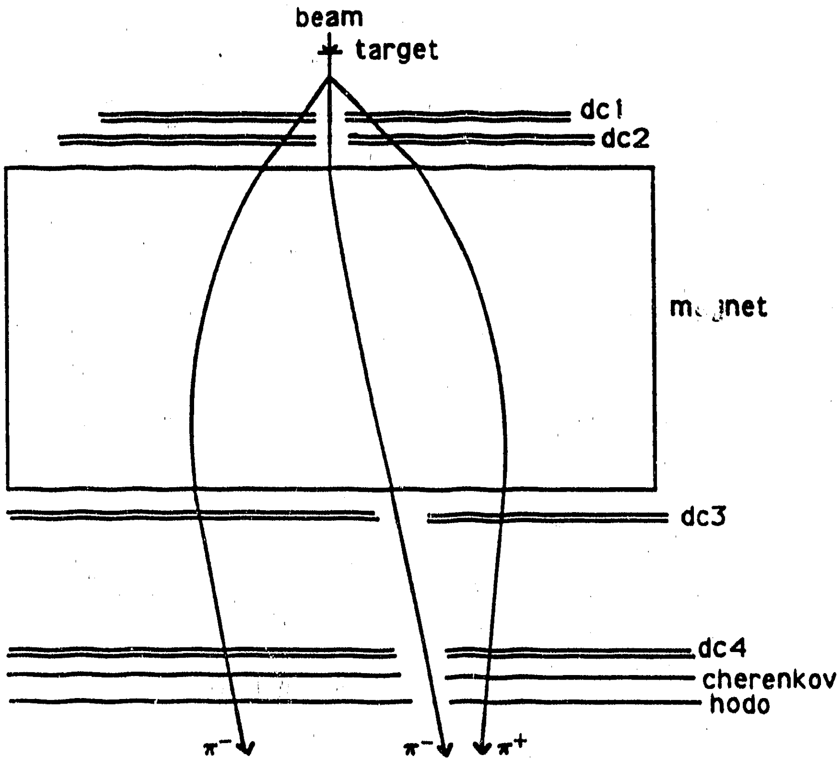

**Fig. 2.** Top view of a magnetic spectrometer for detecting $\pi^+\pi^-$ from the $(\pi^-, K^\circ)$ reaction.

To calculate the acceptance and missing-mass resolution of this spectrometer, we assume that the drift chambers are located at 17.5, 35, 162.5, 187.5 cm downstream of the target with a position resolution of 100 $\mu m(\sigma)$. The magnet entrance is 40 cm from the target. Multiple scattering in the detectors is taken into account. Since the $(\pi^-, K^\circ)$ cross section is forward peaked, the spectrometer acceptance is calculated by throwing $K^\circ$ events uniformly in the angular range $0^\circ < \theta_{cm} < 15^\circ$.

Figure 3 shows the solid angle of the spectrometer for detecting $K_S \rightarrow \pi^+\pi^-$ as a function of the magnetic field for two different values of the vertical gap. Also shown in Fig. 3 is the spectrometer acceptance corresponding to no hole in each detector plane. This hole clearly reduces the acceptance significantly.

Figure 4 shows the missing-mass resolution as a function of the magnetic field for target thickness of 1 gm/cm$^2$ and 0.1 gm/cm$^2$. At low magnetic field, the missing-mass resolution is dominated by the chamber resolution and multiple scattering. At high magnetic field, the target thickness contributes significantly to the resolution. We have not yet explored all the options to arrive at the

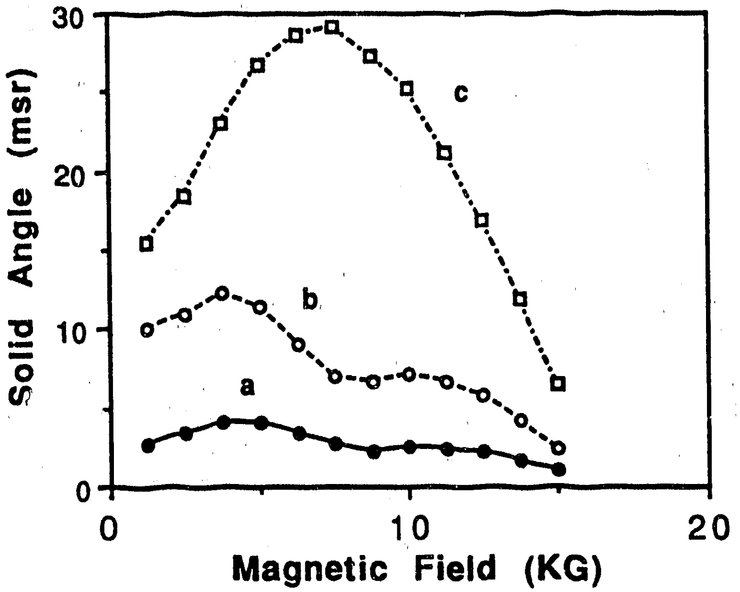

Fig. 3. Solid angle of the magnetic spectrometer for detecting $K_S \rightarrow \pi^+\pi^-$. Curves a and b correspond to a vertical gap in the magnet of 65 cm and 130 cm, respectively. Curve c corresponds to 130 cm gap with no beam holes in each detector plane.

most optimal configuration. Nevertheless, Figs. 3,4 show that a missing-mass resolution of 2 MeV (FWHM) and an acceptance of 5 msr can be readily achieved.

Table III compares the charateristics of detecting the ${}^{12}C(\pi^+, K^+){}^{12}_{\Lambda}C(g.s.)$ and the ${}^{12}C(\pi^-, K^\circ){}^{12}_{\Lambda}B(g.s.)$ reactions at PILAC. The decay-loss factor refers to the $K^+$ decay loss, or the $K^\circ \rightarrow \pi^+\pi^-$ decay branching ratio. The count rate is calculated assuming a 1 gm/cm$^2$ carbon target and a cross section of 10 $\mu b$/sr. Table III shows that the count rate for $(\pi^-, K^\circ)$ detection is $\sim$ 4 times smaller than the $(\pi^+, K^+)$, mainly due to the smaller $\pi^-$ beam intensity. Nevertheless, the expected $(\pi^-, K^\circ)$ count rate is already several times greater than in the previous $(\pi^+, K^+)$ experiments[1,17] at AGS.

### 2. $K_S \rightarrow \pi^\circ\pi^\circ$ Detection

The LAMPF NMS consists of two 6 × 10 arrays of CSI crystals. The dimension of each CSI crystal is 10 cm × 10 cm × 30 cm. Two layers of active BGO converters are followed by drift chambers to detect the $\gamma$- ray conversion point. The design goal of NMS is to achieve 2 %(FWHM) in energy resolution

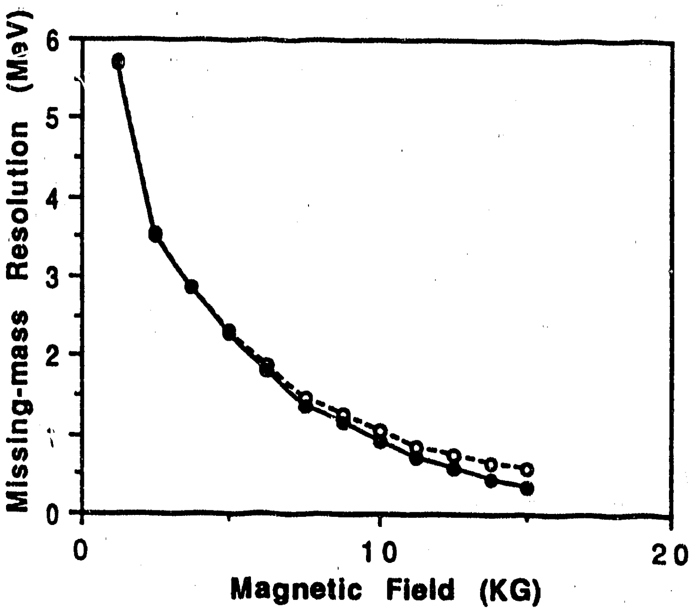

**Fig. 4.** Missing-mass resolution ($\sigma$) as a function of the magnetic field. The solid and dashed curves correspond to a carbon target thickness of 0.1 gm/cm$^2$ and 1.0 gm/cm$^2$, respectively.

**TABLE III. Comparison between the $(\pi^+, K^+)$ and the $(\pi^-, K^\circ)$ Reactions at PILAC**

| | $^{12}C(\pi^+, K^+)^{12}_{\Lambda}C(g.s.)$ | $^{12}C(\pi^+, K^+)^{12}_{\Lambda}C(g.s.)$ |
|---|---|---|
| beam intensity | $10^9/sec$ | $1.7 \times 10^8/sec$ |
| decay-loss factor | 0.1 | 0.34 |
| solid angle | 10 msr | 5 msr |
| missing-mass resolution | 200 KeV | 2 MeV |
| count rate | 1800/hr | 510/hr |

for 100 MeV $\gamma$- ray, and 250 $\mu m$(FWHM) conversion point resolution.

To simulate the $K_S \rightarrow \pi^\circ\pi^\circ$ detection, we require that the four $\gamma$- rays from the $K_S$ decay hit within the fiducial area of the NMS. Events with two $\gamma$- rays hitting the same CSI crystal are rejected. To determine the $K_S$ decay vertex, we require the four $\gamma$- rays to originate from the same vertex point and vary the vertex location until a best fit to the $\pi^\circ$ and $K_S$ masses is found. There are three mass contraints, given by the two $\pi^\circ$ and the $K_S$, which determine the three coordinates of the decay vertex. The accuracy in the vertex determination depends on the accuracy in measuring the conversion points and the $\gamma$- ray energies.

Figure 5 shows the solid angle acceptance of NMS as a function of the distance from the target to the converter plane. The acceptance falls rapidly as a function of distance. Also shown in Fig. 5 is the acceptance with a larger detection system consisting of 10 × 12 CSI arrays. With the spectrometer set at a distance of 50 cm, the acceptance is 2 msr for NMS and 7 msr for the larger spectrometer. This is very comparable to the acceptance discussed earlier for the $K^\circ \to \pi^+\pi^-$ detection.

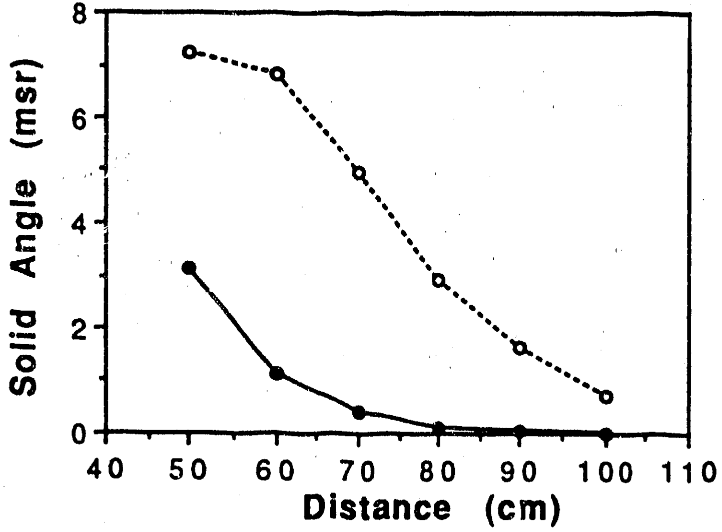

**Fig. 5.** Solid angle of NMS for detecting the $K_S \to \pi^\circ\pi^\circ$ as a function of the distance from the target to the converter plane. The dashed curve corresponds to an upgraded NMS with a 10 × 12 CSI array.

The missing-mass resolution of the NMS for detecting $K_S$ is found to be $\sim$ 3 MeV ($\sigma$), mainly due to the uncertainty in the decay vertex and $\gamma$- ray energy. It appears difficult to do high-resolution study with the $K_S \to \pi^\circ\pi^\circ$

detection. However, in coincidence experiments such as $(\pi^-, K^\circ\gamma)$, this missing-mass resolution is adequate for tagging. In fact, the NMS would be ideal for the $(\pi^-, K^\circ\gamma)$ measurements since the $\gamma$ ray can also be detected in NMS with good acceptance.

## IV. SUMMARY

The $(\pi^-, K^\circ)$ reaction is complementary to the $(\pi^+, K^+)$ reaction and offers another means to study Λ-hypernulei at PILAC. From the Monte-Carlo simulation of the $K_S \rightarrow \pi^+\pi^-$ detection with a simple magnetic spectrometer, and the $K_S \rightarrow \pi^\circ\pi^\circ$ detection with the LAMPF Neutral Meson Spectrometer, We conclude that the $(\pi^-, K^\circ)$ reaction can be well pursued at PILAC.

## V. ACKNOWLEDGEMENTS

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