Letter of Intent
for
Search for Θ^+ hypernuclei using (K^+, p) reaction

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Abstract

Assuming the existence of Θ^+, one can easily guess that there may exist $S = +1$ hypernuclei which contain Θ^+. In this Letter, we would like to express our intention to perform an experimental search for such hypernuclei with good mass resolution (~ 3 MeV) using (K^+, p) reactions. This reaction is favorable for production of hypernuclei because Θ^+ is produced with small recoil momentum transfer.

As the first step, we will measure the cross section of the elementary reaction, $d(K^+, p)\Theta^+$. The experiment can be performed at K1.8 beamline with limited sensitivity, or preferably at K1.1 beamline. Assuming a cross section of 1 μb/sr and an intensity of 3×10^6 K^+ per cycle, we will be able to obtain enough yield (27 counts per hour with a target thickness of 2 g/cm^2). Main background sources are quasi-free reactions (elastic and charge-exchange), which can be largely suppressed by requiring particles from Θ^+ decay (p, K^+, and/or K^0_s) in sideway counters.

If the measurement of elementary reaction is successful, we will move to a measurement with a ^{4}He target, for which a yield similar to deuteron target case would be obtained. Heavier hypernuclei are more difficult to observe, but may still be feasible depending on the cross section and background level in the elementary reaction.

1 Physics Motivation

The first experimental report on the discovery of the Θ^+ pentaquark which has positive strangeness $S = +1$ by the LEPS collaboration [1] cast severe questions on our understanding of hadron physics and raised active discussions in this field. Although its existence is not established yet [2], one can guess that there may exist $S = +1$ hypernuclei which contain Θ^+. Since the width of Θ^+ is expected to be very narrow (< 1 MeV/c), we can also expect narrow hypernuclear states, which can be searched for by high resolution spectroscopies.

Existence of such hypernuclei is not only interesting in itself, but it is also important from a point of view that the binding energy and the decay width in nuclei may give a hint about the nature of Θ^+ as it comes from selfenergy of Θ^+ in nuclei. For example, Ref. [3] pointed out there

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could be a deeply attractive potential if the coupling of Θ^+ to $NK\pi$ is strong, while the coupling of Θ^+-NK alone cannot produce a potential attractive enough for a bound state. Several other models, mainly based on mean field approaches, have also predicted strong attractive potentials [4, 5, 6, 7, 8].

So far, hypernuclei with negative strangeness, especially, those with $S = -1$ have been studied extensively and many interesting features of hypernuclei were revealed. Exploration of new region in (hyper-)nuclear chart is expected to bring exciting new physics as it had always done so. In this point of view, the extenstion of hypernuclear chart towards positive strangeness region as well as negative strangeness region is very interesting.

2 Reaction for Θ^+ hypernuclear production

Production cross section of hypernuclei can be written schematically as

$$\sigma = \sigma_{\rm ele} \times N_{\rm eff} \times f$$

where $\sigma_{\rm ele}$ is the cross section for the elementary reaction, $N_{\rm eff}$ is the effective nucleon number which include the distortion effect and f is a matching factor for momentum and angular momentum transfer. This schematic formula tells us two most important requirements on the production methods:

1. Elementary reaction should have a large cross section.
2. Momentum transfer should be small (w.r.t. nuclear Fermi momentum).

Backgrounds and mass resolution should also be considered.

In this point of view, (K^+, π^+) reaction, as suggested by Nagahiro *et al.* [9], is not suitable because of the large momentum transfer ($\sim$ 500 MeV/c) and small cross section for the elementary reaction ($<$ 3.5 μb/sr at p_{K^+} = 1.2 GeV/c as reported by KEK-PS E559 [10]). The (π^-, K^-) reaction used in J-PARC E19 has even larger momentum transfer ($\sim$ 1 GeV/c) and small cross section ($<$ 2.9 μb/sr at p_{π^-} = 1.92 GeV/c as reported by KEK-PS E522 [11]), and is not good for hypernuclear production, too.

Here we propose (K^+, p) reaction in the forward region for which the momentum transfer can be smaller than Fermi momentum; it becomes nearly zero at around p_{K^+} = 600 MeV/c, and is as small as $\sim$ 100 MeV/c even at p_{K^+} = 1 GeV/c (see Fig. 1). Another merit for the reaction is that high resolution missing mass spectroscopy is possible. This is a nucleon knockout reaction, and the elementary process is on a deuteron target, namely, $d(K^+, p)\Theta^+$. Since the cross section for this elementary process is not known, we would like to measure it first, and then move to nuclear target if the measurement is successful.

3 The elementary $d(K^+, p)\Theta^+$ reaction

3.1 Cross section estimation

In a semi-classical model, this reaction occurs via two-step processes as explained below. In the first step, the proton in the target deuteron is kicked out quasi-elastically by the incident kaon (i.e., $pK^+ \to pK^+$). A quasi-free charge exchange reaction ($nK^+ \to pK^0$) may also occur. Then,

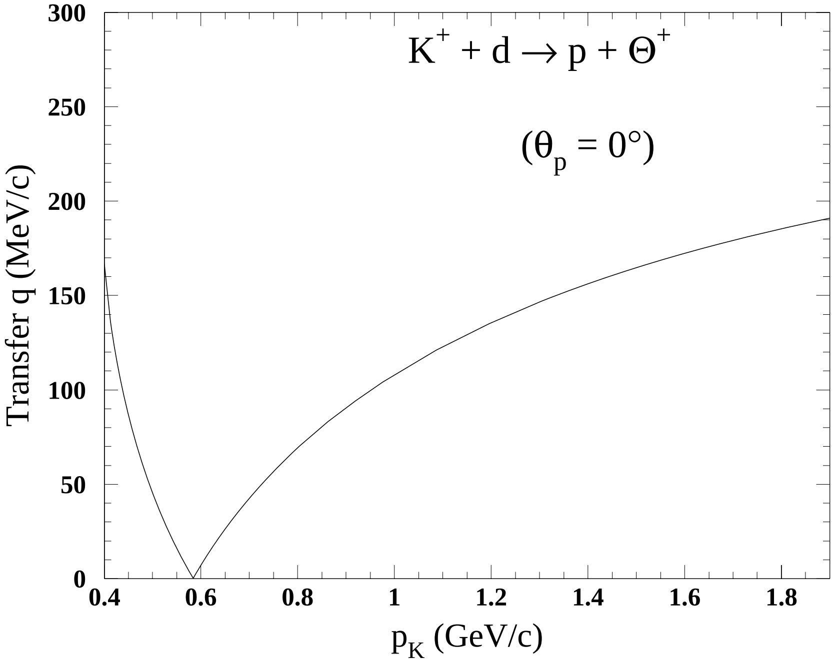

Figure 1: Momentum transfer of the $d(K^+, p)\Theta^+$ reaction at 0 degree.

the remaining (spectator) nucleon and the recoiling kaon may form a Θ^+ resonance. As a baseline estimation, using an approximation that the kaon and the nucleons in the intermediate states are on the mass shell (on-shell approximation), cross section can be written in a quite simple form as

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}\Omega \mathrm{d}M_{NK}} \propto \frac{\mathrm{d}\sigma_{q.f.}}{\mathrm{d}\Omega} \frac{\Gamma^2_{\Theta^+}}{(M_{NK} - M_{\Theta^+})^2 + (\Gamma_{\Theta^+}/2)^2}$$

where $\frac{\mathrm{d}\sigma_{q.f.}}{\mathrm{d}\Omega}$ represents the differential cross section of the quasi-free reaction ($pK^+ \to pK^+$ and/or $nK^+ \to pK^0$) and the following part is for the probability to form Θ^+ resonance with M_{NK}, M_{Θ^+}, and Γ_{Θ^+} being invariant mass of the spectator nucleon and the recoiling kaon (or equivalently missing mass of the $d(K^+, p)$ reaction), mass of Θ^+ (assumed to be 1540 MeV/c^2 hereafter), and natural width of Θ^+, respectively. Within this framework, the cross section has following features:

- If we neglect Fermi motion in the deuteron, angular distribution has a narrow (width being determined by Γ_{Θ^+}) peak at finite angle. Actual distribution is smeared by Fermi momentum, but the peak position is almost the same.
- The total cross section is proportional to Γ_{Θ^+}.

For $\frac{\mathrm{d}\sigma_{q.f.}}{\mathrm{d}\Omega_{\mathrm{cm}}} = 10/4\pi$ mb/sr[1] and $\Gamma_{\Theta^+} = 1$ MeV, the angular distribution is shown in Fig. 2 as calculated by Nagahiro and Hosaka [12]. Thus, this baseline estimation gives ~ 1 μb/sr in the

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[1] Angular distribution is assumed to be uniform in the center-of-mass system, although measurements [14] show it is actually not true.

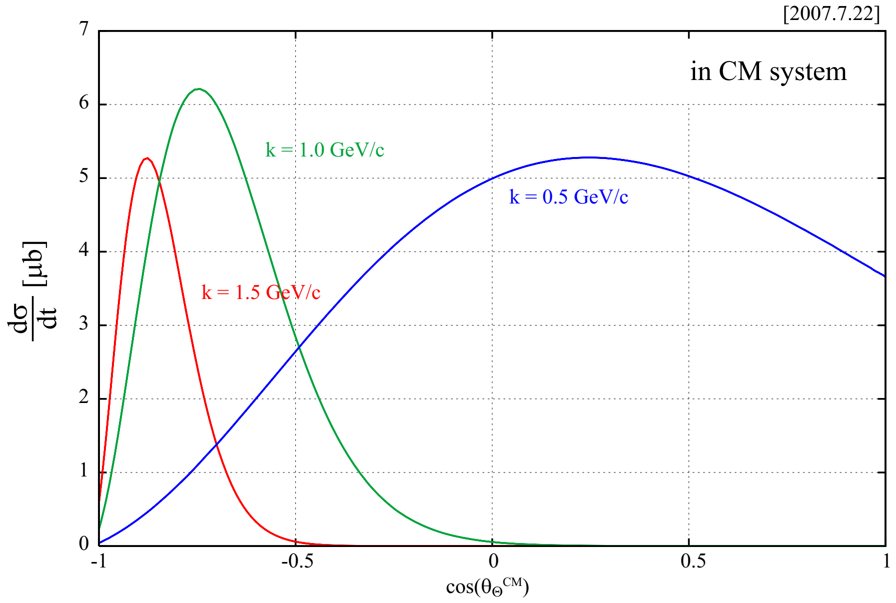

Figure 2: CM differential cross sections of the $d(K^+,p)\Theta^+$ reaction for $p_{K^+} = 0.5$, 1.0, and 1.5 GeV/c calculated by Nagahiro and Hosaka with on-shell approximation [12]. Note that horizontal axis is Θ^+ production angle, $\theta_\Theta^{\rm CM}$, which can be easily converted to proton angle in the CM system as $\cos\theta_p^{\rm CM} = -\cos\theta_\Theta^{\rm CM}$. The vertical axis is $\frac{{\rm d}\sigma}{{\rm d}t} = 2\pi\frac{{\rm d}\sigma}{{\rm d}\theta_\Theta^{\rm CM}}$, where $t = \cos\theta_\Theta^{\rm CM}$.

center-of-mass system at the peaking angle.

On the other hand, Friedmann and Gal suggested that the cross section could be as large as 0.1-0.5 mb based on the kaon absorption data from various nuclear targets [13]. They argued that this extra reactivity may be explained by adding a two-nucleon absorption channel $K^+nN \to \Theta^+N$.

3.2 Background estimation

Unlike the (K^+,π^+) reaction, there is no background contribution from kaon decays. Main background would be quasi-free reactions, such as $pK^+ \to pK^+$ and $nK^+ \to pK^0$. Over wide ranges of incident K^+ momentum and reaction angles, the differential cross sections of these processes were measured [14]. From those data, one can estimate $\frac{{\rm d}\sigma}{{\rm d}\Omega_{\rm lab}}(K^+p \to pK^+) = 5$ mb/sr and $\frac{{\rm d}\sigma}{{\rm d}\Omega_{\rm lab}}(K^+n \to pK^0) = 1.5$ mb/sr for $p_{K^+} \sim 1$ GeV/c and $\theta_p \sim 0$ degree. Although they are much larger than the Θ^+ production cross section, most of those backgrounds appear in the lighter missing mass than Θ^+. For $p_{K^+} = 1$ GeV/c and $\theta_p = 0$ degree, the proton momentum that corresponds to Θ^+ production is 1.1 GeV/c, while the quasi-free reactions have a peak at $p_p = 1.2$ GeV/c. In order to give $p_p = 1.1$ GeV/c by the quasi-free reactions, Fermi momenta of more than 200 MeV/c, which is quite large compared to typical deuteron Fermi momentum ($\sim$ 50 MeV/c), are necessary. Therefore, one can expect background in the missing mass spectrum is quite small (< 1 μb/sr/MeV).

Furthermore, in the quasi-free reactions, the spectator nucleon is almost at rest, so we can suppress such backgrounds by requiring the other nucleon in sideway detectors. However, we have to note that, eventuallly, two-step processes become dominant so that the S/N ratio would be, within the on-shell approximation model, limited to ~ 1.

3.3 Experimental details

We will perform a missing mass spectroscopy experiment and need following experimental apparatus:

- A beam spectrometer for incident kaons.
- Another spectrometer for outgoing protons.
- Sideway counters to detect decay protons, K^+, and/or pions from K^0 decay are desirable to suppress backgrounds.

It is noted that missing mass resolution is determined by the two spectrometers, and high resolution is not required for the sideway counters.

As for the beamline, K1.8 or K1.1 would be the only choice as we need high intensity, separated K^+ beam around 1 GeV/c. In K1.8 beamline, spectrometers for both particles are available. Especially, the SKS-plus spectrometer for the outgoing protons enables us to achieve a good missing mass resolution of 3 MeV/c^2. The incident kaon momentum would be 1.1 GeV/c in order to avoid beam kaons directly passing through the SKS-plus spectrometer, and the expected kaon intensity is $\sim 3 \times 10^5$ per cycle. Then, the expected Θ^+ yield can be written by:

$$N_{\Theta^+} = N_{K^+} \cdot t \cdot \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_{\mathrm{lab}}} \cdot \Delta\Omega \cdot \epsilon \cdot \eta$$

where

- N_{K^+} is the number of K^+ irradiated on the target (3×10^8 per hour)
- t is the deuteron target thickness (liquid deuterium of 2 g/cm^2, or 6×10^{23} /cm^2)
- $\Delta\Omega$ is the spectrometer acceptance (30 msr for SKS-plus)
- ϵ is the overall efficiency for the spectrometer system (assumed to be 0.5)
- η is the tagging efficiency of the sideway counters

or $2.7\times\eta$ counts/hour/(μb/sr). Thus, a quite large number of events can be obtained with a cross section of a few μb/sr. If the cross section is as large as 0.1 mb as Friedman suggested[2], the experiment is rather easy; in this case, we would not need to tag particles in sideway counters, so that $\eta = 1$ can be used. Even when the cross section is too small to be observed, background study is at least possible.

For smaller cross sections, such as expected from on-shell approximation calculation, we would need higher beam intensity and/or larger spectrometer acceptance. Preferably we would like to use K1.1 beamline, where we can expect more than 10 times higher kaon intensity at $p_{K^+} = 1.1$

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[2] This corresponds to 42 μb/sr of laboratory differential cross section at 0 degree assuming CM angular distribution is flat.

GeV/c. Assuming the proton spectrometer has the same features as SKS-plus (or one could use SKS-plus itself), the expected yield becomes $27 \times \eta$ counts/hour/(μb/sr). With $\eta \sim 0.1$ and residual $S/N \sim 1$, a sensitivity of better than ~ 0.5 μb/sr is possible. For further improvement, we could use an even better spectrometer, such as the HKS spectrometer [15], which has an acceptance of 20 msr and an excellent energy resolution of < 2 MeV.

At K1.8, use of higher momentum beam increases kaon beam intensity (e.g., $\sim 2 \times 10^6$ per cycle at $p_{K^+} = 1.5$ GeV/c). Larger spectrometer acceptance ($\sim$ 100 msr) can be obtained using SKS-minus spectromter, with a slight decrease of missing mass resolution ($\sim$ 4 MeV). In these cases, however, we have to handle high intensity beam particles directly passing through the spectrometer.

4 Hypernuclear production

If the elementary reaction is successfully observed, we will then move to hypernuclear production using ^{4}He target. Because two nucleons are involved in the reaction, the cross section scales with $A(A-1)$ instead of A, and is favorable to hypernuclear production. In addition, the smallness of the momentum transfer enables efficient production of bound states. Therefore, the hypernuclear production rate would be about the same as or even larger than that for the elementary reaction. Here, one thing we have to consider is that the Fermi motion is larger for nuclear targets which may affect the S/N ratio. Heavier hypernuclei are more difficult to observe, but may still be feasible depending on the cross section and background level in the elementary reaction.

5 Summary

We would like to perform an experiment to search for Θ^+ hypernuclei via (K^+, p) reaction. Firstly, we will measure cross section of the elementary reaction, $d(K^+, p)\Theta^+$. We can reach to a sensitivity of ~ 0.5 μb/sr or better. If the elementary reaction is successfully observed, we will then move to hypernuclear production using ^{4}He target, where production rate would be about the same as or even larger than that for the elementary reaction.

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