Pentaquark hypernucleus and multi-quark states beyond 5

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- Motivation
- Theoretical predictions for the \( \Theta^+ \) hypernucleus
- What is the suitable reaction?
  - momentum transfer for several candidate reactions
  - ‘magic momentum’ in one baryon knockout reaction
- Experimental setup
- Summary
Motivation

- Another confirmation for the $\Theta^+$ existence or at least existence of $S=+1$ nucleus

- $\Theta$-N interaction: $\Theta$-N scattering only studied through $\Theta$-bound states → feedback to $\Theta^+$ properties and internal structure

- Medium modification of $\Theta^+$ very low $M^*(\Theta)$: $\Theta \rightarrow KN$, stable for the strong decay!

- Pentaquarks in neutron star
  If $U(\Theta^+)=-100$ MeV, 5% fraction of $\Theta$ in the core of compact star at $\rho=4\rho_0$ → limit of $M_{\text{nstar}}$ is reduced
Need more reactivity in $K^+$-Nucleus dynamics $\rightarrow$ more $\Theta^+$ in $K^+A$?

- $t\rho$ optical potential did not explain $K$-$A$ scattering and $\sigma_R$ data at low energy in spite of weak $K$-$N$ interaction.
- if add density dependent term
  
  $$t\rho \rightarrow t\rho(r) + B\rho\rho(r)$$

  good fit is taken.
- assume this $\Delta V_{opt}$ term is due to
  
  $$K^+nN \rightarrow \Theta^+N$$

  process, the absorption cross section is $\sim$mb!

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Gal, Friedman, PRL94,072301(2005)

FIG. 1. Data and calculations for $K^+$ reaction cross sections per nucleon ($\sigma_R/A$) at $p_{lab} = 488$ MeV/c are shown in the upper part. Calculated $K^+$ absorption cross sections per nucleon ($\sigma_{abs}/A$) are shown in the lower part; see text.
Schematic model by Miller

- $\Theta$ is treated as a nucleon vibration due to the coherent $q\bar{s}$ excitation (like giant dipole resonance)
  - $q\bar{s}$: pseudoscalar, $L=1$ (positive parity of $\Theta$)
  - number of states: $3(\text{color}) \times 3(L_z) \times 2(u\bar{s} \text{ or } d\bar{s}) = 18$
- determine the $V$ (interaction between $q\bar{s}$ and $N$) and $\mu$ (mass of $q\bar{s}$) to reproduce $M_\Theta$
- In $\Theta N$ system, coherent cloud also interacts with another $N$ via $V$
- $\rightarrow$ Very large attractive $\Theta N$ potential
  - $U(r) \sim -490\text{MeV}$ at $\rho = \rho_0$!
Selfenergy of $\Theta^+$ associated with decay loops

H-C. Kim et al., J. Kor. Phys. Soc.46, 393(2005)
Cabrera et al., PLB608, 231(2005)

- Selfenergy of $\Theta$ in nuclei is evaluated with decay channels
- Only with KN channel $\to$ too weak to bind $\Theta$
- Add $K\pi N$ channel
  $\to$ strong attractive potential
Assume $\Theta$ is $\frac{1}{2}^+$. SU(3) antidecouplet Couplings are chosen to reproduce $N^*(1710) \to N\pi\pi$ and SU(3) symmetry
- $U(r)= -60 \sim -120$ MeV, width:
  Pauli blocking and binding $\to$ reduce $K\pi N$ channel $\to$ broaden, but not large
Mean field approach

QMC model: Panda et al., PRC72,058201(2005)
Ryu et al., PRC72,045206
RMF model: Zhong et al., PRC71,015206; PRC72,065212
QMF model: Shen, Toki, PRC71,065208

- Baryons in nuclear medium interact through the scalar ($\sigma$) and vector meson ($\omega, \rho$) fields
- Coupling constants in nuclear sector ($g_\sigma^N, g_\omega^N, g_\rho^N$) and $m_\sigma$ are determined to produce nuclear saturation properties
- For $\Theta$, assume $g_\sigma^\Theta=4/3g_\sigma^N$, $g_\omega^\Theta=4/3g_\omega^N$, ($g_\rho^\Theta=0$ if $\Theta(I=0)$) because $\sigma$, $\omega$ and $\rho$ couple only to $u$ and $d$ quarks
  (for $\Lambda$, $g_\sigma^\Lambda=2/3g_\sigma^N$, $g_\omega^\Lambda=2/3g_\omega^N$)
- $U = U_s + U_v \sim g_\sigma^\Theta \sigma_0 + g_\omega^\Theta \omega_0$
Mean field approach

- RMF: $U = -50 \sim -90$ MeV for the point-like $\Theta$ but $-90$ MeV $\rightarrow$ -37.5 MeV for $\Theta$ as a $K\pi N$ bound state
- QMF: $U = -50$ MeV
QCD sum rule of $\Theta^+$ in nuclear matter

Navarra et al., PLB606, 335(2005)

- $\Sigma_s$: positive and $\Sigma_v$: negative!
- But $U = \Sigma_s + \Sigma_v$ is still negative:
  $U = -40\sim -90$ MeV
  strongly depends on the value of the gluon condensate

Fig. 2. The ratio $m^*_\Theta/m_\Theta$ (solid line), the vector and scalar self-energies (dotted and dashed lines, respectively) as functions of the Borel parameter $M^2$, for $y = 0.3$. 

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Summary of the theoretical predictions for $\Theta^+(1/2^+)$

- Miller’s schematic model: $U(\Theta^+)< -100$ MeV
- Hadronic SU(3) approach: $U(\Theta^+)= -60$–$-120$ MeV
  (selfenergy associated with $KN$ and $K\pi N$ decays)
- Mean field theory
  RMF model: $U(\Theta^+)= -37.5$–$-90$ MeV
  QMF model: $U(\Theta^+)$~$-50$ MeV
- QCD sum rule: $U(\Theta^+)= -40$–$-90$ MeV

All give sufficiently large attractive potentials to bind $\Theta^+$ in nucleus, but what is the bridge between different models?
What is the suitable reaction for producing $\Theta^+$ hypernucleus?

- Elementary one-nucleon or two-nucleon process can produce $\Theta^+$ with reasonable cross sections
- Two-body reaction process is preferable to the missing mass spectroscopy
- Momentum difference between the produced $\Theta^+$ and the recoil nucleus should be small
  $\rightarrow$ small momentum transfer $q$ in Lab system
- Small background (BG) process or some BG reduction methods should exist:
  $\rightarrow$ coincidence with backward decay products
Momentum transfer in \((K^+, \pi^+\)) reaction

\((\Theta^+\) has still not been found in \(p(K^+, \pi^+)X\))

- not small \(q\)
- but possible for \(\Theta^+\) bound nucleus

Use

\[M(\Theta^+) = 1535\ \text{MeV}\]
Calculated spectra of $^{12}\text{C}(K^+,\pi^+)^{11}\text{B}_0$ reaction

Nagahiro et al., PLB620,125(2005)

$V(r) = -60$ MeV

$V(r) = -120$ MeV
Momentum transfer in \((\gamma,K^+)\) reaction

\[(\Theta^+ \text{ has been found in } 'n'(\gamma,K^+)X \text{ at LEPS})\]

- large \(q\)
- not good for \(\Theta^+\) bound nucleus

\[\gamma + A \rightarrow K^- + \Theta^+(A-1)\]

\[(\theta_K = 0^\circ)\]

\[S_n = E_B(\Theta)\]
Momentum transfer in \((\gamma, \Lambda(1116))\) reaction

\((\Theta^+ \text{ has still not been found in } d(\gamma, \Lambda)X \quad (\Lambda \rightarrow p\pi^-))\)

- very small \(q\)
- magic momentum around 1670 MeV
Momentum transfer in $\gamma, \Lambda^*(1520)$ reaction

( $\Theta^+$ has been found in $d(\gamma, \Lambda^*)X$ at LEPS  ($\Lambda^* \rightarrow pK^-$))

• small $q$, especially, above 2 GeV

• magic momentum around 3220 MeV (higher than LEPS energy)
Momentum transfer in \((K^+, p)\) reaction

\((\Theta^+ \text{ has not been searched in } d(K^+, p)X)\)

- small \(q\), even at 1400 MeV (1.8 GeV/c)
- magic momentum around 270 MeV
- should be done at J-Parc!

\[
K^+ + A \rightarrow p + \Theta^+ \cdot (A-2)  \\
(\theta_p = 0^\circ)  \\
S_d = E_B(\Theta)
\]
Comment on $\gamma d \rightarrow \Theta^+ \Lambda^* (1520)$

if $K^+$ is on shell ($m_K^2 = \varepsilon_K^2 - \vec{p}_K^2$) and
Θ is produced only at the formation energy
$((\varepsilon_n + \varepsilon_K)^2 - (\vec{p}_n + \vec{p}_K)^2 = M_\Theta^2)$
⇒ calculate $p_n$ dependence of
the $\Theta^+$ production rate

$\gamma d \rightarrow pp\pi$

$p_p$ (slow $p$) distribution
Multi-quark state beyond 5
-- 8 quark dibaryon candidate --

- If a $\Theta^+N$ bound state is found, it could be a candidate of exotic 8 quark state
- e.g.) $^3$He($\gamma,\Lambda^*$)${}^2$H$_\Theta$ or $^3$He($\gamma,\Sigma^+$)${}^2[n\Theta]$
Detector setup

- Good missing mass resolution and acceptance for forward going $\Lambda(\rightarrow p\pi^-)$, $\Lambda^*(\rightarrow pK^-)$ [if possible, $\Sigma^+(\rightarrow p\pi^0, n\pi^+)$]
- Coincidence measurement with decay products, especially, at backward angles, which have relatively low momentum
Summary

• Pentaquark hypernucleus is interesting and important for another confirmation of $\Theta^+$ and the study of the $\Theta N$ interaction.

• Several theoretical model calculations predict the existence of bound $\Theta^+$ states, although the mutual relations between different models are not clear.

• Momentum transfer for the $\Theta^+$ production process is small in one baryon knockout reactions at forward angles like $(\gamma,\Lambda)$, $(\gamma,\Lambda^*)$, and $(K^+,p)$.

• Suggest an idea of adding a small solenoid to detect the backward decay products in addition to the E949 detector. (any detailed study has not been done yet.)