Meson-induced pentaquark productions

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Exotic hadrons in QCD

$\Theta^+ : \text{strangeness } S = +1, \text{ baryon number } B = 1$

minimal quark content $\sim uudds\bar{s} : \text{exotic!}$


c.f. $\Lambda(1405) \sim uud s\bar{u}, Z(4430) \sim c\bar{c}d\bar{u} : \text{crypto-exotic hadrons}$

Exotic hadrons are

- **not well established** in experiments ($\sim$300 normal hadrons).
- **not excluded** in QCD.
- easily constructed in effective models.

(Non)existence of exotic hadrons : Saturation?

c.f. nucleus: Coulomb repulsion, drip line, ...
hydrogen molecule: covalent bond, ...

Exotic hadrons --> quark binding mechanism (confinement)
Introduction

Pentaquark $\Theta^+$

$\gamma d \rightarrow K^+K^-pn$ reaction

New results from LEPS

Y. Kato, Talk at FB20, M. Niiyama, Talk at HYP12

- $K^+, K^-$ detected. momentum of $n$ is determined by MMSA.

proton rejected, summed data
Introduction

**Meson-induced experiments**

\[ \pi^- p \rightarrow K^- X : J-PARC \text{ E19}, \quad K^+ p \rightarrow \pi^+ X : KEK \text{ E559} \]


- upper limit (averaged over detected angles)
\[ < 0.26 \, \mu b/sr \text{ for } \pi^- p \rightarrow K^- X, \quad < 3.5 \, \mu b/sr \text{ for } K^+ p \rightarrow \pi^+ X \]

Impact on the existence of \( \Theta^+ \)?
Meson-induced $\Theta^+$ production

Theoretical study of reactions

Meson-induced $\Theta^+$ production: relatively simple

Effective Lagrangian approach $\rightarrow$ upper limit of $\Gamma_{\Theta}$

We examine isospin $I=0$, spin-parity $J^P=1/2^\pm, 3/2^\pm$ cases.

- Born terms (must exist if $\Theta^+$ decays into $KN$)

- Other possible contributions: unknown couplings

Born terms only $\rightarrow \sigma$ is proportional to $\Gamma_{\Theta}$
Interference with other contributions

Our aim: upper limit of cross section --> upper limit of $\Gamma_\Theta$

- Destructive interference --> underestimation

$$\sigma \propto |T_{\text{Born}}|^2 = |\bar{T}_{\text{Born}}\sqrt{\Gamma_\Theta}|^2 < 1$$

$$|\bar{T}_{\text{Born}}\sqrt{\Gamma_\Theta} + T_{\text{other}}|^2 < 1$$

10^-9

Interference pattern in general depends on the reaction.

- Negative result in **various** low energy reactions

($\pi^-p \rightarrow K^-X, K^+p \rightarrow \pi^+X, pp \rightarrow \Sigma^+X, \gamma p \rightarrow K^0X, ...$)

It is unnatural that all the negative results are explained by destructive interference.

--> Born diagrams will provide a **conservative upper limit**.
Meson-induced $\Theta^+$ production

**Effective Lagrangians**

### Pseudoscalar (PS) scheme

\[
\mathcal{L}_{1/2}^\pm_{KN\Theta} = g_{1/2}^{1/2\pm} \bar{\Theta}^+ \Gamma KN + \text{h.c.}
\]

\[
\Gamma = \begin{cases} 
  i\gamma_5 & \text{(positive parity)} \\
  1 & \text{(negative parity)}
\end{cases}
\]

\[
\mathcal{L}_{\pi NN} = ig_{\pi NN} \bar{N} \gamma_5 \pi N
\]

- **Coupling constants: decay width of $\Theta^+$**

\[
g_{1/2}^{1/2\pm} = \sqrt{\frac{2\pi M_\Theta \Gamma_\Theta}{|k|(E + M)}}, \quad g_{\pi NN} = 13.5
\]

### Pseudovector (PV) scheme

\[
\mathcal{L}_{1/2}^\pm_{KN\Theta} = \frac{-ig_A^{*\pm}}{2f} \bar{\Theta}^+ \gamma_\mu \Gamma \partial^\mu KN + \text{h.c.}
\]

\[
\mathcal{L}_{\pi NN} = \frac{g_A}{2f} \bar{N} \gamma_\mu \gamma_5 \partial^\mu \pi N
\]

- **Generalized GT relation**

\[
g_A^{*\pm} = \frac{2f}{M_\Theta \pm M_N} g_{1/2}^{1/2\pm}, \quad g_A = 1.25, \quad f = 93 \text{ MeV}
\]
Meson-induced $\Theta^+$ production

**Total cross sections**

Theoretical uncertainties:
- two schemes of **meson-baryon coupling** (PV, PS)
- two types of hadron **form factor** (Fs, Fc)

Total cross sections with $J^P=1/2^+$ case ($\Gamma_\Theta = 1$ MeV)

- Threshold behavior of PS is different from PV.
  --> chiral low energy theorem
Meson-induced $\Theta^+$ production

Total cross sections for various quantum numbers

Upper limit in experiments
- J-PARC E19: $\pi^-p \rightarrow K^-X$ $\sigma \lesssim 10^{-1}$ $\mu$b
- KEK E559: $K^+p \rightarrow \pi^+X$ $\sigma \lesssim 10^0$ $\mu$b

Total cross sections at experimental energies ($\Gamma_\Theta = 1$ MeV)

If we consider the width should be larger than 0.1 MeV; --> spin 3/2 cases are ruled out.
Meson-induced $\Theta^+$ production

Comparison with J-PARC data

Differential cross section at $P_{\text{lab}} = 1.92$ GeV ($\Gamma_{\Theta} = 1$ MeV)

- Angular dependence is not so strong.
  J-PARC E19 experiment: $K^+$ detected in forward angles.

J-PARC experiment --> upper limit of $\Gamma_{\Theta}$

- (narrow width of $1/2^-$ is theoretically unreasonable)
We study pentaquark productions in meson-induced reactions with Born diagrams.

Cross sections for $J^P=1/2^\pm$, $3/2^\pm$ cases.

Spin $3/2$ cases --> large cross section

$\Gamma_\Theta \ll 0.1$ MeV: unlikely for hadrons

Spin $1/2$ cases may be possible.

upper limit of $\Gamma_\Theta$ with J-PARC exp.