Pentaquark hypernucleus and multi-quark states beyond 5

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- Motivation
- Theoretical predictions for the Θ^+ 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 Θ^+ existence
  or at least existence of *S*=+1 nucleus

- Θ-N interaction: ~~Θ-N scattering~~
  only studied through Θ-bound states
  → feedback to Θ^+ properties and internal structure

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

- Pentaquarks in neutron star
  If $U(\Theta^+)=-100$ MeV, 5% fraction of Θ in the core of compact star at $\rho=4\rho_0$ → limit of M_{nstar} is reduced

Need more reactivity in K^+-Nucleus dynamics → more Θ^+ in K^+A ?

- $t\rho$ optical potential did not explain *K*-*A* scattering and σ_R data at low energy in spite of weak *K*-*N* interaction.
- if add density dependent term

$$t\rho \to t\rho(r) + B\overline{\rho}\rho(r)$$

good fit is taken.

- assume this ΔV_{opt} term is due to

$$K^+ nN \to \Theta^+ N$$

process, the absorption cross section is ~mb !

Gal, Friedman, PRL94,072301(2005)

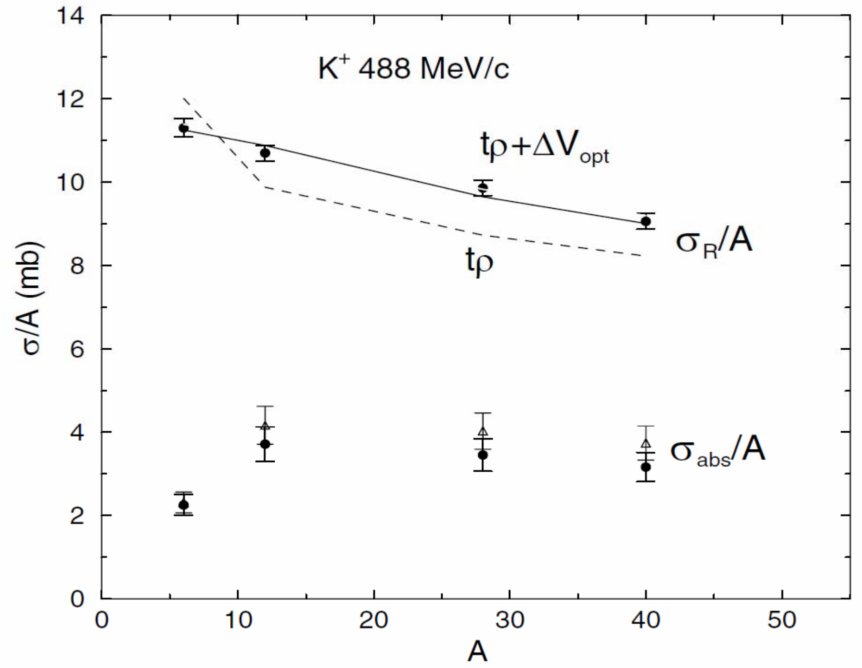
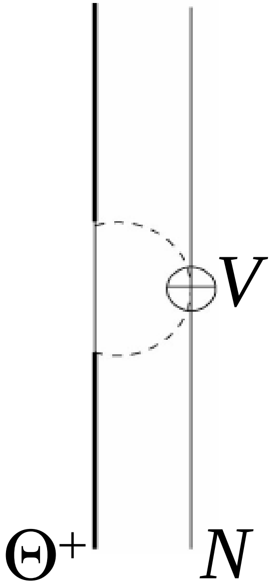


FIG. 1. Data and calculations for K^+ reaction cross sections per nucleon (σ_R/A) at $p_{\rm lab} = 488$ MeV/c are shown in the upper part. Calculated K^+ absorption cross sections per nucleon ($\sigma_{\rm abs}/A$) are shown in the lower part; see text.

Schematic model by Miller

Miller, PRC70,022202(2004)

- Θ 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 Θ)
  number of states: 3(color)x3(L_z)x2($u\bar{s}$ or $d\bar{s}$)=18
- determine the V(interaction between $q\bar{s}$ and N) and μ (mass of $q\bar{s}$) to reproduce M_Θ
- In ΘN system, coherent cloud also interacts with another N via V
- → Very large attractive ΘN potential
  U(r)~ -490MeV at $\rho=\rho_0$!



Selfenergy of Θ^+ associated with decay loops

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

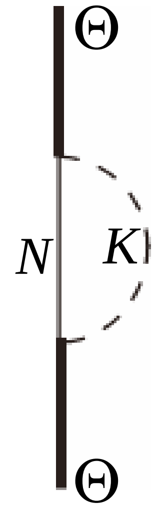
- Selfenergy of Θ in nuclei is evaluated with decay channels
- Only with KN channel → too weak to bind Θ
- Add *KπN* channel

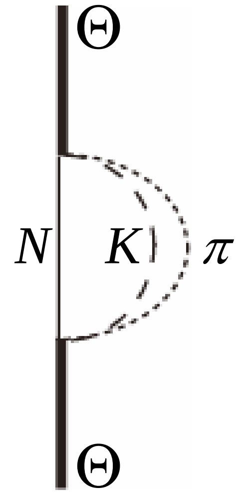
  → strong attractive potential

  Assume Θ is ½$^+$. SU(3) antidecouplet

  Couplings are chosen to reproduce

  N*(1710) →*Nππ* and SU(3) symmetry





- *U*(*r*)= -60 ~ -120 MeV, width:

  Pauli blocking and binding → reduce

  KπN channel → broaden, but not large

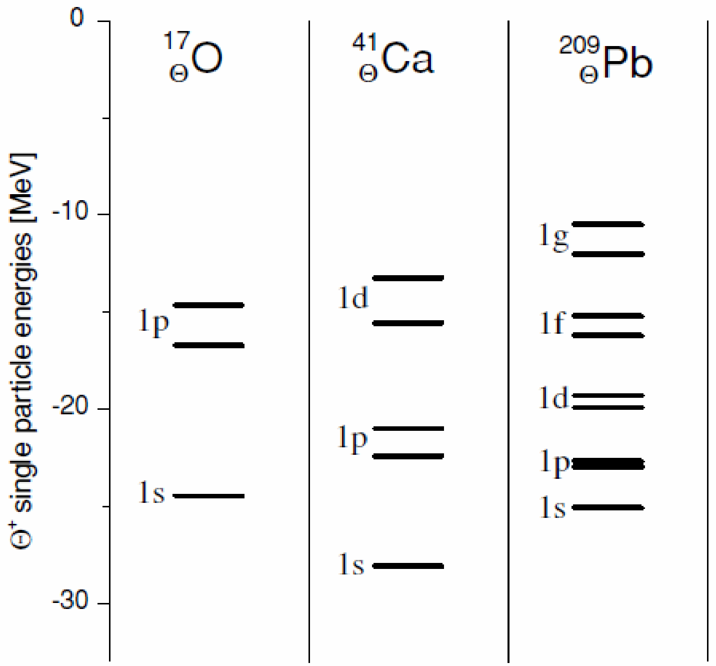
Mean field approach

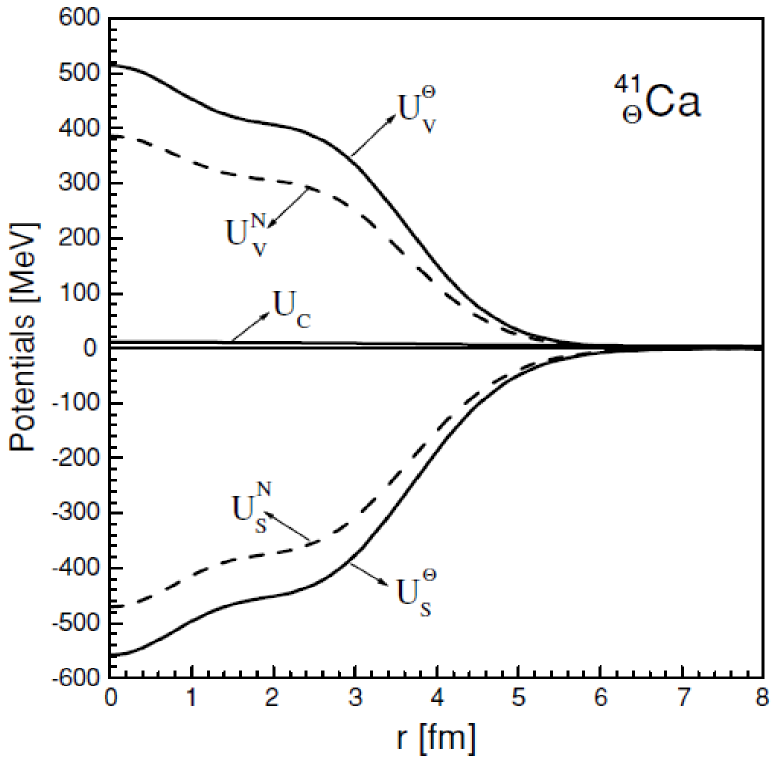
QMC model: Panda et al., PRC72,058201(2005)
Ryu et al.,PRC72,045206
RMF model: Zhong et al., PRC71,015206;PRC72,065212
QMF model: Shen, Toki, PRC71,065208

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

Mean field approach

- RMF: *U*= -50 ~ -90 MeV for the point-like Θ
  but -90 MeV → -37.5 MeV for Θ as a *KπN* bound state
- QMF: *U*= -50 MeV





QCD sum rule of Θ+ in nuclear matter

Navarra et al., PLB606,335(2005)

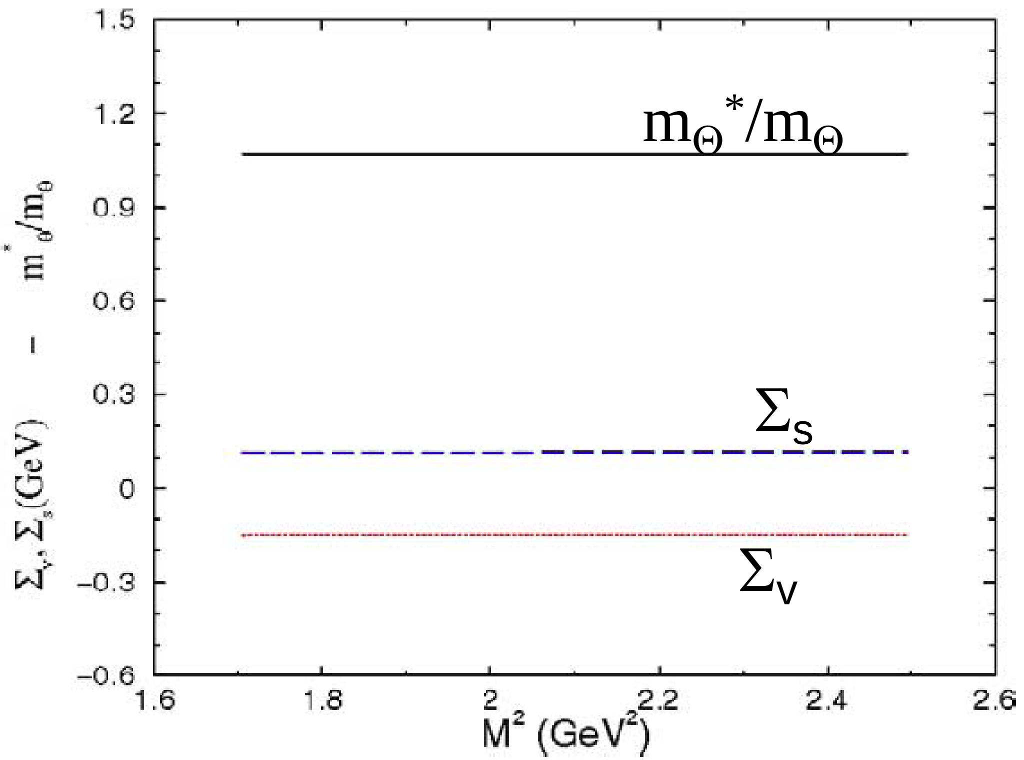


Fig. 2. The ratio m^*_Θ/m_Θ (solid line), the vector and scalar self-energies (dotted and dashed lines, respectively) as functions of the Borel parameter M^2, for $y = 0.3$.

- Σ_s:positive and Σ_v:negative !
- But $U = \Sigma_s + \Sigma_v$: is still negative :

  U= -40~-90 MeV

  strongly depends on the value of the gluon condensate

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

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

All give sufficiently large attractive potentials to bind Θ^+ in nucleus, but what is the bridge between different models ?

What is the suitable reaction for producing Θ^+ hypernucleus ?

- Elementary one-nucleon or two-nucleon process can produce Θ^+ with reasonable cross sections
- Two-body reaction process is preferable to the missing mass spectroscopy
- Momentum difference between the produced Θ^+ and the recoil nucleus should be small

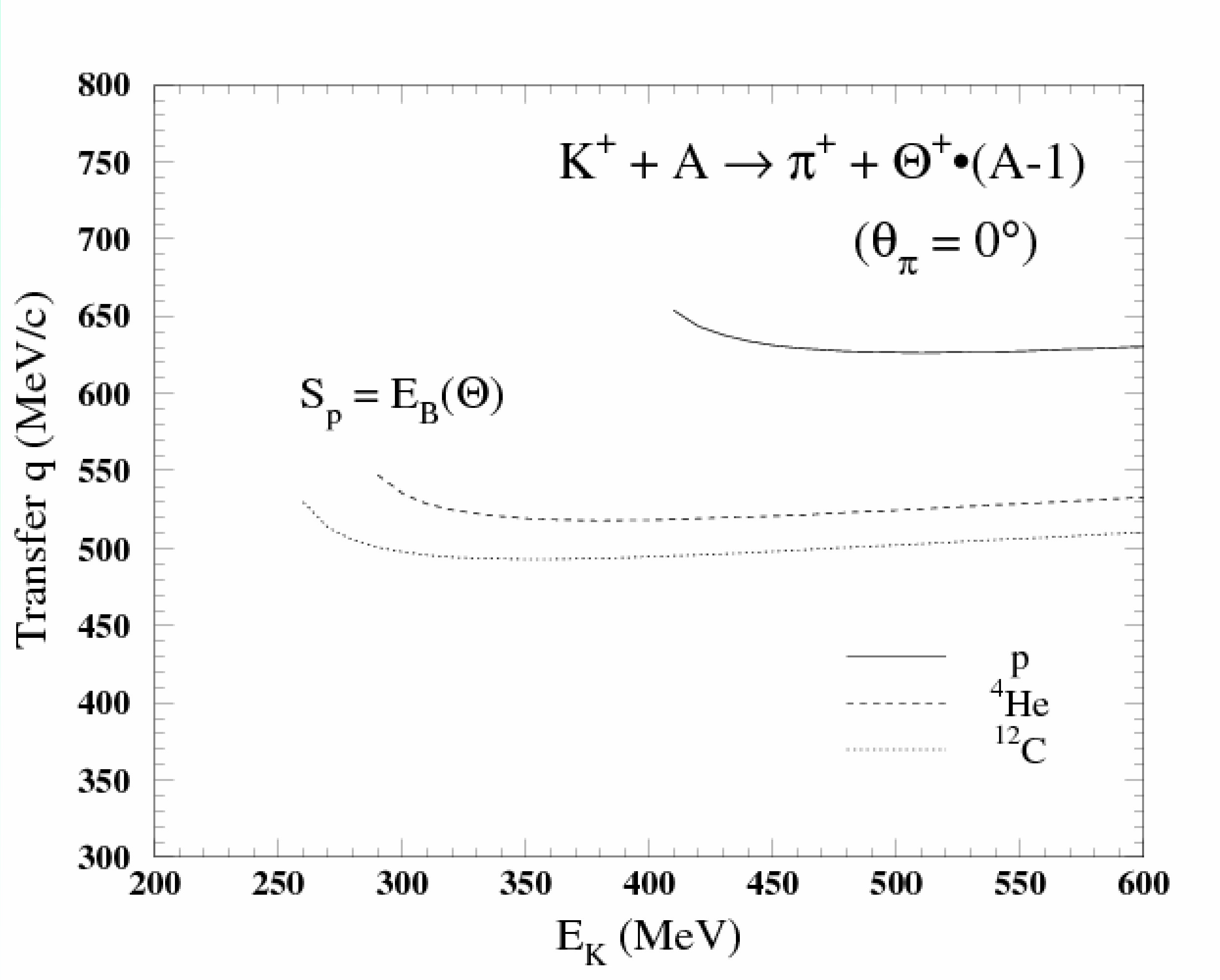
  → small momentum transfer *q* in Lab system
- Small background (BG) process or

  some BG reduction methods should exist :

  → coincidence with backward decay products

Momentum transfer in (K^+,π^+) reaction

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



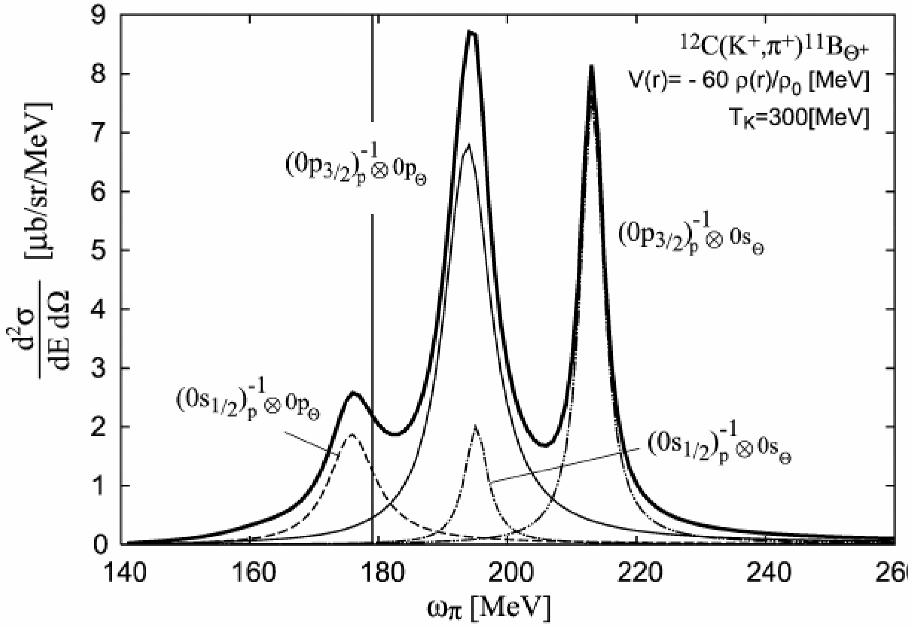
- not small q
- but possible for Θ^+bound nucleus

Use $M(\Theta^+)$=1535 MeV

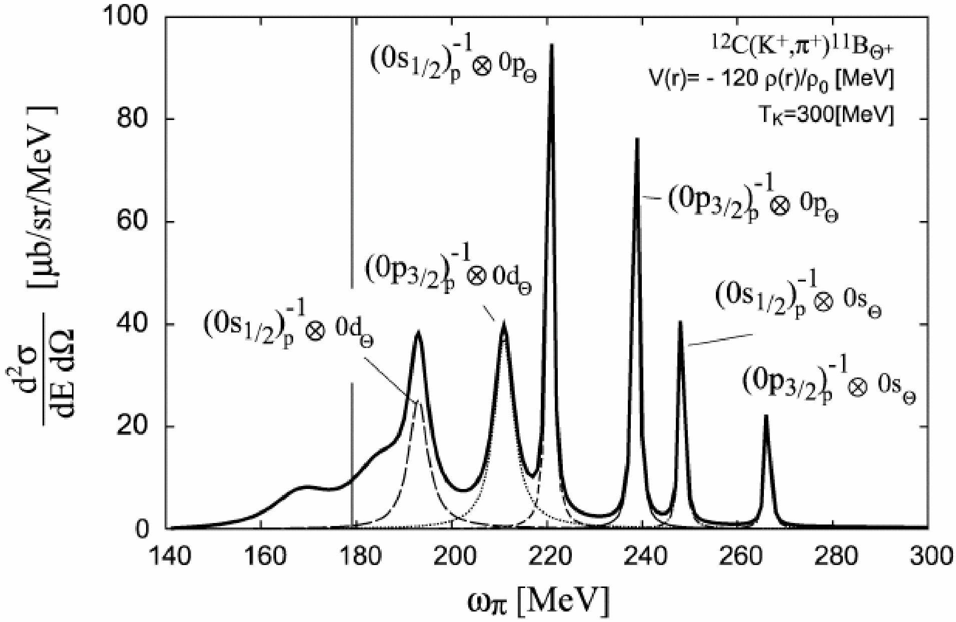
Calculated spectra of $^{12}C(K^+,\pi^+)^{11}B_\Theta$ reaction

Nagahiro et al., PLB620,125(2005)

V(r)= -60 MeV

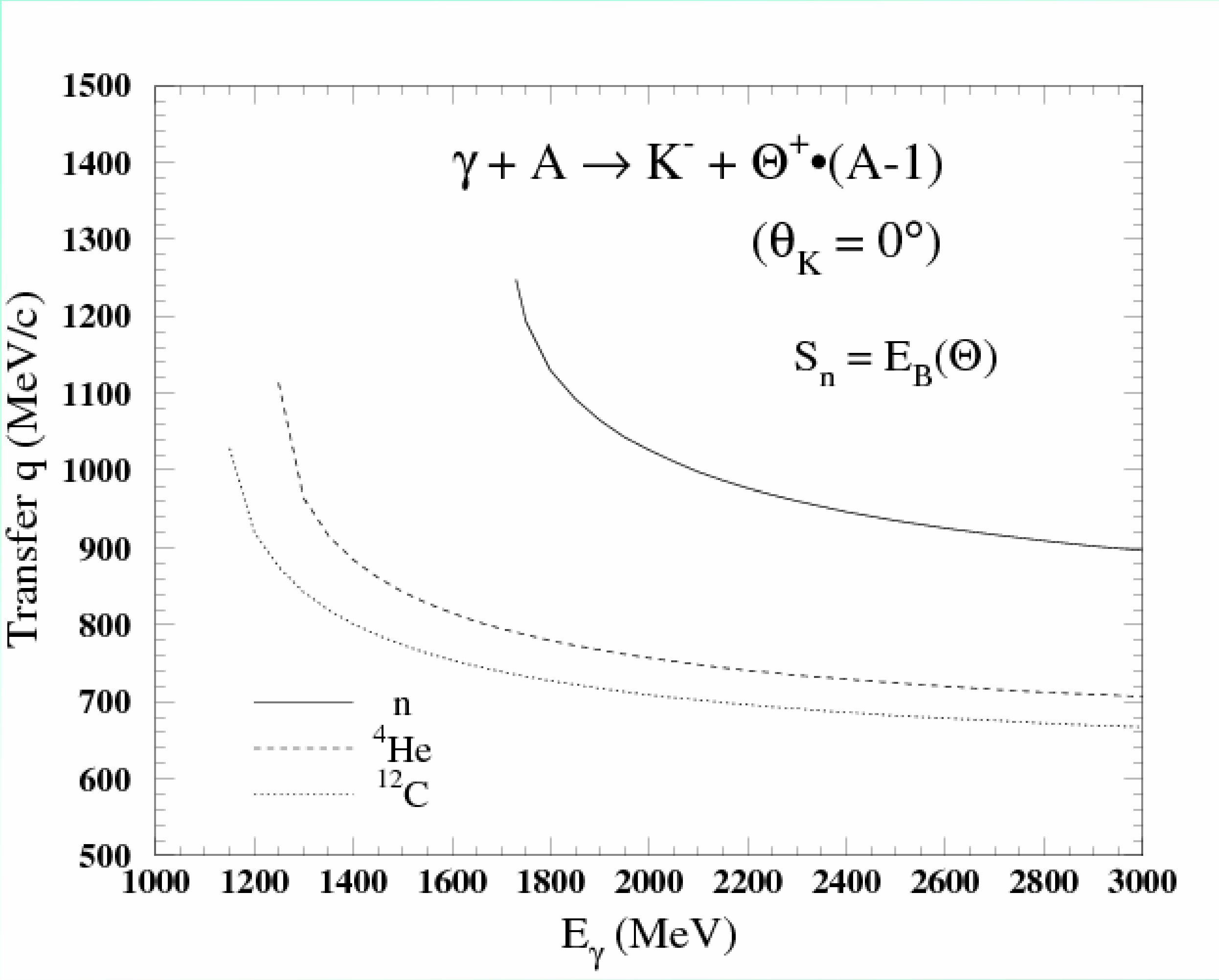


V(r)= -120 MeV



Momentum transfer in (γ, K^+) reaction

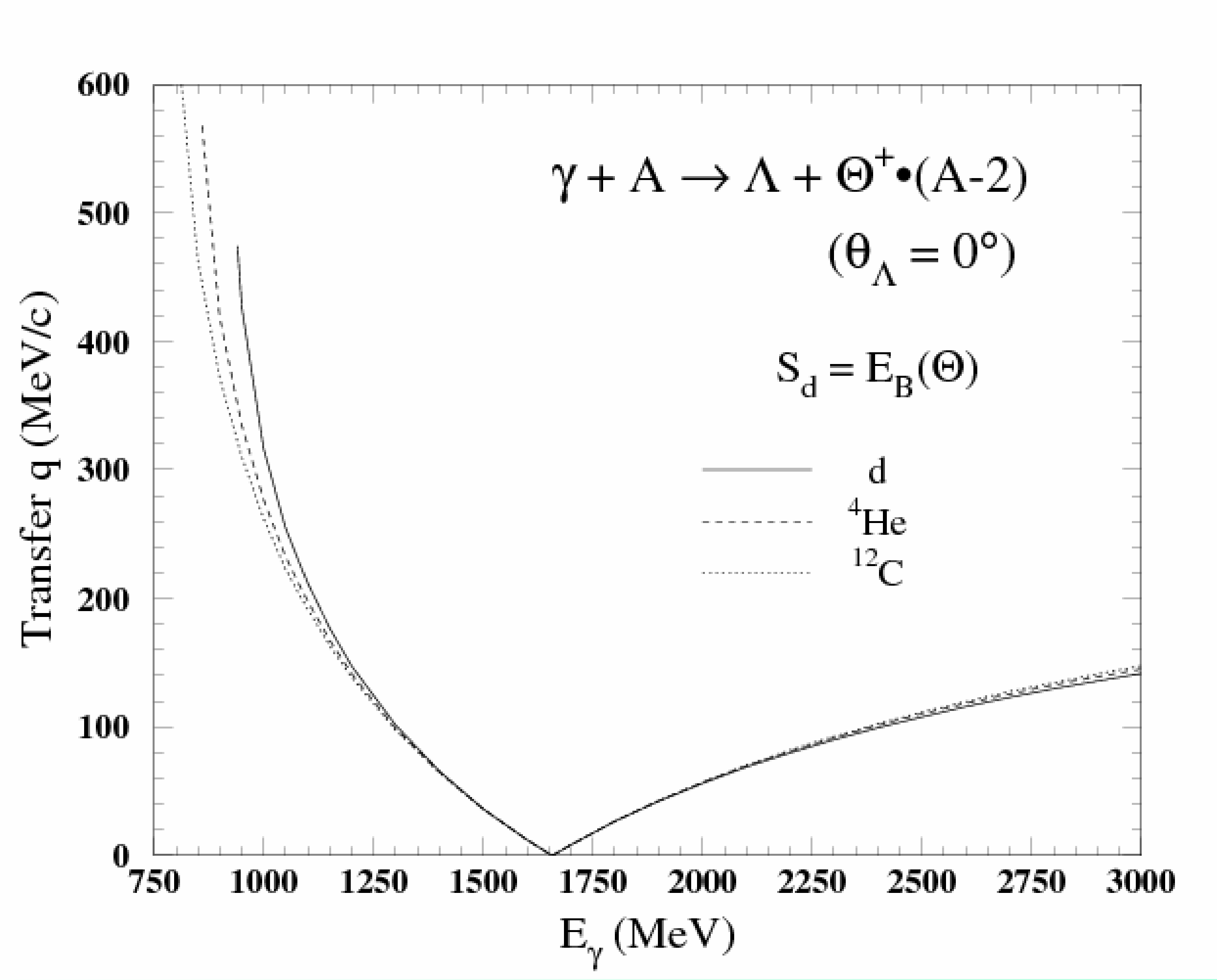
(Θ^+ has been found in 'n'(γ, K^+)X at LEPS)



- large q
- not good for Θ^+bound nucleus

Momentum transfer in (γ,Λ(1116)) reaction

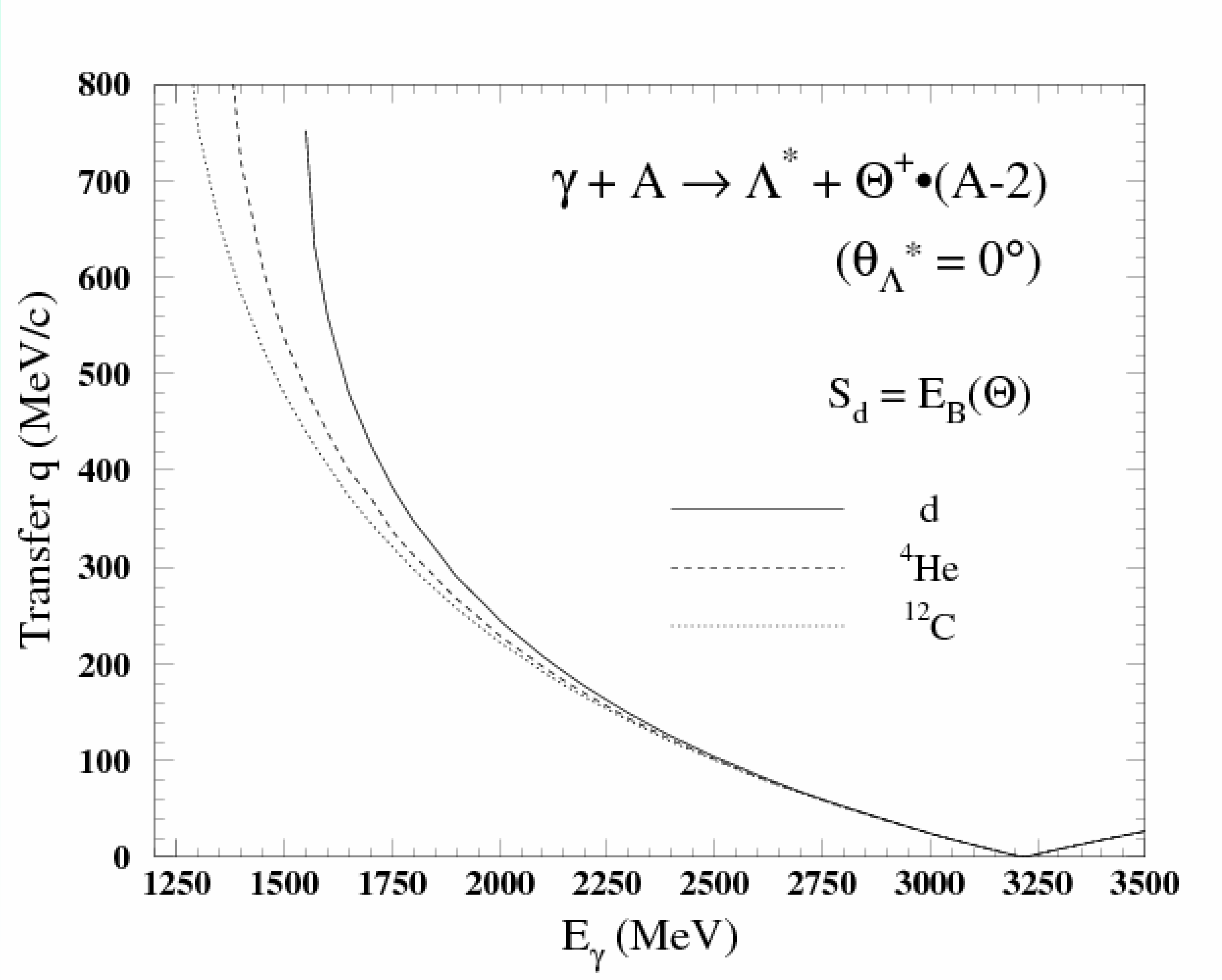
(Θ^+ has still not been found in $d(\gamma,\Lambda)X$ ($\Lambda \rightarrow p\pi^-$))



- very small q
- magic momentum around 1670 MeV

Momentum transfer in $(\gamma,\Lambda^*(1520))$ reaction

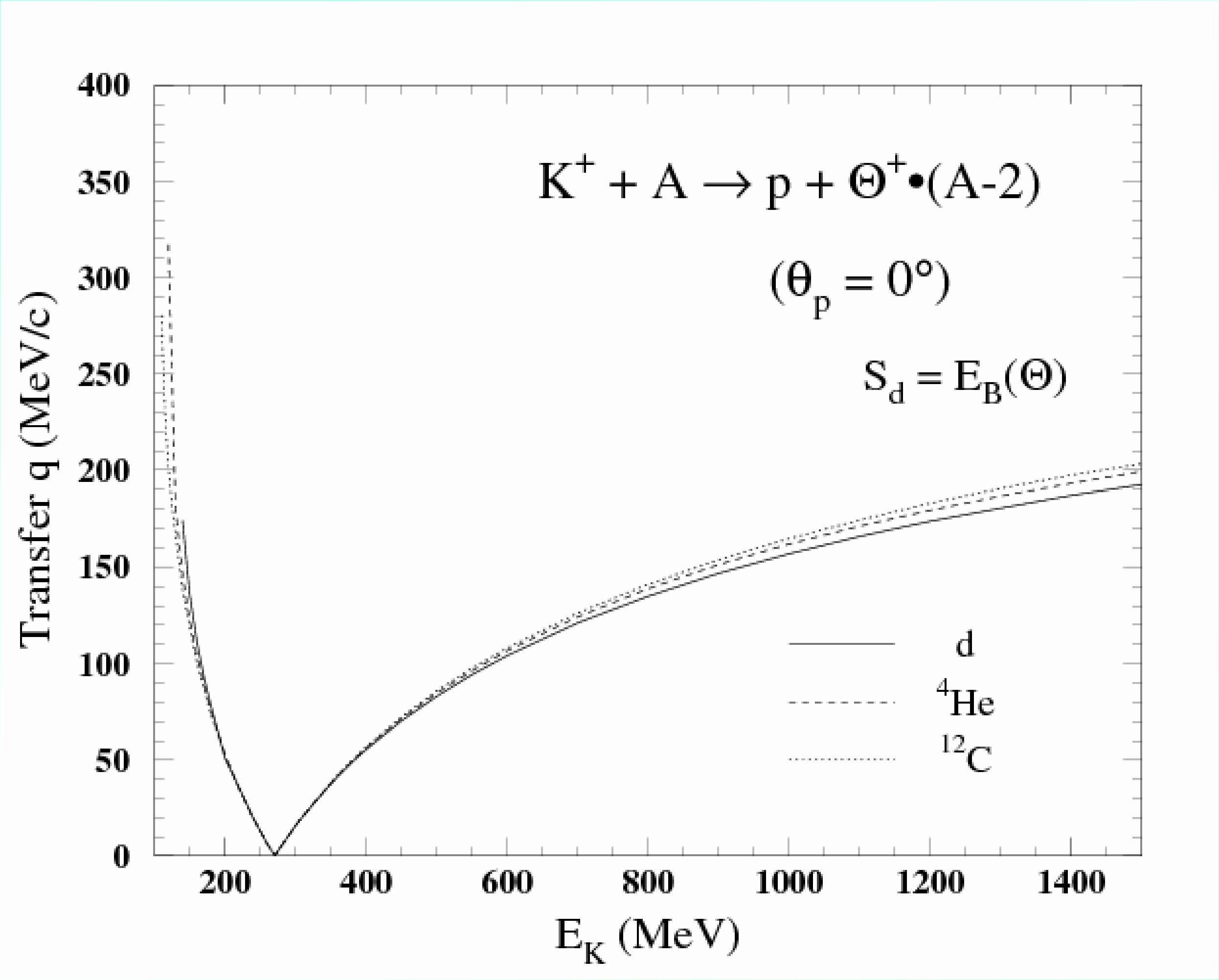
(Θ^+ has been found in $d(\gamma,\Lambda^*)X$ at LEPS ($\Lambda^* \rightarrow pK^-$))



- small q, especially, above 2 GeV
- magic momentum around 3220 MeV (higher than LEPS energy)

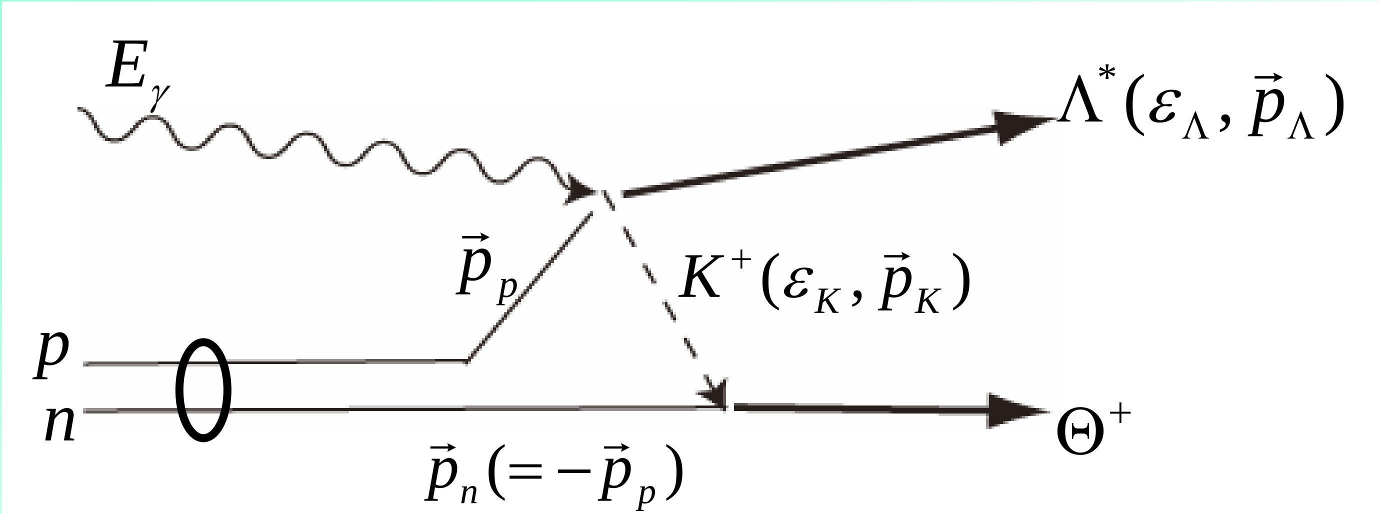
Momentum transfer in (K^+,p) reaction

(Θ^+ 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 !

Comment on $\gamma\, d \rightarrow \Theta^{+}\Lambda^{*}(1520)$



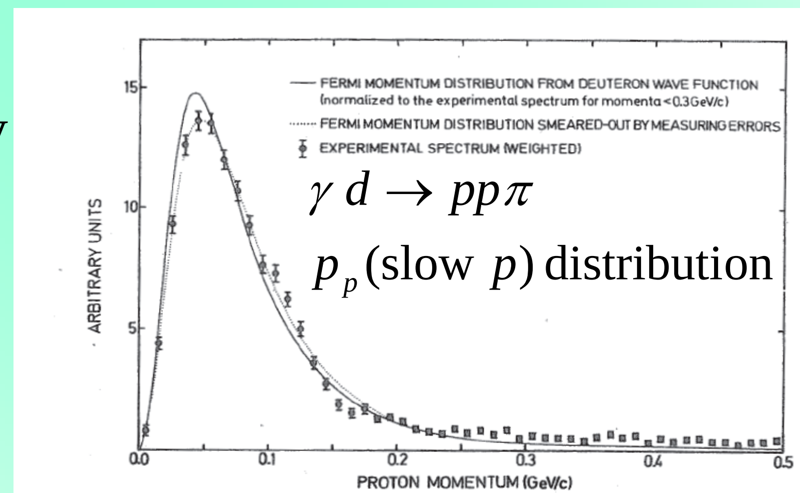
if K^+ : on shell $(m_K^2 = \varepsilon_K^2 - \vec{p}_K^{\,2})$ and

Θ is produced only at the formation energy

$$((\varepsilon_n + \varepsilon_K)^2 - (\vec{p}_n + \vec{p}_K)^2 = M_\Theta^2)$$

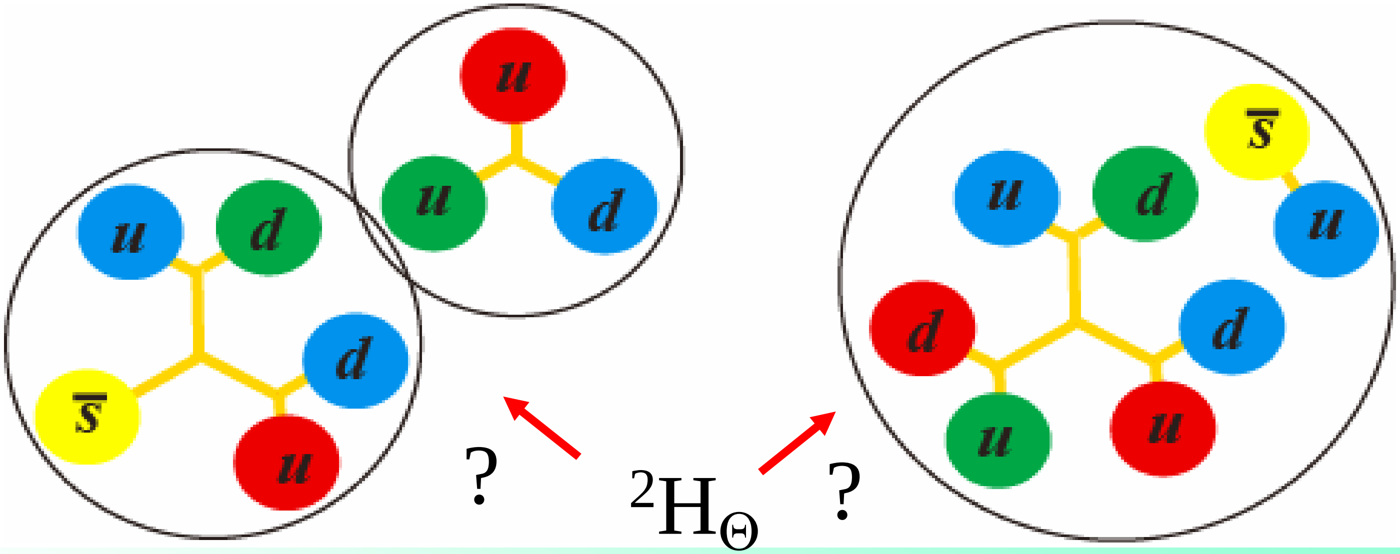
$\Rightarrow$ calculate p_n dependence of

the Θ^+ production rate



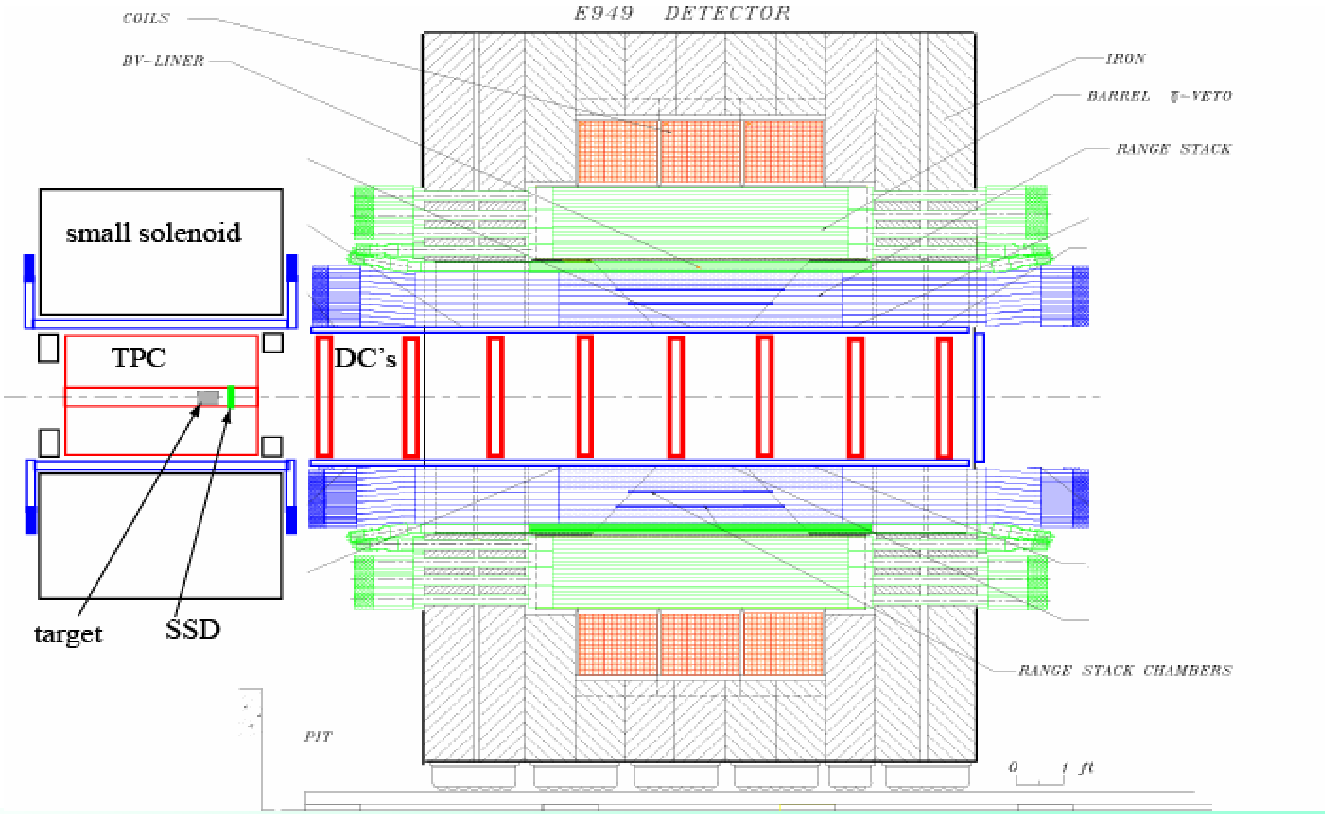
Multi-quark state beyond 5
-- 8 quark dibaryon candidate --

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



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 Θ^+ and the study of the ΘN interaction.
- Several theoretical model calculations predict the existence of bound Θ^+ states, although the mutual relations between different models are not clear.
- Momentum transfer for the Θ^+ production process is small in one baryon knockout reactions at forward angles like (γ,Λ), (γ,Λ^*), 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.)