Interaction of the Θ^+ with the nuclear medium and Θ^+ Hypernuclei

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Introduction: The Θ^+ particle

- Observation of Θ^+ peak by LEPS at Spring8:

  "EVIDENCE FOR A NARROW S = +1 BARYON RESONANCE IN PHOTOPRODUCTION FROM THE NEUTRON." By LEPS Collaboration (T. Nakano et al.). Phys.Rev.Lett.91:012002,2003

- Confirmed by several groups and already three stars in the PDG.
  $I(J^P) = 0(?^?)$

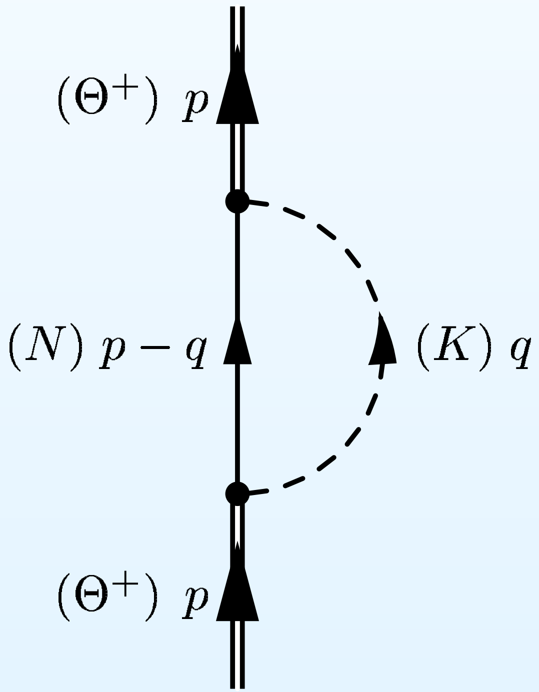
- Mass =1539.2 ± 1.6, Width =0.9 ± 0.3 PDG

- Also several experiments at high energies fail to see it

Further references exp + theo : http://www.rcnp.osaka-u.ac.jp/ hyodo/research/Thetapub.html

Introduction: The Θ^+ particle

- Mass $=1539.2 \pm 1.6$, Width $=0.9 \pm 0.3$, PDG, from $K^+ n \to K^0 p$ and $K^+ d$ cross sections *It is very narrow! (Typical widths ~ 100 MeV)*
- NK is the only strong decay mode allowed for a $S=1$ particle of this mass.



Introduction: Θ^+ nuclear effects?

- How does the Θ^+ interact with the nucleus?
- Mass and/or width changes?
- Other decay channels

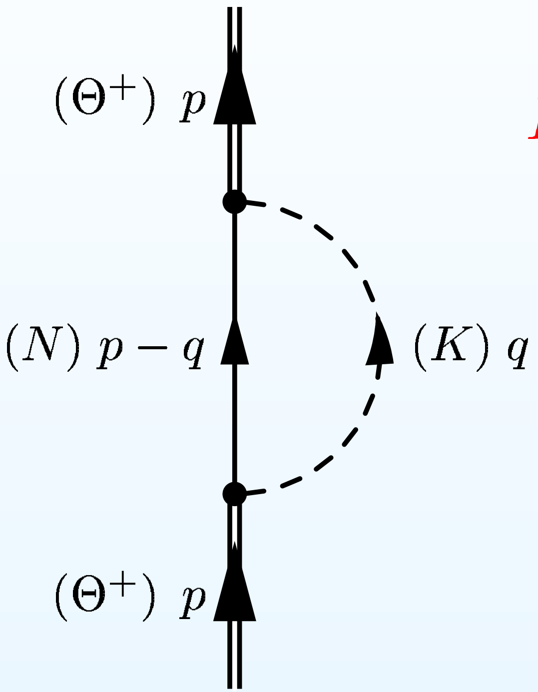
And if the interaction is attractive and strong enough...

Are there **S=1** Hypernuclei?
What are the energy levels?
What are their widths?
How can one produce them?

Contents

- Θ^+ selfenergy from KN decay
- Medium effects...
  - ...on the nucleon
  - ...on the kaon
- Other sources of Θ^+ selfenergy: the *two-meson* cloud
  - Medium effects on the pion
- Bound Θ^+ states?

Θ^+ selfenergy from KN decay



KN couplings

- $t_{K^+n} = g_{K^+n}; \quad t_{K^0p} = -g_{K^+n}$
  for $J^P = \frac{1}{2}^-$, $L = 0$
- $t_{K^+n} = -i\bar{g}_{K^+n}\vec{\sigma}\vec{q}$; $t_{K^0p} = i\bar{g}_{K^+n}\vec{\sigma}\vec{q}$
  for $J^P = \frac{1}{2}^+$, $L = 1$

For the $L = 0$ case

$$\Sigma_{KN}(p) = 2i\int \frac{d^4q}{(2\pi)^4}(-ig_{K^+n})^2 \frac{M}{E_N}\,\frac{i}{p^0-q^0-E_N+i\epsilon}\,\frac{i}{q^2-m_K^2+i\epsilon}$$

Θ^+ selfenergy from KN

$$\Sigma_{KN}(p) = 2i \int \frac{d^4q}{(2\pi)^4} (-i g_{K^+n})^2 \frac{M}{E_N} \frac{i}{p^0 - q^0 - E_N + i\epsilon} \frac{i}{q^2 - m_K^2 + i\epsilon}$$

$\rightarrow$ The imaginary part of Σ_{KN} gives the width

$$\Gamma = -2\,\mathrm{Im}\,\Sigma_{KN} = \frac{g_{K^+n}^2}{\pi} \frac{q_{on}}{M_{\Theta^+}}$$

$\rightarrow$ The experimental width allows to obtain g_{K^+n}

- The formulas for $L = 1$ are obtained by the substitution

$$g_{K^+n}^2 \rightarrow \tilde{g}_{K^+n}^2 \vec{q}^{\,2}$$

Σ_{KN} scales like Γ !

Medium effects

- The nucleon propagator is modified

$$\frac{1}{p^0-q^0-E_N(\vec{p}-\vec{q})+i\epsilon} \rightarrow$$
$$\frac{1-n(\vec{p}-\vec{q})}{p^0-q^0-E_N(\vec{p}-\vec{q})-V_N+i\epsilon} + \frac{n(\vec{p}-\vec{q})}{p^0-q^0-E_N(\vec{p}-\vec{q})-V_N-i\epsilon} \,,$$

  with $n(.)$ the nucleon occupation number

  and $V_N = -k_F^2/2M_N$ the Thomas-Fermi potential

- The kaon propagator is modified

$$\frac{1}{q^2-m_K^2+i\epsilon} \rightarrow \frac{1}{q^2-m_K^2-\Pi_K(q,\rho)} \,,$$

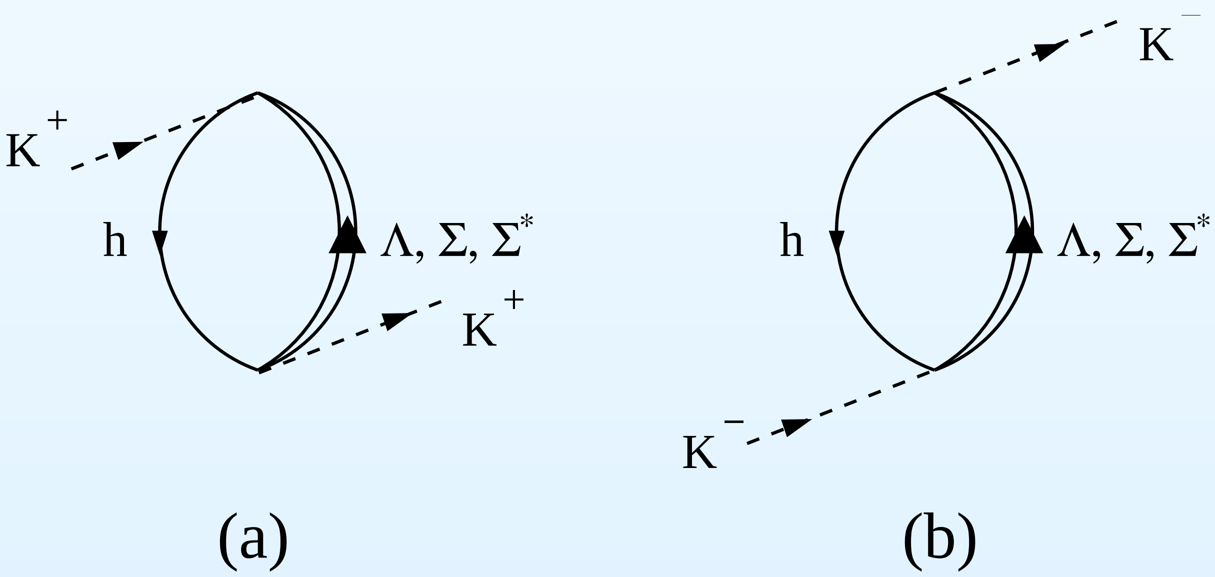
  where $\Pi_K(q,\rho)$ is the kaon selfenergy

Medium effects - The kaon

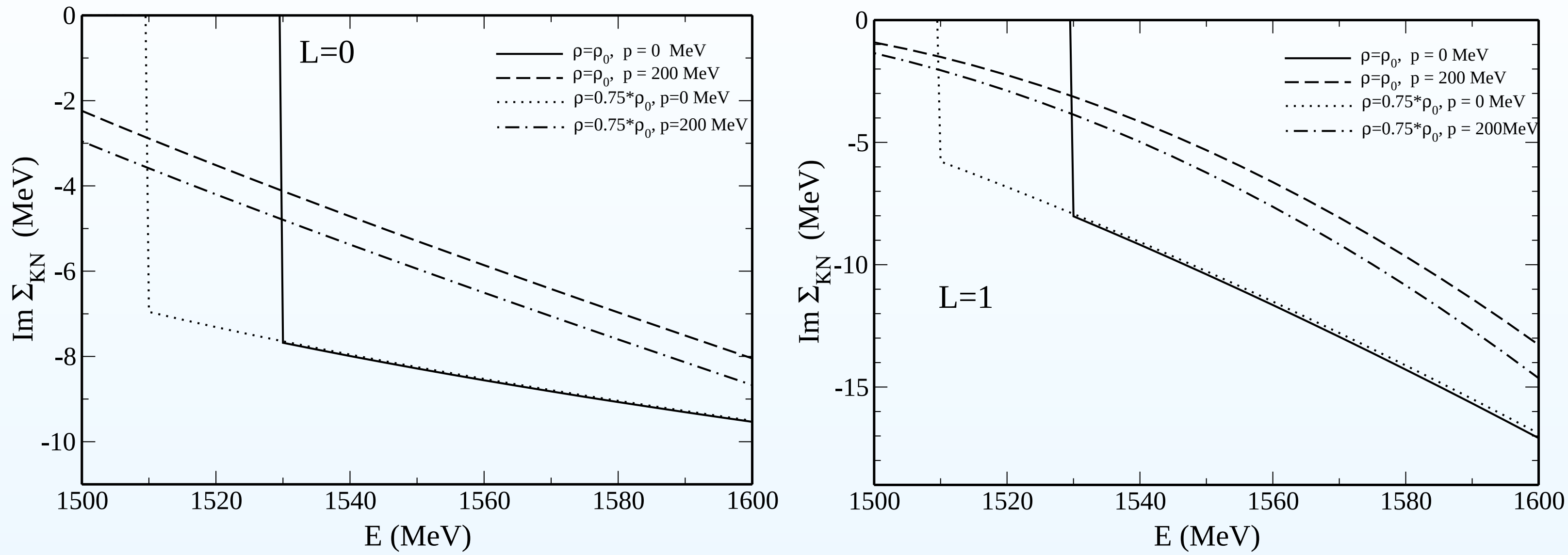
- $\Pi_K(q,\rho)$ contains a $s-$wave and a $p-$wave part. The $s-$wave part is well approximated by

  $$\Pi_K^{(s)}(\rho) = 0.13\, m_K^2 \rho/\rho_0 \ \ [\text{MeV}^2]\,,$$

- The quite small $p-$wave part includes only crossed terms (a) of Yh excitations



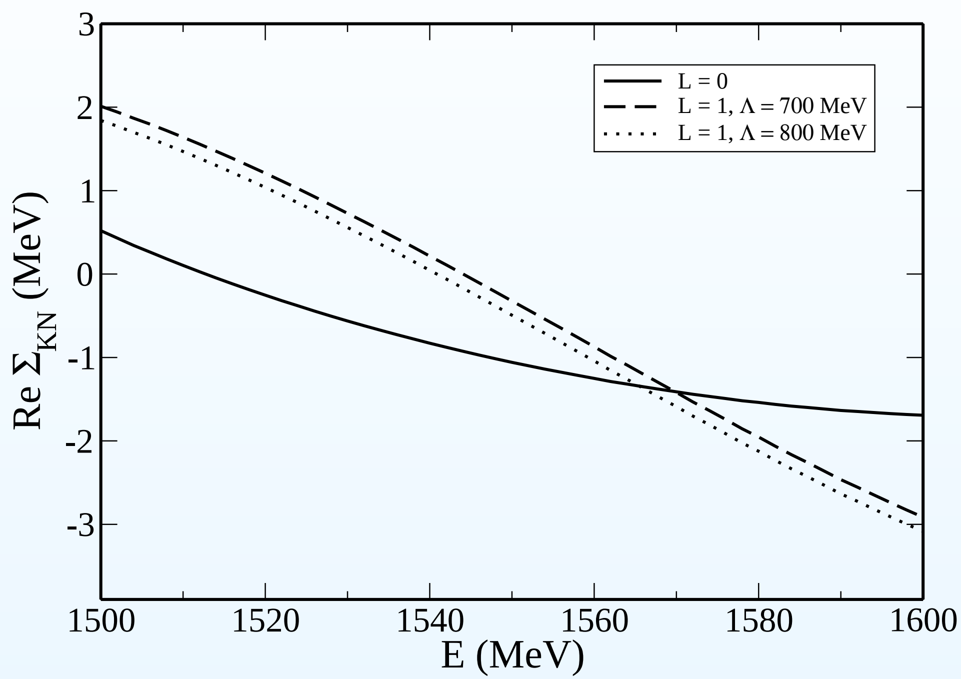
In medium $\Theta^+ \to KN$ width



ImΣ_{KN} for $L = 0$ and 1, obtained assuming a free width of 15 MeV

- The finite Θ^+ momentum makes Pauli blocking effective at the Θ^+ mass and the width is further reduced !
- Small width for possible bound states.

Real part of the selfenergy $\Theta^+ \to KN$



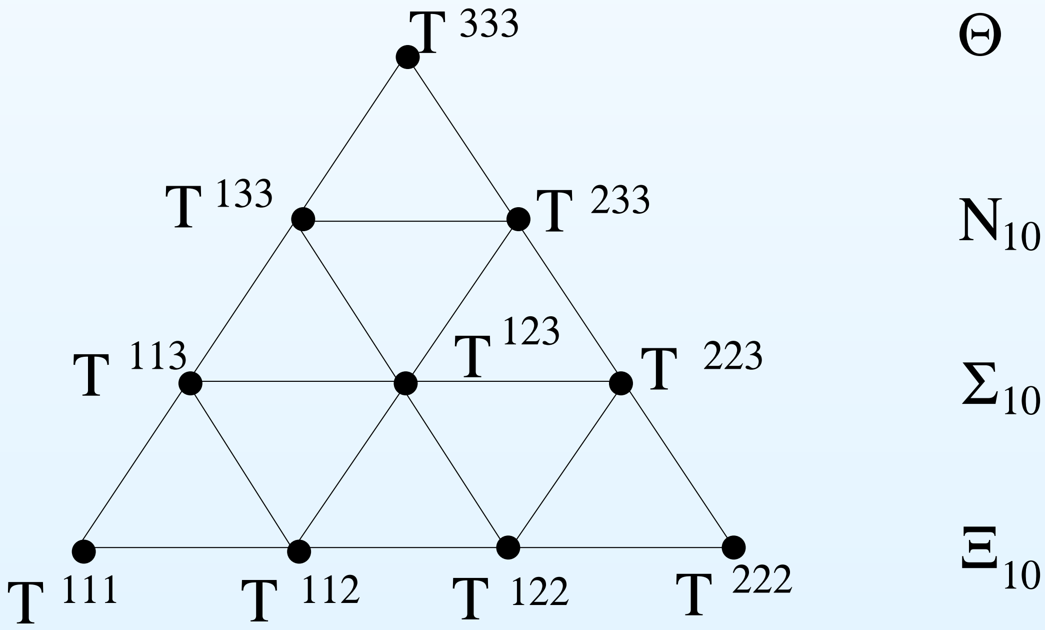
ReΣ_{KN} at $\rho = \rho_0$. A momentum of the Θ^+ of 200 MeV is taken

- Loop integral is convergent after subtraction of the vacuum selfenergy for the $L = 0$ case and weakly cut off dependent for the $L = 1$ case.
- Very small potential!
- Qualitatively agrees with previous work *H.C. Kim et al, hep-ph/0402141*.

Θ^+ selfenergy from the two-meson cloud

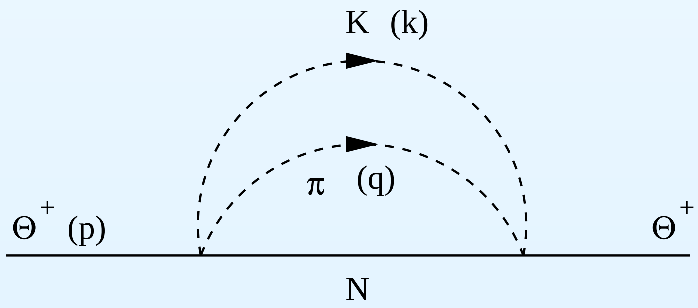
Indications of the relevance of the two meson cloud

- Θ^+ is just $30\ MeV$ below the $N\,K\,\pi$ threshold
- The Θ^+ is supposed to belong to the antidecuplet to which the $N^*(1710)$ also belongs. The $N^*(1710)$ has a strong coupling to $\pi\pi N$



Θ^+ selfenergy from the two-meson cloud

- There is work claiming the Θ^+ to be a bound state of $K\pi N$, Bicudo and Marques , Phys. Rev. D 2004.
- In Llanes, Oset, Mateu , Phys. Rev.C 2004, the $K\pi N$ interaction in $L = 0, I = 0, 1/2^+$ is found attractive but not enough to bind. The interaction is repulsive in $I = 1$.
- All these elements indicate that although the Θ^+ might not be a pure $K\pi N$ bound state, it should have a sizeable fraction of a two meson cloud (heptaquark in quark counting).



$\Theta^+ \to K\, N\, \pi$ selfenergy

Hyodo, Hosaka, Llanes, Oset, Pelaez, Vicente Vacas. Some assumptions:

- Θ^+ is $J^P = \frac{1}{2}^+$ and belongs to an $SU(3)$ antidecuplet
- We choose two $SU(3)$ symmetric Lagrangians
  - $\mathcal{L}_1 = i g_{\bar{10}} \epsilon^{ilm} \bar{T}_{ijk} \gamma^\mu B^j_l (V_\mu)^k_m$,
  - $\mathcal{L}_2 = \frac{1}{2f} \tilde{g}_{\bar{10}} \epsilon^{ilm} \bar{T}_{ijk} (\phi \cdot \phi)^j_l B^k_m$,
    with V_μ two-meson vector current,
    $V_\mu = \frac{1}{4f^2}(\phi \partial_\mu \phi - \partial_\mu \phi \phi)$,
    and T_{ijl}, B^j_l, ϕ^k_m $SU(3)$ tensors for the antidecuplet states, the octet of $\frac{1}{2}^+$ baryons and the octet of 0^- mesons
  - Minimal number of derivatives + Relevance for couplings to protons or neutrons

$\Theta^+ \rightarrow K\, N\, \pi$ selfenergy

- $N^*(1710)$ couples strongly to the same $SU(3)$ antidecuplet.
- The couplings are fitted to the $N^*(1710) \rightarrow N(\pi\pi, p\text{-wave}, I = 1)$ and to the $N^*(1710) \rightarrow N(\pi\pi, s\text{-wave}, I = 0)$ decay widths

$\rightarrow$ The corresponding Θ^+ selfenergy is a combination of pieces like

$$\Sigma^j(p) = -\int \frac{d^4k}{(2\pi)^4} \int \frac{d^4q}{(2\pi)^4} |t^j|^2 \frac{1}{k^2-m_1^2+i\epsilon} \frac{1}{q^2-m_2^2+i\epsilon} \frac{M}{E_N} \frac{1}{p^0-k^0-q^0-E_N+i\epsilon}$$

$\rightarrow$ Real part is regularized with a cutoff [a]

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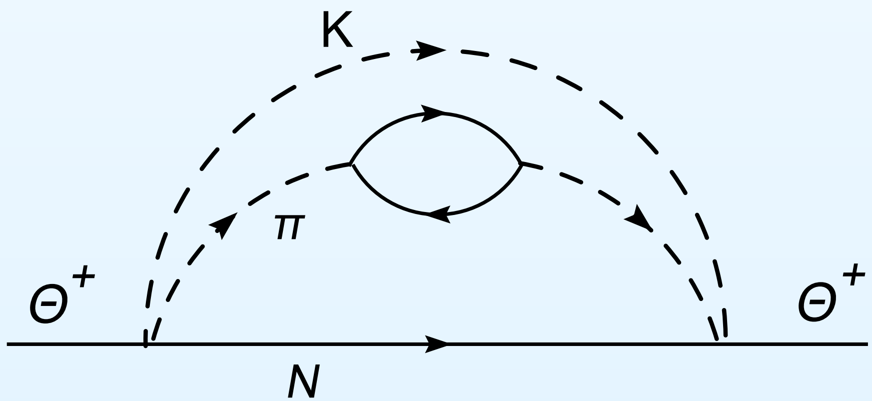
[a] In vacuum this selfenergy provides a mass reduction of $\approx 100-150$ MeV for the Θ^+ and a contribution to the splitting of the andidecuplet states of around ≈ 20 MeV

"$\Theta^+ \to K\, N\, \pi$" selfenergy

- In contrast with the kaons the pions are strongly affected by the nuclear medium!
  - Absorption, excitation of *particle-hole* and $\Delta-$*hole* states
  - Strong attractive potential
- In the nuclear medium, new channels are open like $\Theta^+ \to K\, N\, (p-h)$, as a *particle-hole* excitation requires only a few MeV's



Medium effects

- The nucleon propagator is modified

$$\frac{1}{p^0 - q^0 - E_N(\vec{p}-\vec{q}) + i\epsilon} \rightarrow$$
$$\frac{1 - n(\vec{p}-\vec{q})}{p^0 - q^0 - E_N(\vec{p}-\vec{q}) - V_N + i\epsilon} + \frac{n(\vec{p}-\vec{q})}{p^0 - q^0 - E_N(\vec{p}-\vec{q}) - V_N - i\epsilon} ,$$

- The kaon propagator is modified

$$\frac{1}{q^2 - m_K^2 + i\epsilon} \rightarrow \frac{1}{q^2 - m_K^2 - \Pi_K(q,\rho)} ,$$

Medium effects

- The pion propagator is modified

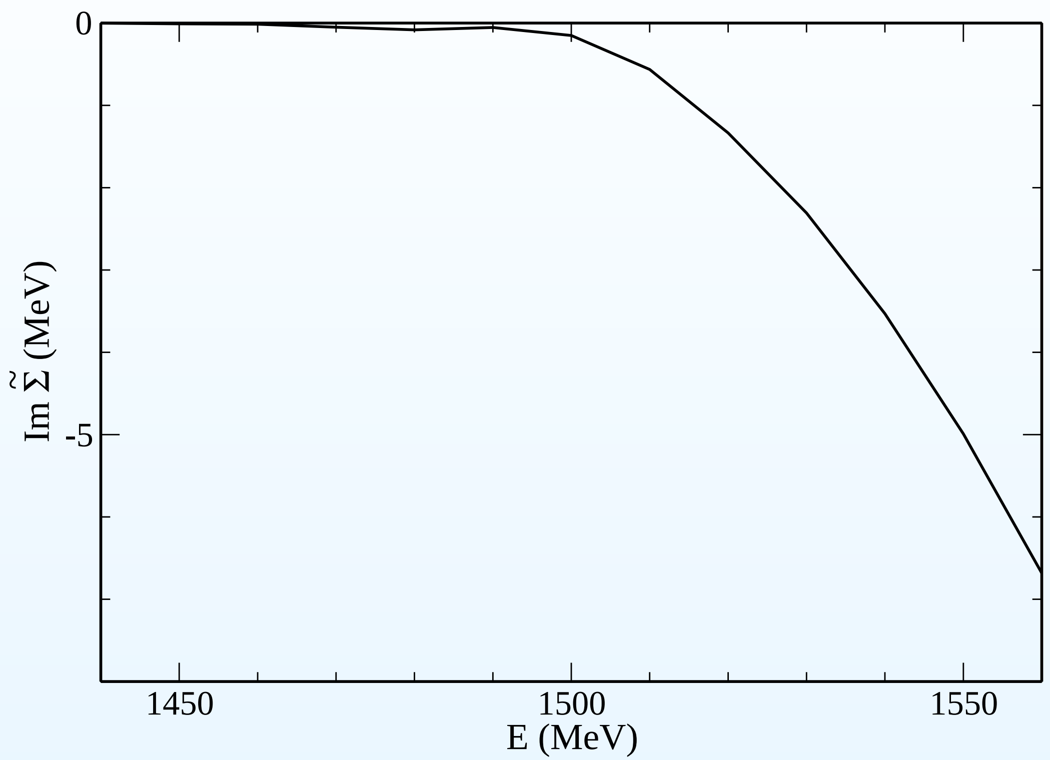
$$\frac{1}{q^2 - m_\pi^2 + i\epsilon} \to \frac{1}{q^2 - m_\pi^2 - \Pi_\pi(q,\rho)},$$

where $\Pi_\pi(q,\rho)$ is the well known [a] pion selfenergy. The main ingredients are:

  - Coupling to *nucleon-hole* and Δ*-hole* excitations
  - Short range correlations.

[a] i.e. T.E.O. Ericson and W. Weise's Pions in Nuclei or E. Oset, H. Toki and W. Weise, Phys. Rept. 83 (1982) 281

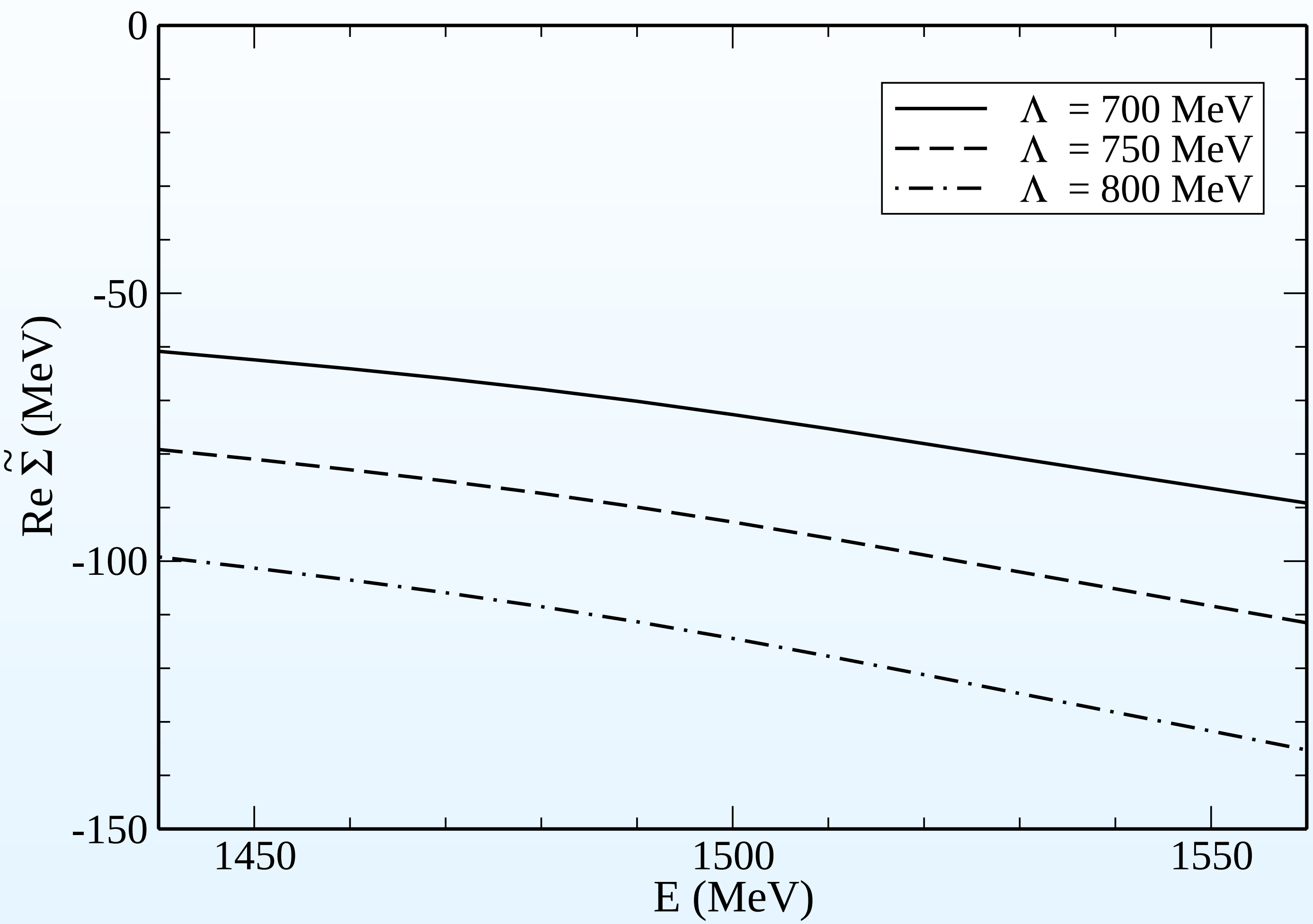
Width from $\Theta^+ \to K\,N\,\pi$ channel



Imaginary part of the two-meson contribution to the Θ^+ selfenergy at $\rho = \rho_0$.

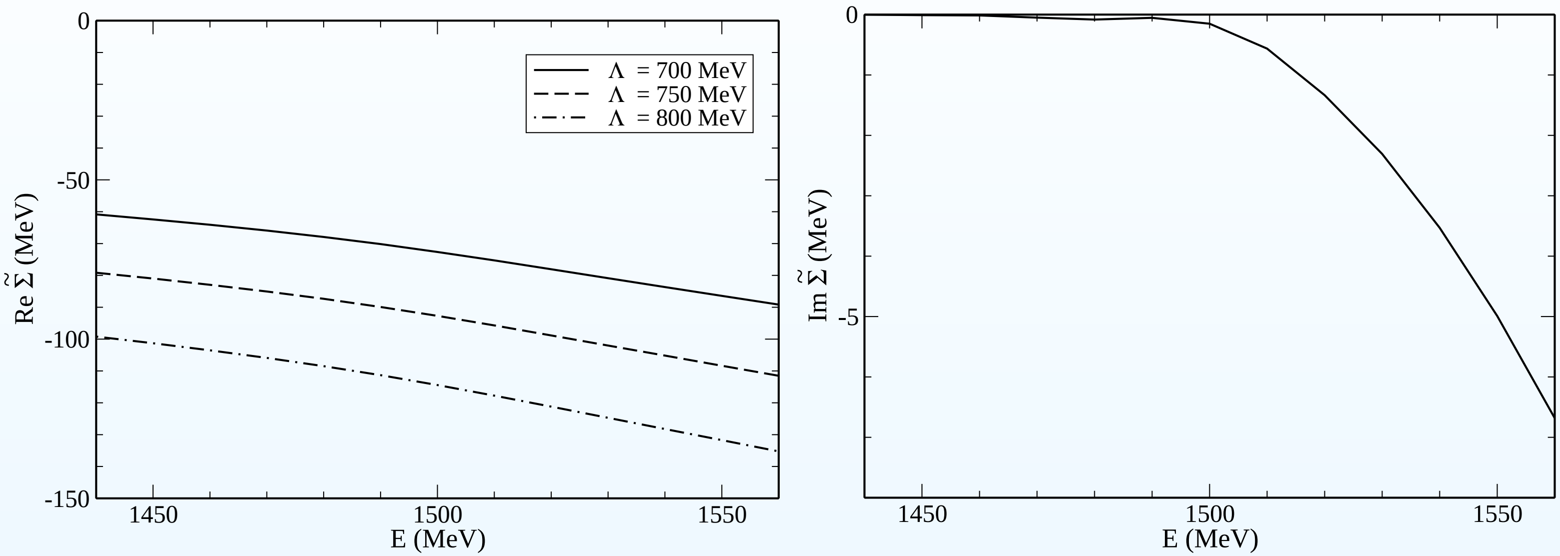
- At 1540 MeV would add around 8 MeV to the width (for $\rho = \rho_0$)
- at 1520 MeV around 3 MeV (for $\rho = \rho_0$), and smaller for smaller densities

Real part of Σ from the $\Theta^+ \to K\,N\,\pi$ channel



Real part of the two-meson contribution to the Θ^+ selfenergy at $\rho = \rho_0$ after subtraction of the vacuum selfenergy.

Σ from the $\Theta^+ \to K\, N\, \pi$ channel



- Large attraction, strong enough to bind the Θ^+ in any nucleus.
- For typical ($\Delta E \sim -20$ MeV) bound states the width would be below 8 MeV and much lower if the free width is smaller than 15 MeV.

Bound Θ^+ states?

Θ^+ binding energies

$V = -60$ MeV ρ/ρ_0		$V = -120$ MeV ρ/ρ_0	
E_i (MeV), ^{12}C	E_i (MeV), ^{40}Ca	E_i (MeV), ^{12}C	E_i (MeV), ^{40}Ca
-34.0 (1s)	-42.6 (1s)	-87.3 (1s)	-98.2 (1s)
-14.6 (1p)	-30.9 (1p)	-59.5 (1p)	-83.3 (1p)
-0.3 (2s)	-18.7 (1d)	-32.0 (2s)	-67.5 (1d)
	-17.9 (2s)	-31.9 (1d)	-65.9 (2s)
	-6.3 (1f)	-8.6 (2p)	-50.8 (1f)
	-5.6 (2p)	-5.6 (1f)	-48.5 (2p)
			-33.5 (1g)
			...

There are already suggestions for experimental observation in Nagahiro et al. nucl-th/0408002, with the (K,π) reaction in nuclei

Plans to make the experiment at KEK, Imai et al.

Summary

- We have evaluated the selfenergy of the Θ^+ in the nuclear medium associated to the KN and the MMB decay channels.
- The potential associated to the KN decay is small, even assuming a large free width of around 15 MeV for the Θ^+
- Pauli blocking and the small phase space from the Θ^+ binding decrease the Θ^+ width in the nucleus from the KN decay.
- We find a large attractive Θ^+ potential in the nucleus associated to the two meson cloud of the antidecuplet.
- A new decay channel opens for the Θ^+ in the medium, $\Theta^+ N \to NNK$.
- The width from this channel, together with the one from KN decay, is still small compared to the separation of the bound levels of the Θ^+ in light and intermediate nuclei.

Summary

- This opens the possibility of the existence of Θ^+ hypernuclei *BUT!*

In reaching the former conclusions there are several assumptions done.

1. The Θ^+ is assumed to be $1/2^+$ associated to an $SU(3)$ antidecuplet;
2. The $N^*(1710)$ is supposed to couple largely to this antidecuplet;
3. Some values of the cut off have been chosen to obtain reasonable numbers for the free Θ^+ selfenergy;
4. The $N^*(1710)$ width and the partial decay ratios, used to obtain the coupling constants, have large experimental uncertainties.

- With all these assumptions one must accept a large uncertainty in the results. However, we think the order of magnitude obtained for the potential is such that even with a wide margin of uncertainty, the possibility of bound state formation is quite safe.

H. Nagahiro *et al*, nucl-th/0408002