Investigation of the trineutron in pionless EFT

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Outline

- Introduction: Tetraneutron and trineutron
- Trineutron in pionless EFT
- Summary

1. Introduction

- Recent result from RIKEN exp. suggested a formation of tetraneutron around the threshold.

  K. Kisamori et al.,PRL116,052501(2016)

- Recent theoretical works reported difficulty of its formation.

  See, e.g., Hiyama et al., PRC93,044004(2016)

- For trineutron both experimental and theoretical works have been reporting negative results of its formation.

Though it is unlikely to see a formation of trineutron in pionless EFT, we may study it for study of the tetraneutron system in the future...

Halo/Cluster EFT

- Effective Field Theories (EFTs)
  - Model independent approach
  - Separation scale
  - Counting rules
  - Parameters should be fixed by experiments
  - For the study of three-body systems the unitary limit can be chosen as a first approximation.

Unitary limit and limit cycle

- Three-body systems in unitary (asymptotic) limit
  - If an interaction is singular, the system exhibits cyclic singularities, so called limit cycle.
  - It is necessary to introduce a counter term for renormalization.
- Efimov-like bound states
  Infinitely many three-body bound states (whose energies $B^{(n)}$) appear, for three-boson case,

$$B^{(n)} = \left(e^{-2\pi/s_0}\right)^{n-n*} \kappa_*^2/m \,,$$

where $s_0 \simeq 1.00624$ and $e^{\pi/s_0} \simeq 22.7$.

No Efimov effect with P-waves

- Impossible because of negative probability

  Y. Nishida, PRA86,012710(2012)

- Applicable at small range of the cutoff values

  E.Braaten et al., PRA86,012711(2012)

- Formation of unphysical bound state

  C.A. Bertulani et al, NPA712,37(2002)

We expand the effective range corrections in the P-wave dressed dineutron propagator.

2. Trineutron in pionless EFT

- Trineutron system for $J^\pi = \frac{1}{2}^{\pm}$ states including ${}^1S_0$ and ${}^3P_0$ two-neutron interaction are considered at leading order.
- Three-body contact interactions for the $J^\pi = \frac{1}{2}^{\pm}$ states are introduced to make a bound state and study the limit-cycle-like divergence in the system.

Effective Lagrangian

$$\mathcal{L} = \mathcal{L}_n + \mathcal{L}_{s(nn)} + \mathcal{L}_{p(nn)} + \mathcal{L}_{Ln} + \cdots ,$$

where

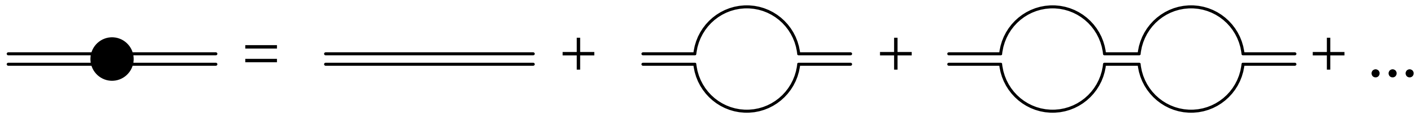
$$\begin{aligned}
\mathcal{L}_n &= n^\dagger \left[iv\cdot\partial + \frac{(v\cdot\partial)^2 - \partial^2}{2m_n} \right] n + \cdots , \\
\mathcal{L}_{s(nn)} &= \sigma_s d_s^\dagger \left[iv\cdot\partial + \frac{(v\cdot\partial)^2 - \partial^2}{4m_n} + \Delta_s \right] d_s - y_s \left[d_s^\dagger \left(n^T P^{({}^1S_0)} n \right) + \text{H.c.} \right] + \cdots , \\
\mathcal{L}_{p(nn)} &= \sigma_p d_p^\dagger \left[iv\cdot\partial + \frac{(v\cdot\partial)^2 - \partial^2}{4m_n} + \Delta_p \right] d_p - y_p \left[d_p^\dagger \left(n^T P^{({}^3P_0)} n \right) + \text{H.c.} \right] + \cdots , \\
\mathcal{L}_{Ln} &= -m_n y_s^2 \frac{g(\Lambda)}{\Lambda^2} n^\dagger d_s^\dagger d_s n - \frac{y_p^2}{4m_n} h(\Lambda) n^\dagger d_p^\dagger d_p n + \cdots ,
\end{aligned}$$

where

$$P^{({}^1S_0)} = -i\frac{1}{2}\sigma_2 , \quad P^{({}^3P_0)} = -i\frac{1}{2}\sigma_2 \vec{\sigma} \cdot \left(-i \frac{\overrightarrow{D} - \overleftarrow{D}}{2m_n} \right) ,$$

Two-body parts: S-wave

- Dressed dineutron propagator for S-wave



- Renormalized dressed dineutron propagator

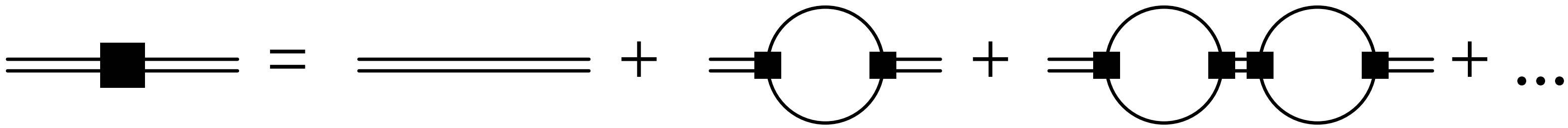
$$D_s(p_0, \vec{p}) \quad = \quad \frac{1}{\frac{1}{a_{nn}} - \sqrt{-m_n p_0 + \frac{1}{4}\vec{p}^2 - i\epsilon}} \,.$$

with

$$a_{nn} = -18.5 \pm 0.4 \text{ fm}\,.$$

Two-body part: P-wave

- Dressed dineutron propagator for P-wave



- Renormalized dineutron propagator for ${}^1P_0$ channel

$$D_p(p_0,\vec{p}) \quad = \quad \frac{1}{\frac{1}{a_p} + \frac{1}{2}r_p\left(\frac{1}{4}\vec{p}^2 - m_n p_0 - i\epsilon\right) + \left(\frac{1}{4}\vec{p}^2 - m_n p_0 - i\epsilon\right)^{3/2}}\,,$$

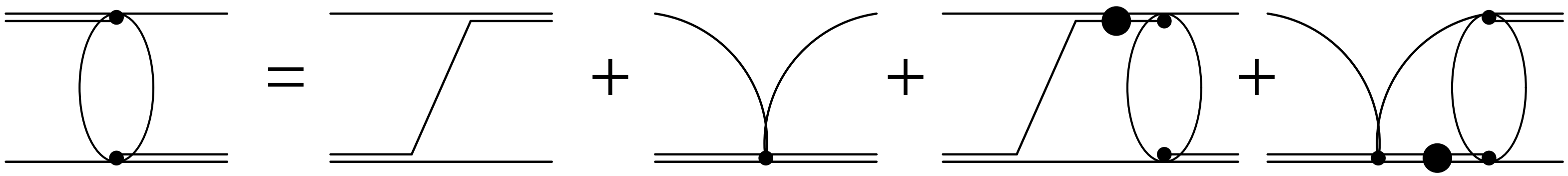
where a_p and r_p are the scattering volume and effective momentum for ${}^3P_0$ channel. a_p and r_p are fitted by using phase shift for np channel up to $k = 160$ MeV:

$$a_p = -6.52 \pm 0.00\ \text{fm}^3\,, \quad r_p = 7.27 \pm 3.71\ \text{fm}^{-1}.$$

Then we expand it as

$$D_p(p_0,\vec{p}) \quad = \quad a_p - \frac{1}{2}a_p^2 r_p\left(\frac{1}{4}\vec{p}^2 - m_n p_0\right) - a_p^2\left(\frac{1}{4}\vec{p}^2 - m_n p_0 - i\epsilon\right)^{3/2}\ .$$

Three-body parts: $J^\pi = \frac{1}{2}^+$ channel

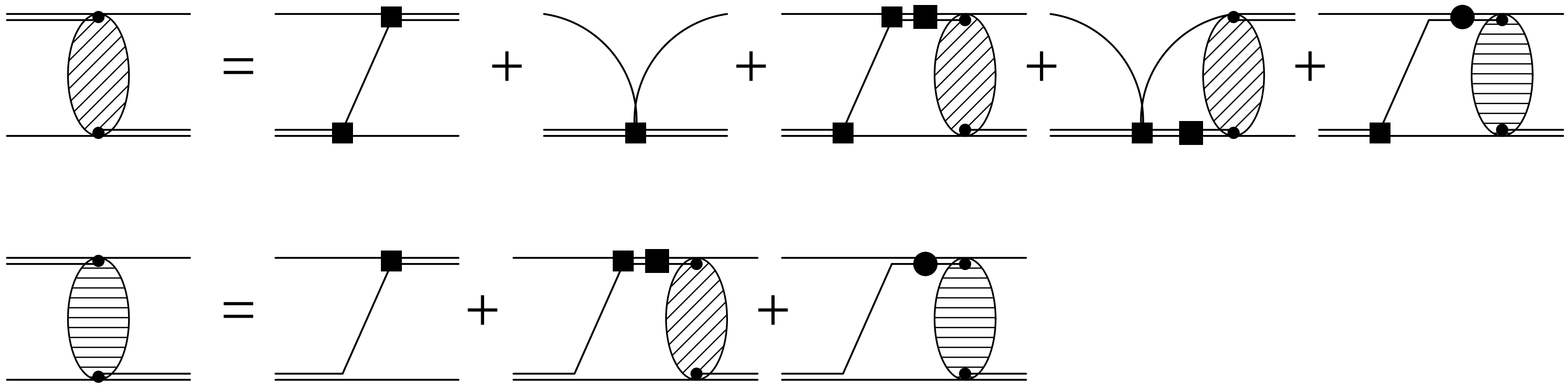


$$t(p,k) = -4\pi\left[K_{ss}(p,k;E) + \frac{g(\Lambda)}{\Lambda^2}\right] + \frac{2}{\pi}\int_0^\Lambda dl l^2 \left[K_{ss}(p,l;E) + \frac{g(\Lambda)}{\Lambda^2}\right] \frac{t(l,k)}{\frac{1}{a_{nn}} - \sqrt{-mE + \frac{3}{4}l^2}},$$

where

$$K_{ss}(p,l;E) = \frac{1}{2pl}\ln\left(\frac{p^2+l^2+pl-mE}{p^2+l^2-pl-mE}\right).$$

Three-body parts: $J^\pi = \frac{1}{2}^-$ ***channel***



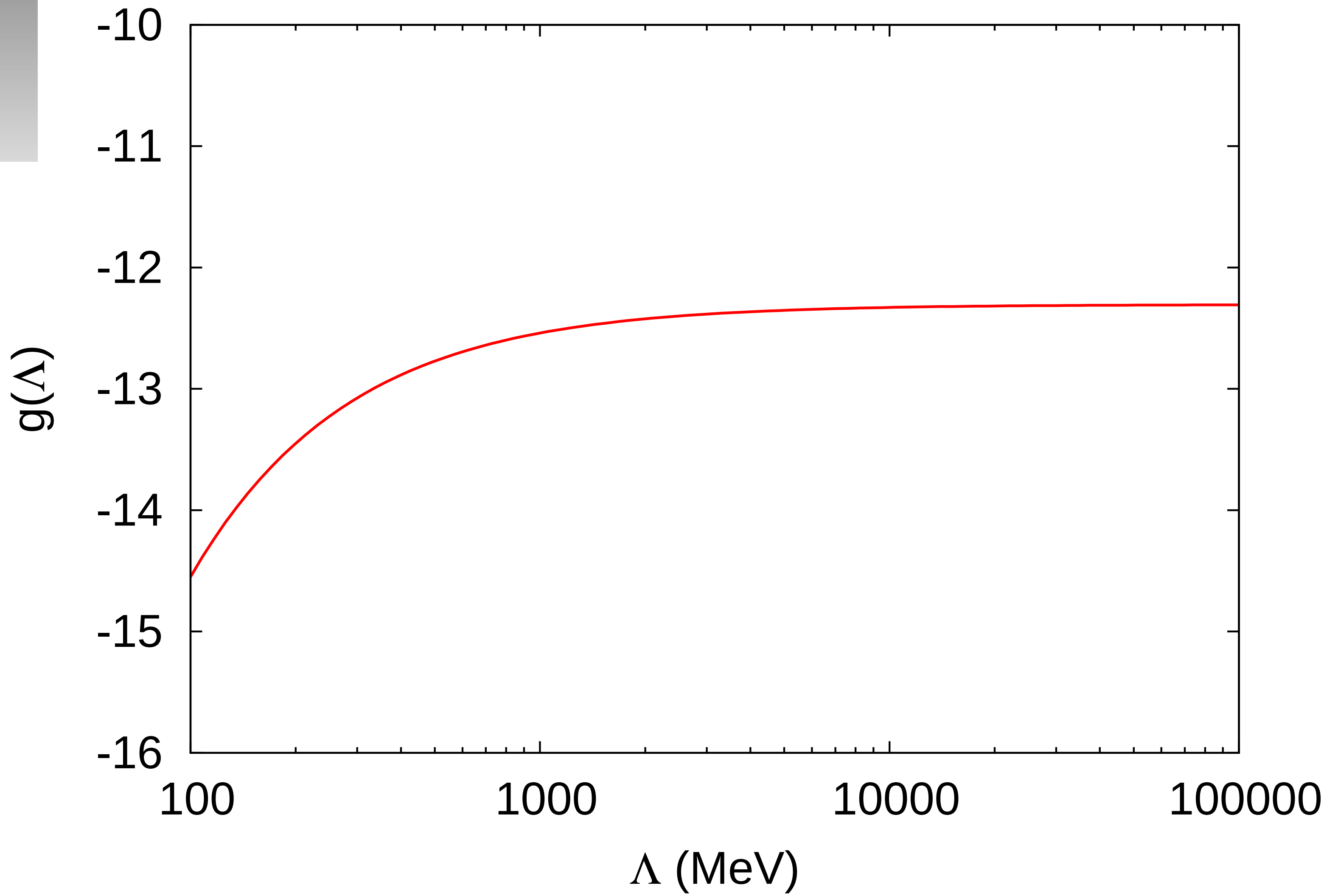
$$
\begin{aligned}
a(p,k) \quad &= \quad -\frac{2\pi}{m_n r_P}\left[K_{pp}(p,k;E)+h(\Lambda)\right] \\
&+\frac{1}{\pi m_n r_p}\int_0^\Lambda dl l^2 \left[K_{pp}(p,l;E)+h(\Lambda)\right] D_s\left(E-\frac{1}{4m_n}l^2,\vec{l}\right) a(l,k) \\
&+\frac{1}{\pi}\sqrt{\frac{2}{m_n r_p}}\int_0^\Lambda dl l^2 K_{ps}(p,l;E) D_s\left(E-\frac{1}{4m_n}l^2,\vec{l}\right) b(l,k)\,,
\end{aligned}
$$

$$
\begin{aligned}
b(p,k) &= -2\pi\sqrt{\frac{2}{m_n r_p}}K_{sp}(p,k;E) \\
&+\frac{1}{\pi}\sqrt{\frac{2}{m_n r_p}}\int_0^\Lambda dl l^2 K_{sp}(p,l;E)D_p\left(E-\frac{1}{4m_n}l^2,\vec{l}\right)a(l,k) \\
&+\frac{2}{\pi}\int_0^\Lambda dl l^2 K_{ss}^{(-)}(p,l;E)D_s\left(E-\frac{1}{4m_n}l^2,\vec{l}\right)b(l,k)\,,
\end{aligned}
$$

$$
\begin{aligned}
K_{pp}(p,k;E) &= \frac{p^2+k^2}{pk}\ln\left(\frac{p^2+k^2+pk-m_nE}{p^2+k^2-pk-m_nE}\right) \\
&+\frac{5}{2}\left[1-\frac{p^2+k^2-m_nE}{2pk}\ln\left(\frac{p^2+k^2+pk-m_nE}{p^2+k^2-pk-m_nE}\right)\right]\,, \\
K_{ps}(p,l;E) &= \frac{1}{p}\ln\left(\frac{p^2+l^2+pl-m_nE}{p^2+l^2-pl-m_nE}\right) \\
&+\frac{1}{2l}\left[1-\frac{p^2+l^2-m_nE}{2pl}\ln\left(\frac{p^2+l^2+pl-m_nE}{p^2+l^2-pl-m_nE}\right)\right]\,, \\
K_{ss}^{(-)}(p,l;E) &= \frac{1}{2pl}\left[1-\frac{p^2+l^2-m_nE}{2pl}\ln\left(\frac{p^2+l^2+pl-m_nE}{p^2+l^2-pl-m_nE}\right)\right]\,.
\end{aligned}
$$

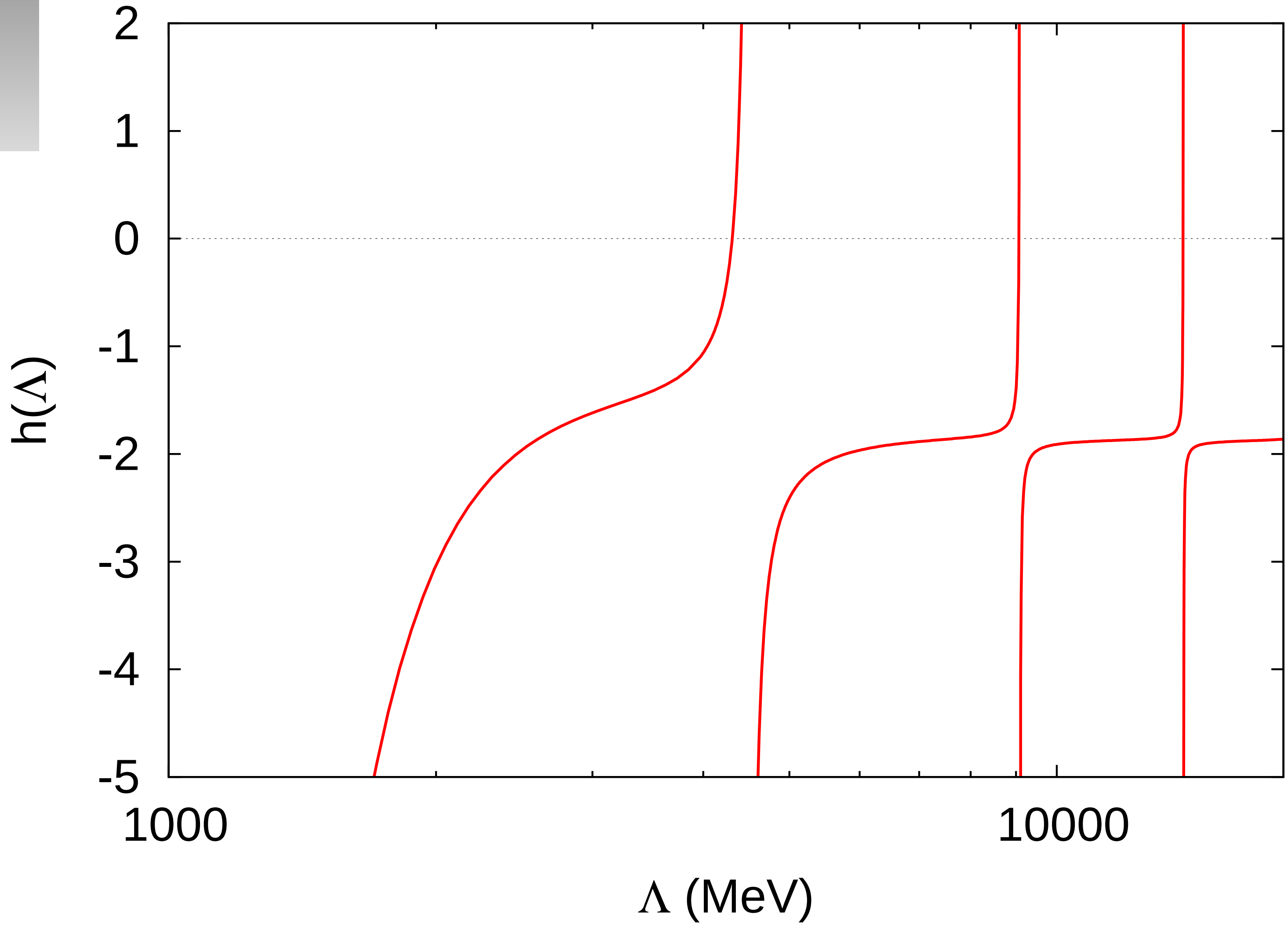
Numerical results: $J^\pi = \frac{1}{2}^+$ ***channel***

- $E = 0$



Numerical results: $J^\pi = \frac{1}{2}^-$ channel

- $E = 0$



Summary

- The trineutron system was studied in pionless EFT at LO.
- $J^\pi = \frac{1}{2}^+$ state does not exhibit the limit cycle, but $J^\pi = \frac{1}{2}^-$ state does. In addition, p-wave interaction is more attractive than that of s-wave in the asymptotic cutoff region. At small cutoff value, however, the both interactions are repulsive, and no bound state is formed.
- It seems that there is no systematic way to deal with the p-wave dressed dineutron propagator.