Thought about neutron oscillation: coherence, damping etc.

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- Coherence
- N-antiN –interactions
- Damping

Coherence

Phase difference $\triangle\varphi << 1$

$$q = |\vec{p}_f - \vec{p}_i|$$

Zero angle scattering $\Rightarrow$ $q = 0$

Neutron Optics

- Fermi potential

$$V(\vec{r}) = -\frac{2\pi\hbar^2}{m}\sum_i f_i \delta(\vec{r} - \vec{r}_i)$$

$$V \sim 100 neV$$

Neutron Optics

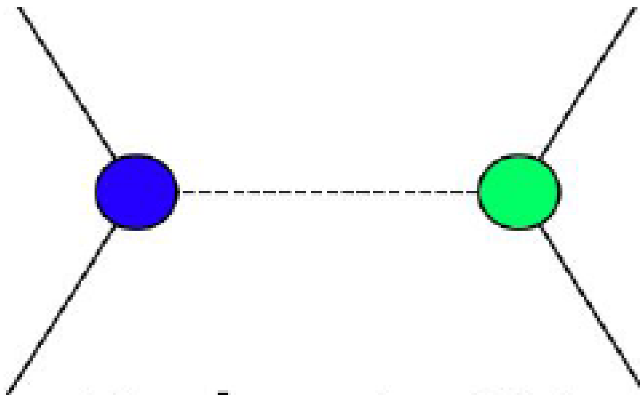
$$n_{\pm}^2 = 1 + \frac{4\pi}{k^2} \sum_i N_i f_{\pm}^i \qquad \sim (\vec{\sigma}_n \cdot \vec{I})$$

Then $$\Delta n = n_+ - n_- = \frac{2\pi}{k^2} \sum_i N_i (f_+^i - f_-^i)$$

$$\psi(z) = \alpha_+(0) e^{ikn_+ z} \begin{pmatrix} 1 \\ 0 \end{pmatrix} + \alpha_-(0) e^{ikn_- z} \begin{pmatrix} 0 \\ 1 \end{pmatrix} = e^{ikn_+ z} \left\{ \alpha_+(0) \begin{pmatrix} 1 \\ 0 \end{pmatrix} + \alpha_-(0) e^{-ik\Delta n z} \begin{pmatrix} 0 \\ 1 \end{pmatrix} \right\}$$

$$\omega_P = \frac{d\varphi}{dz} = \frac{2\pi N \hbar}{M_n} \sum_i N_i \Re e (f_+^i - f_-^i)$$

N-antiN interactions



How they know who is who?

Effective Field Theory

The one-pion exchange potential is given by

$$V_{1\pi}(q) = \left(\frac{g_A}{2F_\pi}\right)^2 \left(1 - \frac{p^2 + p'^2}{2m^2}\right) \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 \frac{\boldsymbol{\sigma}_1 \cdot \mathbf{q}\, \boldsymbol{\sigma}_2 \cdot \mathbf{q}}{\mathbf{q}^2 + M_\pi^2}, \qquad (2.1)$$

where $\mathbf{q} = \mathbf{p}' - \mathbf{p}$ is the transferred momentum defined in terms of the final ($\mathbf{p}'$) and initia
($\mathbf{p}$) center-of-mass momenta of the baryons (nucleon or antinucleon). M_π and m denot

$$N\bar{N} \Leftrightarrow -NN$$

L-Y. Dai, J. Haidenbauer, and Ulf-G. Meisner (2017)

Neutron transmission

P-violation:

$$(\vec{\sigma}_n \cdot \vec{k})$$

$$\Delta\sigma_V = \frac{4\pi}{k}\,\mathrm{Im}\{\Delta f_V\}$$

$$\frac{d\psi}{dz} = \frac{2\pi N}{k}\,\mathrm{Re}\{\Delta f_V\}$$

PV N-N potential

n	c_n^{DDH}	$f_n^{DDH}(r)$	$c_n^{\not\pi}$	$f_n^{\not\pi}(r)$	c_n^{π}	$f_n^{\pi}(r)$	$O_{ij}^{(n)}$
1	$+\frac{g_\pi}{2\sqrt{2}m_N}h_\pi^1$	$f_\pi(r)$	$-\frac{\mu^2 C_6^{\not\pi}}{\Lambda_\chi^3}$	$f_\mu^{\not\pi}(r)$	$+\frac{g_\pi}{2\sqrt{2}m_N}h_\pi^1$	$f_\Lambda^\pi(r)$	$(\tau_i \times \tau_j)^z(\boldsymbol{\sigma}_i + \boldsymbol{\sigma}_j)\cdot \boldsymbol{X}_{ij,-}^{(1)}$
2	$-\frac{g_\rho}{m_N}h_\rho^0$	$f_\rho(r)$	0	0	0	0	$(\tau_i \cdot \tau_j)(\boldsymbol{\sigma}_i - \boldsymbol{\sigma}_j)\cdot \boldsymbol{X}_{ij,+}^{(2)}$
3	$-\frac{g_\rho(1+\kappa_\rho)}{m_N}h_\rho^0$	$f_\rho(r)$	0	0	0	0	$(\tau_i \cdot \tau_j)(\boldsymbol{\sigma}_i \times \boldsymbol{\sigma}_j)\cdot \boldsymbol{X}_{ij,-}^{(3)}$
4	$-\frac{g_\rho}{2m_N}h_\rho^1$	$f_\rho(r)$	$\frac{\mu^2}{\Lambda_\chi^3}(C_2^{\not\pi} + C_4^{\not\pi})$	$f_\mu^{\not\pi}(r)$	$\frac{\Lambda^2}{\Lambda_\chi^3}(C_2^{\pi} + C_4^{\pi})$	$f_\Lambda(r)$	$(\tau_i + \tau_j)^z(\boldsymbol{\sigma}_i - \boldsymbol{\sigma}_j)\cdot \boldsymbol{X}_{ij,+}^{(4)}$
5	$-\frac{g_\rho(1+\kappa_\rho)}{2m_N}h_\rho^1$	$f_\rho(r)$	0	0	$\frac{2\sqrt{2}\pi g_A^3 \Lambda^2}{\Lambda_\chi^3}h_\pi^1$	$L_\Lambda^\pi(r)$	$(\tau_i + \tau_j)^z(\boldsymbol{\sigma}_i \times \boldsymbol{\sigma}_j)\cdot \boldsymbol{X}_{ij,-}^{(5)}$
6	$-\frac{g_\rho}{2\sqrt{6}m_N}h_\rho^2$	$f_\rho(r)$	$-\frac{2\mu^2}{\Lambda_\chi^3}C_5^{\not\pi}$	$f_\mu^{\not\pi}(r)$	$-\frac{2\Lambda^2}{\Lambda_\chi^3}C_5^{\pi}$	$f_\Lambda(r)$	$\mathcal{T}_{ij}(\boldsymbol{\sigma}_i - \boldsymbol{\sigma}_j)\cdot \boldsymbol{X}_{ij,+}^{(6)}$
7	$-\frac{g_\rho(1+\kappa_\rho)}{2\sqrt{6}m_N}h_\rho^2$	$f_\rho(r)$	0	0	0	0	$\mathcal{T}_{ij}(\boldsymbol{\sigma}_i \times \boldsymbol{\sigma}_j)\cdot \boldsymbol{X}_{ij,-}^{(7)}$
8	$-\frac{g_\omega}{m_N}h_\omega^0$	$f_\omega(r)$	$\frac{2\mu^2}{\Lambda_\chi^3}C_1^{\not\pi}$	$f_\mu^{\not\pi}(r)$	$\frac{2\Lambda^2}{\Lambda_\chi^3}C_1^{\pi}$	$f_\Lambda(r)$	$(\boldsymbol{\sigma}_i - \boldsymbol{\sigma}_j)\cdot \boldsymbol{X}_{ij,+}^{(8)}$
9	$-\frac{g_\omega(1+\kappa_\omega)}{m_N}h_\omega^0$	$f_\omega(r)$	$\frac{2\mu^2}{\Lambda_\chi^3}\tilde{C}_1^{\not\pi}$	$f_\mu^{\not\pi}(r)$	$\frac{2\Lambda^2}{\Lambda_\chi^3}\tilde{C}_1^{\pi}$	$f_\Lambda(r)$	$(\boldsymbol{\sigma}_i \times \boldsymbol{\sigma}_j)\cdot \boldsymbol{X}_{ij,-}^{(9)}$
10	$-\frac{g_\omega}{2m_N}h_\omega^1$	$f_\omega(r)$	0	0	0	0	$(\tau_i + \tau_j)^z(\boldsymbol{\sigma}_i - \boldsymbol{\sigma}_j)\cdot \boldsymbol{X}_{ij,+}^{(10)}$
11	$-\frac{g_\omega(1+\kappa_\omega)}{2m_N}h_\omega^1$	$f_\omega(r)$	0	0	0	0	$(\tau_i + \tau_j)^z(\boldsymbol{\sigma}_i \times \boldsymbol{\sigma}_j)\cdot \boldsymbol{X}_{ij,-}^{(11)}$
12	$-\frac{g_\omega h_\omega^1 - g_\rho h_\rho^1}{2m_N}$	$f_\rho(r)$	0	0	0	0	$(\tau_i - \tau_j)^z(\boldsymbol{\sigma}_i + \boldsymbol{\sigma}_j)\cdot \boldsymbol{X}_{ij,+}^{(12)}$
13	$-\frac{g_\rho}{2m_N}h_\rho'^1$	$f_\rho(r)$	0	0	$-\frac{\sqrt{2}\pi g_A \Lambda^2}{\Lambda_\chi^3}h_\pi^1$	$L_\Lambda^\pi(r)$	$(\tau_i \times \tau_j)^z(\boldsymbol{\sigma}_i + \boldsymbol{\sigma}_j)\cdot \boldsymbol{X}_{ij,-}^{(13)}$
14	0	0	0	0	$\frac{2\Lambda^2}{\Lambda_\chi^3}C_6^{\pi}$	$f_\Lambda(r)$	$(\tau_i \times \tau_j)^z(\boldsymbol{\sigma}_i + \boldsymbol{\sigma}_j)\cdot \boldsymbol{X}_{ij,-}^{(14)}$
15	0	0	0	0	$\frac{\sqrt{2}\pi g_A^3 \Lambda^2}{\Lambda_\chi^3}h_\pi^1$	$\tilde{L}_\Lambda^\pi(r)$	$(\tau_i \times \tau_j)^z(\boldsymbol{\sigma}_i + \boldsymbol{\sigma}_j)\cdot \boldsymbol{X}_{ij,-}^{(15)}$

$$V_{ij} = \sum_\alpha c_n^\alpha O_{ij}^{(n)}; \qquad X_{ij,+}^{(n)} = [\vec{p}_{ij}, f_n(r_{ij})]_+$$

3-nucleon system

$$(E - H_0 - V_{ij})\,\psi_k = V_{ij}(\psi_i + \psi_j),$$

$$V_{ij} = V_{ij}^{TC} + V_{ij}^{TP}$$

$$\psi_k = \psi_k^{+} + \psi_k^{-}.$$

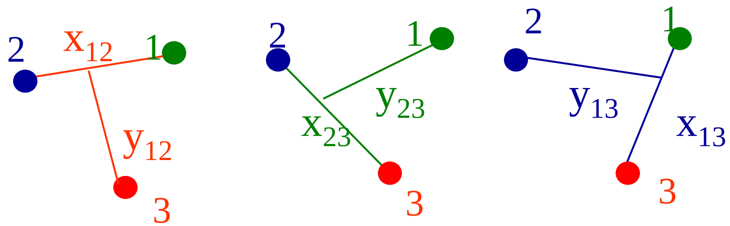
$$\begin{aligned}\left(E - H_0 - V_{ij}^{TC}\right)\psi_k^{+} &= V_{ij}^{TC}(\psi_i^{+} + \psi_j^{+}),\\ \left(E - H_0 - V_{ij}^{TC}\right)\psi_k^{-} &= V_{ij}^{TC}(\psi_i^{-} + \psi_j^{-}) + V_{ij}^{TP}(\psi_i^{+} + \psi_j^{+} + \psi_k^{+})\end{aligned}$$

- Define Faddeev component

$$F_{ij} = -G_0 V_{ij} \Psi$$

$F_{ij}=0$ then $V_{ij}=0$

$$\Psi(\vec{x},\vec{y}) = \sum_{i<j}^{3} F_{ij}(\vec{x}_{ij},\vec{y}_{ij})$$



- One gets system of Faddeev eq.

$$\begin{cases} \left(E - V_{12} - \widehat{H}_0\right) F_{12} = V_{12}(F_{23} + F_{13}) \\ \left(E - V_{23} - \widehat{H}_0\right) F_{23} = V_{23}(F_{12} + F_{23}) \\ \left(E - V_{13} - \widehat{H}_0\right) F_{13} = V_{13}(F_{23} + F_{12}) \end{cases}$$

- Partial wave decomposition

$$F_{ij}(\vec{x}_{ij},\vec{y}_{ij}) = \sum_{\alpha} \frac{f_\alpha(x_{ij},y_{ij})}{x_{ij}y_{ij}} \left| \left[\left(l_x s_x\right)_{j_x} s_k \right]_S l_y \right\rangle_{JM} \otimes \left| \left(t_i t_j\right)_{t_x} t_k \right\rangle_{TT_Z}$$

- Sum of free equations gives Schrödinger eq.

$$\left(E - V_{12} - V_{23} - V_{13} - \widehat{H}_0\right) \Psi \equiv 0$$

- To introduce 3-body interaction

$$W_{ijk} = W_{ij}^{3b} + W_{jk}^{3b} + W_{ki}^{3b}$$

$$V_{ij} \to V_{ij}^{2b} + W_{ij}^{3b}$$

courtesy of R. Lazauskas

n-d elastic scattering

TABLE IX. Coefficients J_n^π for AV18 and AV18 + UIX strong potentials and πEFT-I and πEFT-II parameter sets for parity-violating potentials. $J^\pi_{2,3,6,7,10,11,12} = 0$.

n	πEFT-I/AV18	πEFT-I/AV18 + UIX	πEFT-II/AV18	πEFT-II/AV18 + UIX
1	0.254	0.254	0.254	0.254
4	0.106×10^{-2}	0.352×10^{-3}	0.309×10^{-3}	0.333×10^{-4}
5	0.741×10^{-2}	0.512×10^{-2}	0.292×10^{-2}	0.221×10^{-2}
8	-0.276×10^{-2}	-0.212×10^{-2}	-0.127×10^{-2}	-0.100×10^{-2}
9	-0.148×10^{-3}	0.301×10^{-3}	-0.278×10^{-4}	0.168×10^{-3}
13	0.976×10^{-1}	0.981×10^{-1}	0.421×10^{-1}	0.423×10^{-1}
14	0.137×10^{-1}	0.136×10^{-1}	0.714×10^{-2}	0.712×10^{-2}
15	0.283	0.284	0.119	0.120

Y.-H., Song, R. Lazauskas, and V. G. (2011)

n-d -> t gamma

TABLE IX. PV observables for PV πEFT-I and πEFT-II potentials and the AV18 + UIX strong potential at $\Lambda = 600$ MeV.

n	πEFT-I			πEFT-II		
	$a_n^{\gamma(n)}$	$P_\gamma^{(n)}$	$A_d^{\gamma(n)}$	$a_n^{\gamma(n)}$	$P_\gamma^{(n)}$	$A_d^{\gamma(n)}$
1	0.0412	−0.106	−0.153	0.0210	−0.0562	−0.0820
4	−0.0108	0.0103	0.00700	−0.0689	0.0653	0.0434
5	−0.0114	0.0113	0.00812	−0.0644	0.0632	0.0446
6	−0.00362	0.00751	0.0100	−0.0209	0.0447	0.0603
8	0.0151	−0.0163	−0.0133	0.0918	−0.0983	−0.0793
9	0.0100	−0.0126	−0.0123	0.0497	−0.0625	−0.0604
13	0.00934	−0.0207	−0.0283	0.0490	−0.109	−0.149
14	0.00987	−0.0220	−0.0302	0.0271	−0.0836	−0.126
15	0.0170	−0.0379	−0.0518	0.110	−0.244	−0.333

Y.-H., Song, R. Lazauskas, and V. G. (2012)

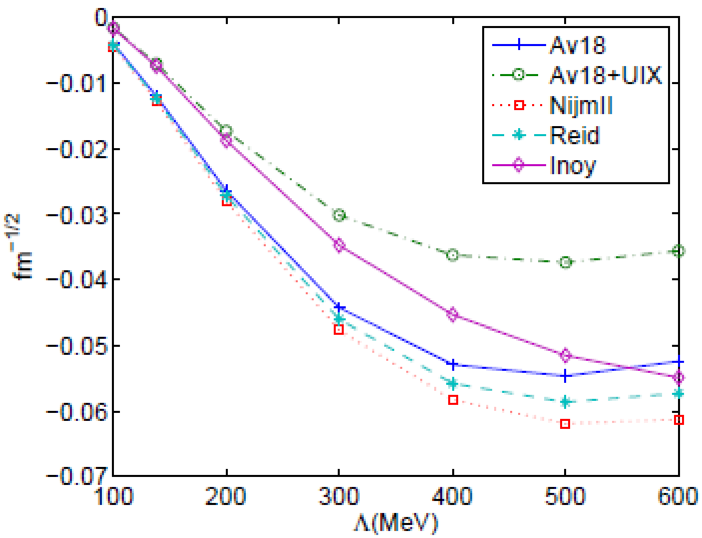
^{3}He and ^{3}H EDM

TABLE III. Contributions to $\frac{2}{\sqrt{6}}\langle\Psi||\hat{D}^{\rm pol}_{TP}||\Psi_{\not T\not P}\rangle$ for ^{3}He(^{3}H) EDMs from different terms of the meson exchange TRIV potential in 10^{-3} $e$fm units. We use the following values for strong couplings constants: $g_\pi = 13.07$, $g_\eta = 2.24$, $g_\rho = 2.75$, $g_\omega = 8.25$. A similar table can be inferred for the case of EFT with and without explicit pion, Table II.

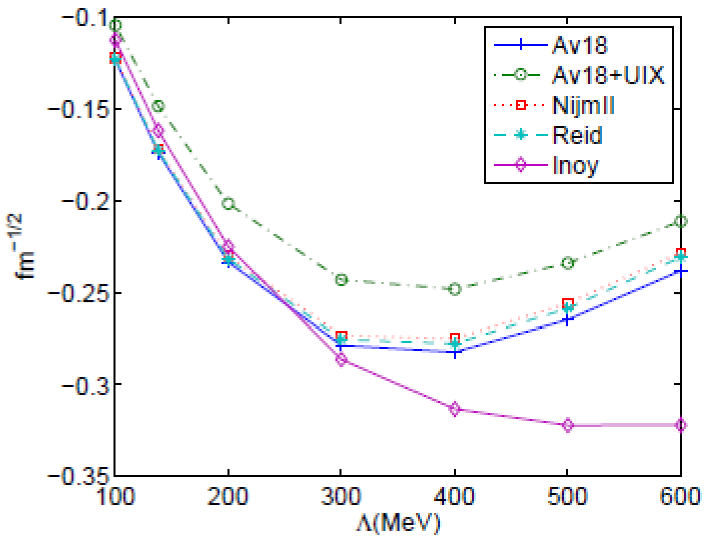
Couplings	AV18	Reid93	NijmII	AV18UIX	INOY	AV18 [21]
$\bar{g}^0_\pi$	77.2(−76.9)	79.5(−79.3)	80.0(−79.8)	71.9(−71.6)	134(−134)	157
$\bar{g}^1_\pi$	141(144)	143(145)	145(148)	138(141)	142(145)	288
$\bar{g}^2_\pi$	88.3(−91.8)	88.7(−91.6)	88.3(−91.3)	87.1(−90.1)	98.5(−102)	444
$\bar{g}^0_\rho$	−0.803(0.814)	−1.06(1.08)	−0.964(0.974)	−0.742(0.751)	−4.40(4.41)	−1.65
$\bar{g}^1_\rho$	1.20(1.21)	1.34(1.35)	1.49(1.50)	1.09(1.09)	2.36(2.37)	2.48
$\bar{g}^2_\rho$	−0.836(0.879)	−0.824(0.858)	−0.811(0.845)	−0.846(0.885)	−1.77(1.85)	4.13
$\bar{g}^0_\omega$	1.84(−1.85)	2.05(−2.06)	1.91(−1.91)	1.54(−1.54)	6.88(−6.91)	4.13
$\bar{g}^1_\omega$	−4.33(−4.46)	−4.74(−4.86)	−5.19(−5.32)	−4.27(−4.38)	−8.49(−8.71)	−9.08
$\bar{g}^0_\eta$	−1.28(1.28)	−1.36(1.36)	−1.31(1.31)	−1.07(1.07)	−3.43(3.45)	–
$\bar{g}^1_\eta$	2.40(2.41)	2.57(2.59)	2.75(2.77)	2.18(2.18)	3.48(3.50)	–

Y.-H., Song, R. Lazauskas, and V. G. (2013)

(a) The possible reason for the existing discrepancy in PV nuclear data analysis using the DDH approach (4)



(a)$\mu^2\widetilde{\mathcal{E}}_{\frac{3}{2}(+)}$ for operator 1



(b)$\mu^2\widetilde{\mathcal{E}}_{\frac{3}{2}(+)}$ for operator 9

Complex potential

$$u'' + K^2 u = 0$$

$$K^2 = \frac{2m}{\hbar^2}\left(E - V\right) = \frac{2m}{\hbar^2}\left(E - V_0\right) - i\frac{2m}{\hbar^2}W = k^2 - i\kappa^2$$

$$u \sim \exp[(\alpha + i\beta)x]$$

Then

$$\beta = \pm\frac{1}{\sqrt{2}}\left[k^2 + \sqrt{k^4 + \kappa^4}\right]$$

$$\alpha = \frac{\kappa^2}{\beta}$$

$$u \sim \exp[(\alpha + i\beta)x]$$

Then if $k \to 0$ or $k << \kappa$

$$\beta \to \pm \frac{\kappa}{\sqrt{2}}$$

$$\alpha \to \pm \frac{\kappa}{\sqrt{2}}$$

if $k = \kappa$

$$\beta \to \pm \sqrt{\frac{3}{2}} k$$

$$\alpha \to \pm \frac{k}{\sqrt{6}}$$

Reflection coefficient

$$|R|^2 = \frac{\alpha^2 + (k_0 - \beta)^2}{\alpha^2 + (k_0 + \beta)^2} = \frac{\kappa^4 + 2\beta^2 (k_0 - \beta)^2}{\kappa^4 + 2\beta^2 (k_0 + \beta)^2}$$

Then if $\kappa >> k, k_0$

$$|R|^2 \simeq \frac{\kappa^4 + 2\beta^4}{\kappa^4 + 2\beta^4} = 1$$

if $\kappa = k >> k_0$

$$|R|^2 \simeq \frac{\kappa^4 + 3\kappa^4}{\kappa^4 + 3\kappa^4} = 1$$

The larger absorption – the better reflection

Observations

- Forward scattering helps to “save” coherence

- Long-range N-antiN –interactions:
  – help to keep scattering as an elastic
  – suppress transitions inside nuclei

- Large absorption potential prevents antiN damping

Thank you!