Parity Violation in Nucleon-Deuteron Interactions

Jared Vanasse

Duke University

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	THEORY	EXPERIMENT
A Small	Theory for small nuclei $A < 4$ easier to calculate less nuclear physics modeling	Nuclei with $A < 4$ are difficult experimentally and require high precision
A Large	Large nuclei $A > 4$ harder to calculate require nuclear physics modeling	Certain larger nuclei possess enhanced parity-violating signals and are easier to measure

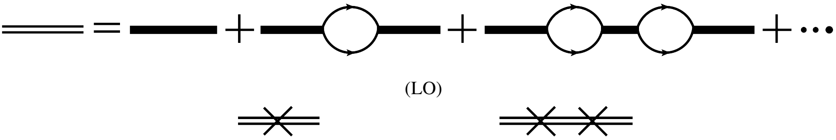
Lagrangian

The Lagrangian in $\mathrm{EFT}_{\not\pi}$ is

$$\mathcal{L} = \hat{N}^\dagger\left(i\partial_0 + \frac{\vec{\nabla}^2}{2M_N}\right)\hat{N} - \hat{t}_i^\dagger\left(i\partial_0 + \frac{\vec{\nabla}^2}{4M_N} - \Delta_{(-1)}^{(^3S_1)} - \Delta_{(0)}^{(^3S_1)}\right)\hat{t}_i$$
$$- \hat{s}_a^\dagger\left(i\partial_0 + \frac{\vec{\nabla}^2}{4M_N} - \Delta_{(-1)}^{(^1S_0)} - \Delta_{(0)}^{(^1S_0)}\right)\hat{s}_a + y_t\left[\hat{t}_i^\dagger\hat{N}^T P_i\hat{N} + H.c.\right]$$
$$+ y_s\left[\hat{s}_a^\dagger\hat{N}^T\bar{P}_a\hat{N} + H.c.\right].$$

The projector $P_i = \frac{1}{\sqrt{8}}\sigma_2\sigma_i\tau_2$ ($\bar{P}_a = \frac{1}{\sqrt{8}}\tau_a\tau_2\sigma_2$) projects out the spin-triplet iso-singlet (spin-singlet iso-triplet) combination of nucleons.

The LO dressed deuteron propagator is given by a bubble sum



(Z-parametrization) At LO coefficients are fit to reproduce the deuteron pole and at NLO to reproduce the residue about the deuteron pole.

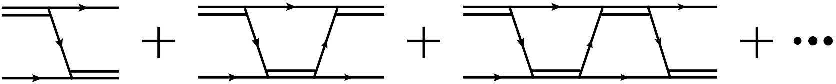
$$\frac{1}{y_t^2}=\frac{M_N^2}{8\pi\gamma_t}\frac{Z_t-1}{1+(Z_t-1)},\quad \Delta_{(-1)}^{(^3S_1)}=\frac{2y_t^2}{M_N}\frac{\gamma_t-\mu}{Z_t-1},\quad \Delta_{(0)}^{(^3S_1)}=\frac{\gamma_t^2}{M_N}$$

The spin-triplet ("deuteron") and spin-singlet dibaryon propagator to NLO in Z-parametrization are given by

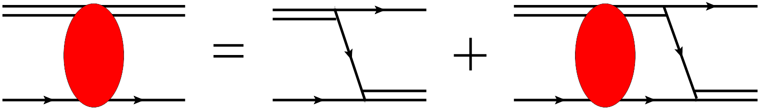
$$iD_{t,s}^{NLO}(p_0,\vec{\mathbf{p}}) = \frac{4\pi i}{M_N y_{t,s}^2}\frac{1}{\gamma_{t,s}-\sqrt{\frac{\vec{\mathbf{p}}^2}{4}-M_N p_0 - i\epsilon}}\times$$
$$\times\left[\underbrace{1}_{\text{LO}}+\underbrace{\frac{Z_{t,s}-1}{2\gamma_{t,s}}\left(\gamma_{t,s}+\sqrt{\frac{\vec{\mathbf{p}}^2}{4}-M_N p_0 - i\epsilon}\right)}_{\text{NLO}}+\cdots\right]$$

Quartet Channel (*nd* Scattering)

At LO in the quartet channel, *nd* scattering is given by an infinite sum of diagrams.



This infinite sum of diagrams can be represented by an integral equation.



Projecting spin and isospin in the quartet channel and projecting out in angular momentum gives

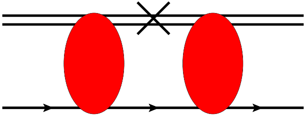
$$t^{\ell}_{0,q}(k,p) = -\frac{y_t^2 M_N}{pk} Q_\ell\left(\frac{p^2+k^2-M_N E-i\epsilon}{pk}\right) -$$
$$+\frac{2}{\pi}\int_0^\Lambda dq q^2 t^{\ell}_{0,q}(k,q)\frac{1}{\gamma_t-\sqrt{\frac{3\vec{\mathbf{q}}^2}{4}-M_N E-i\epsilon}}\frac{1}{qp}\times$$
$$Q_\ell\left(\frac{p^2+q^2-M_N E-i\epsilon}{pq}\right),$$

where

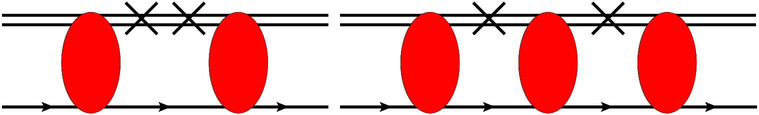
$$Q_\ell(a) = \frac{1}{2}\int_{-1}^{1} dx \frac{P_\ell(x)}{x+a}.$$

Higher Orders

NLO correction is



NNLO corrections are



Note the second diagram contains full off-shell scattering amplitude.

The NLO scattering amplitude is

$$t^{\ell}_{0,q}(k,p)+t^{\ell}_{1,q}(k,p)=B^{\ell}_{0}(k,p)+B^{\ell}_{1}(k,p)+ \\ +\left(K^{\ell}_{0}(q,p,E)+K^{\ell}_{1}(q,p,E)\right)\otimes\left(t^{\ell}_{0,q}(k,q)+t^{\ell}_{1,q}(k,q)\right),$$

where

$$A(q)\otimes B(q)=\frac{2}{\pi}\int_{0}^{\Lambda}dqq^{2}A(q)B(q).$$

The inhomogeneous and homogeneous terms are

$$B^{\ell}_{0}(k,p)=-\frac{y_t^2M_N}{pk}Q_{\ell}\left(\frac{p^2+k^2-M_NE-i\epsilon}{pk}\right),B^{\ell}_{1}(k,p)=0$$

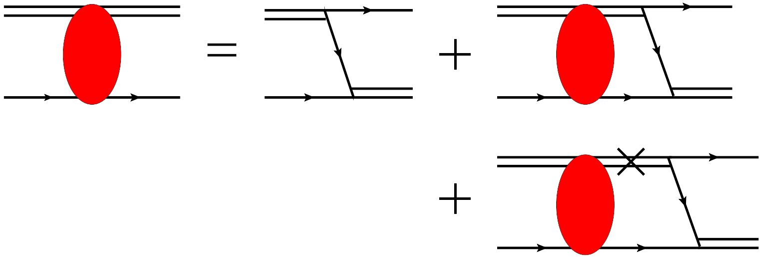
$$K^{\ell}_{n}(q,p,E)=-\frac{M_Ny_t^2}{4\pi}D^{(n)}_{t}\left(E-\frac{q^2}{2M_N},\vec{\mathbf{q}}\right)\frac{1}{qp}Q_{\ell}\left(\frac{q^2+p^2-M_NE-i\epsilon}{pq}\right)$$

Partial Resummation Technique

Denoting $t^{\ell}_{NLO} = t^{\ell}_{0,q} + t^{\ell}_{1,q}$, for the partial resummation technique one finds (Bedaque, Rupak, Grießhammer, and Hammer (2003))

$$t^{\ell}_{NLO}(k,p) = B^{\ell}_{0}(k,p) + B^{\ell}_{1}(k,p) + (K^{\ell}_{0}(q,p,E) + K^{\ell}_{1}(q,p,E)) \otimes t^{\ell}_{NLO}(k,q),$$

with the diagrammatic representation

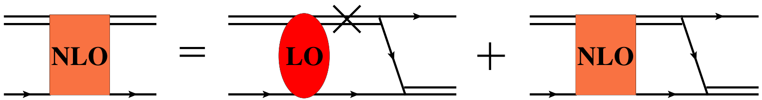


New Full Perturbative technique

Picking out only NLO pieces gives (Vanasse (2013))

$$t^{\ell}_{1,q}(k,p) = B^{\ell}_{1}(k,p) + K^{\ell}_{1}(q,p,E) \otimes t^{\ell}_{0,q}(k,q) + K^{\ell}_{0}(q,p,E) \otimes t^{\ell}_{1,q}(k,q).$$

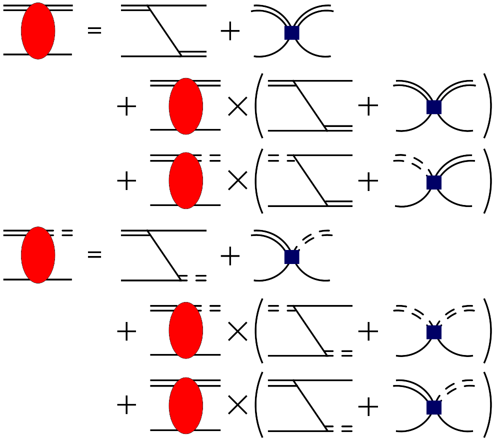
Terms are reshuffled to inhomogeneous term. Kernel at each order is the same. Diagrammatically NLO correction is now given by



Note all corrections are half off-shell.

Doublet Channel *nd* scattering

At LO in the doublet channel, *nd* scattering is given by a coupled set of integral equations



Using the perturbative technique, the doublet *nd* scattering amplitude integral equation at LO is

$$\mathbf{t}_{0,d}^{\ell}(k,p)=\mathbf{B}_{0}^{\ell}(k,p)+\mathbf{K}_{0}^{\ell}(q,p,E)\otimes\mathbf{t}_{0,d}^{\ell}(k,q),$$

and at NLO

$$\mathbf{t}_{1,d}^{\ell}(k,p)=\mathbf{B}_{1}^{\ell}(k,p)+\mathbf{K}_{1}^{\ell}(q,p,E)\otimes\mathbf{t}_{0,d}^{\ell}(k,q)+\mathbf{K}_{0}^{\ell}(q,p,E)\otimes\mathbf{t}_{1,d}^{\ell}(k,q).$$

The Equations are the same as in quartet case but are now matrix equations in cluster configuration space (Grießhammer (2004)).

The vector $\vec{\mathbf{t}}^{\ell}_{n,d}(k,q)$ is

$$\mathbf{t}^{\ell}_{n,d}(k,q)=\left(\begin{array}{c} t^{\ell}_{n,Nt\to Nt}(k,q) \\ t^{\ell}_{n,Nt\to Ns}(k,q) \end{array}\right).$$

The inhomogeneous term is

$$\mathbf{B}^{\ell}_{0}(k,p)=\left(\begin{array}{c} \frac{y_t^2 M_N}{pk}Q_\ell\left(\frac{p^2+k^2-M_NE-i\epsilon}{pk}\right)+\mathcal{H}_0(E,\Lambda)\delta_{\ell 0} \\ -\frac{3y_ty_sM_N}{pk}Q_\ell\left(\frac{p^2+k^2-M_NE-i\epsilon}{pk}\right)-\mathcal{H}_0(E,\Lambda)\delta_{\ell 0} \end{array}\right)$$

$$\mathbf{B}^{\ell}_{1}(k,p)=\left(\begin{array}{c} \mathcal{H}_1(E,\Lambda)\delta_{\ell 0} \\ -\mathcal{H}_1(E,\Lambda)\delta_{\ell 0} \end{array}\right)$$

The homogeneous term is

$$\mathbf{K}_n^{\ell}(q,p,E) = \mathbf{D}^{(n)}(E,\vec{\mathbf{q}})\frac{1}{qp}Q_{\ell}\left(\frac{q^2+p^2-M_NE-i\epsilon}{qp}\right)\begin{pmatrix} 1 & -3 \\ -3 & 1 \end{pmatrix} + \delta_{\ell 0}\sum_{j=0}^{n}\mathbf{D}^{(j)}(E,\vec{\mathbf{q}})\mathcal{H}_{n-j}(E,\Lambda)\begin{pmatrix} 1 & -1 \\ -1 & 1 \end{pmatrix},$$

where

$$\mathbf{D}^{n}(E,\vec{\mathbf{q}}) = \begin{pmatrix} D_t^{(n)}(E-\frac{q^2}{2M_N},\vec{\mathbf{q}}) & 0 \\ 0 & D_s^{(n)}(E-\frac{q^2}{2M_N},\vec{\mathbf{q}}) \end{pmatrix},$$

and the three-body force terms defined by

$$\mathcal{H}(E,\Lambda) = \frac{2H_0^{LO}(\Lambda)}{\Lambda^2} + \frac{2H_0^{NLO}(\Lambda)}{\Lambda^2}.$$

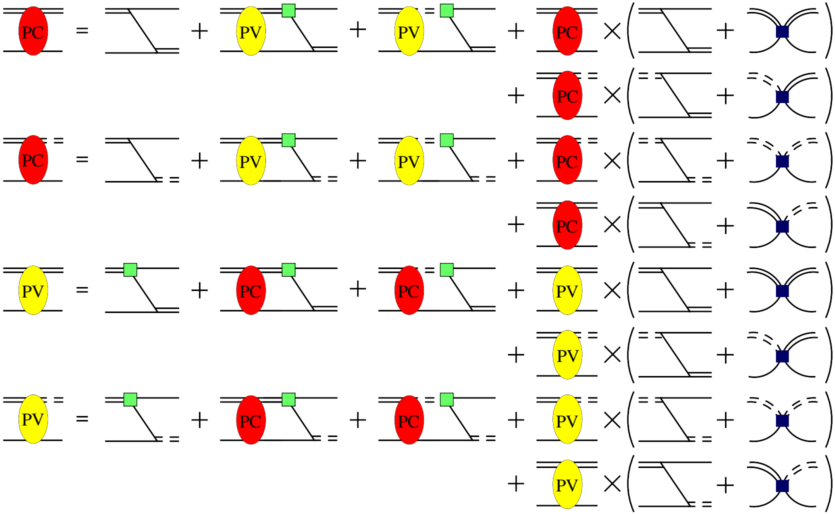
Two-Body Parity Violation

The LO PV Lagrangian in $\mathrm{EFT}_{\not{\pi}}$ has five LEC's

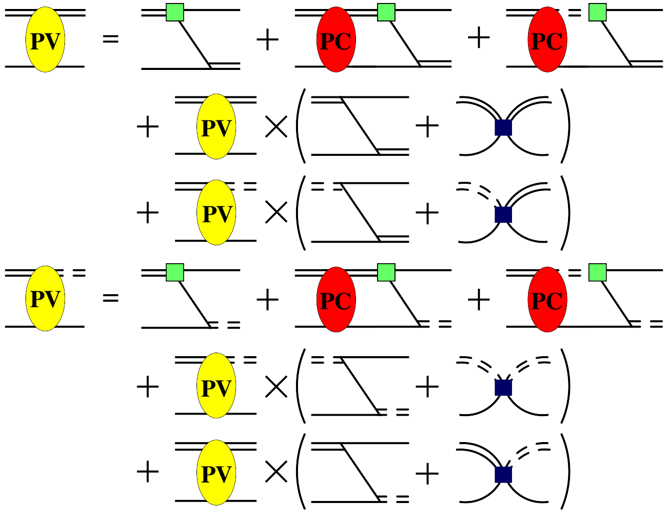
$$\begin{aligned}\mathcal{L}_{PV} = -\Big[& g^{(^3S_1-^1P_1)} t_i^\dagger \left(N^t \sigma_2\tau_2 i \overleftrightarrow{\nabla}_i N\right) \\ & + g^{(^1S_0-^3P_0)}_{(\Delta I=0)} s_a^\dagger \left(N^T \sigma_2 \vec{\boldsymbol{\sigma}}\cdot\tau_2\tau_a i \overleftrightarrow{\nabla} N\right) \\ & + g^{(^1S_0-^3P_0)}_{(\Delta I=1)} \epsilon^{3ab} (s^a)^\dagger \left(N^T \sigma_2 \vec{\boldsymbol{\sigma}}\cdot\tau_2\tau^b \overleftrightarrow{\nabla} N\right) \\ & + g^{(^1S_0-^3P_0)}_{(\Delta I=2)} \mathcal{I}^{ab} (s^a)^\dagger \left(N^T \sigma_2 \vec{\boldsymbol{\sigma}}\cdot\tau_2\tau^b i \overleftrightarrow{\nabla} N\right) \\ & + g^{(^3S_1-^3P_1)} \epsilon^{ijk} (t_i)^\dagger \left(N^T \sigma_2\sigma^k \tau_2\tau_3 \overleftrightarrow{\nabla}^j N\right)\Big] + h.c.,\end{aligned}$$

where $\mathcal{I}^{ab} = diag(1,1,-2)$ and $a \overleftrightarrow{\nabla} b = a(\overrightarrow{\nabla} b) - (\overrightarrow{\nabla} a)b$. Contains all possible $S \to P$ transition operators and isospin structures

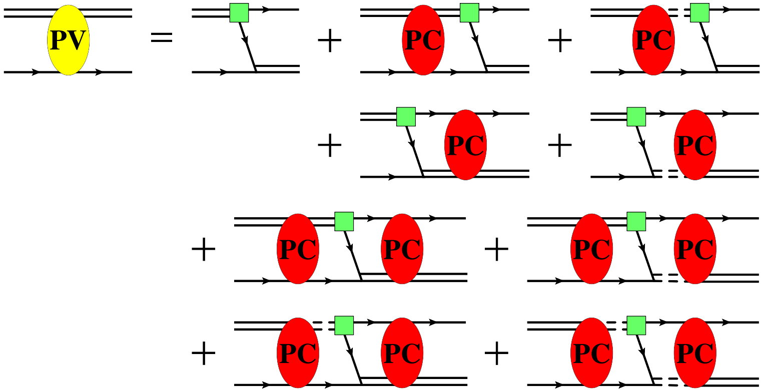
Parity-violation at LO is given by set of coupled integral equations



Dropping terms second order in PV, the above coupled integral equations decouple and one finds



The integral equation gives the sum of diagrams



The sum of all diagrams gives the amplitude

$$(t_{PV}^{xw})_{\alpha a}^{\beta b}(\vec{\mathbf{k}},\vec{\mathbf{p}})=\frac{4M_N}{\sqrt{8}}\mathbf{v}_p^T\,(\mathcal{K}^{xw})_{\alpha a}^{\beta b}(\vec{\mathbf{k}},\vec{\mathbf{p}})\mathbf{v}_p$$

$$-\frac{4M_N}{\sqrt{8}}\int\frac{d^3q}{(2\pi)^3}\mathbf{v}_p^T(\mathcal{K}^{xy})_{\gamma c}^{\beta b}(\vec{\mathbf{q}},\vec{\mathbf{p}})\mathbf{D}\left(E-\frac{\vec{\mathbf{q}}^2}{2M_N},\vec{\mathbf{q}}\right)\left((\mathbf{t}^{yw})_{\alpha a}^{\gamma c}(\vec{\mathbf{k}},\vec{\mathbf{q}})\right)$$

$$-\frac{4M_N}{\sqrt{8}}\int\frac{d^3q}{(2\pi)^3}\left((\mathbf{t}^{xy})_{\gamma c}^{\beta b}(\vec{\mathbf{q}},\vec{\mathbf{p}})\right)^T\mathbf{D}\left(E-\frac{\vec{\mathbf{q}}^2}{2M_N},\vec{\mathbf{q}}\right)(\mathcal{K}^{yw})_{\alpha a}^{\gamma c}(\vec{\mathbf{k}},\vec{\mathbf{q}})\mathbf{v}_p$$

$$+\frac{4M_N}{\sqrt{8}}\int\frac{d^3q}{(2\pi)^3}\int\frac{d^3\ell}{(2\pi)^3}\left((\mathbf{t}^{xz})_{\delta d}^{\beta b}(\vec{\ell},\vec{\mathbf{p}},)\right)^T\mathbf{D}\left(E-\frac{\vec{\mathbf{q}}^2}{2M_N},\vec{\mathbf{q}}\right)$$

$$(\mathcal{K}^{zy})_{\gamma c}^{\delta d}(\vec{\mathbf{q}},\vec{\ell})\mathbf{D}\left(E-\frac{\vec{\ell}^2}{2M_N},\vec{\ell}\right)\left((\mathbf{t}^{yw})_{\alpha a}^{\gamma c}(\vec{\mathbf{k}},\vec{\mathbf{q}})\right)$$

where

$$\mathbf{v}_p=\begin{pmatrix}1\\0\end{pmatrix}.$$

All angular dependence is contained in

$$(\mathcal{K}^{xw})_{\alpha a}^{\beta b}(\vec{\mathbf{q}},\vec{\boldsymbol{\ell}}) = \frac{1}{\vec{\mathbf{q}}^2+\vec{\mathbf{q}}\cdot\vec{\boldsymbol{\ell}}+\vec{\boldsymbol{\ell}}^2-M_N E-i\epsilon}\times$$
$$\times\begin{pmatrix} \left(\mathcal{K}_{PV}^{11}{}^{xw}\right)_{\alpha a}^{\beta b}(\vec{\mathbf{q}},\vec{\boldsymbol{\ell}}) & \left(\mathcal{K}_{PV}^{12}{}^{xw}\right)_{\alpha a}^{\beta b}(\vec{\mathbf{q}},\vec{\boldsymbol{\ell}}) \\ \left(\mathcal{K}_{PV}^{21}{}^{xw}\right)_{\alpha a}^{\beta b}(\vec{\mathbf{q}},\vec{\boldsymbol{\ell}}) & \left(\mathcal{K}_{PV}^{22}{}^{xw}\right)_{\alpha a}^{\beta b}(\vec{\mathbf{q}},\vec{\boldsymbol{\ell}}) \end{pmatrix}$$

where

$$\begin{aligned}\left(\mathcal{K}_{PV}^{11}{}^{xw}\right)_{\alpha a}^{\beta b}(\vec{\mathbf{k}},\vec{\mathbf{p}}) = {} & y_t g^{{}^3S_1-{}^1P_1}(\sigma^x)_\alpha^\beta\delta_a^b(\vec{\mathbf{k}}+2\vec{\mathbf{p}})^w \\ & + i y_t g^{{}^3S_1-{}^3P_1}\epsilon^{w\ell y}(\sigma^y\sigma^x)_\alpha^\beta(\tau_3)_a^b(\vec{\mathbf{k}}+2\vec{\mathbf{p}})^\ell \\ & + y_t g^{{}^3S_1-{}^1P_1}(\sigma^w)_\alpha^\beta\delta_a^b(2\vec{\mathbf{k}}+\vec{\mathbf{p}})^x \\ & - i y_t g^{{}^3S_1-{}^3P_1}\epsilon^{x\ell y}(\sigma^w\sigma^y)_\alpha^\beta(\tau_3)_a^b(2\vec{\mathbf{k}}+\vec{\mathbf{p}})^\ell\end{aligned}$$

The amplitude can be projected in partial waves of $\vec{\mathbf{J}} = \vec{\mathbf{L}} + \vec{\mathbf{S}}$

$$t_{PV}{}^{JM}_{L'S',LS}(k,p) = \frac{1}{4\pi}\int d\Omega_k \int d\Omega_p \left(\mathscr{Y}^M_{J,L'S'}(\hat{\mathbf{p}})\right)^* t_{PV}(\vec{\mathbf{k}},\vec{\mathbf{p}})\mathscr{Y}^M_{J,LS}(\hat{\mathbf{k}}).$$

The projected amplitude is

$$\begin{aligned}
t_{PV}{}^{JM}_{L'S',LS}(k,p) &= \frac{M_N}{\sqrt{8\pi}}\mathbf{v}_p^T\mathcal{K}(k,p)^J_{L'S',LS}\mathbf{v}_p + \\
&-\frac{M_N}{2\sqrt{8\pi^3}}\int_0^\infty dqq^2\mathbf{v}_p^T\mathcal{K}(q,p)^J_{L'S',LS}\mathbf{D}\left(E-\frac{q^2}{2M_N},\vec{\mathbf{q}}\right)\left(t_{PC}{}^{JM}_{LS,LS}(k,q)\right)\\
&-\frac{M_N}{2\sqrt{8\pi^3}}\int_0^\infty dqq^2\left(t_{PC}{}^{JM}_{L'S',L'S'}(q,p)\right)^T\mathbf{D}\left(E-\frac{q^2}{2M_N},\vec{\mathbf{q}}\right)\mathcal{K}(k,q)^J_{L'S',LS}\mathbf{v}_p\\
&+\frac{M_N}{4\sqrt{8\pi^5}}\int_0^\infty dqq^2\int_0^\infty d\ell\ell^2\left(t_{PC}{}^{JM}_{L'S',L'S'}(p,\ell)\right)^T\mathbf{D}\left(E-\frac{q^2}{2M_N},\vec{\mathbf{q}}\right)\\
&\quad\mathcal{K}(q,\ell)^{JM}_{L'S',LS}\mathbf{D}\left(E-\frac{\ell^2}{2M_N},\vec{\boldsymbol{\ell}}\right)\left(t_{PC}{}^{JM}_{LS,LS}(k,q)\right)
\end{aligned}$$

One term of projected $\mathcal{K}(k,p)^{JM}_{L'S',LS}$ is given by

$$\left[\mathcal{K}(k,p)^{J}_{L'S',LS}\right]_{22} = -y_t\left(3g^{{}^1S_0-{}^3P_0}_{(\Delta I=0)} - 2g^{{}^1S_0-{}^3P_0}_{(\Delta I=1)}\right)4\pi\sqrt{6}(-1)^{1/2-L-J}\delta_{S1/2}\delta_{S'1/2}\sqrt{\bar{L'}}$$
$$\times\, C^{0,0,0}_{L',1,L}\left\{\begin{array}{ccc} L' & 1 & L \\ S & J & S' \end{array}\right\}\frac{1}{kp}(kQ_{L'}(a)+pQ_L(a))$$

where

$$\bar{x} = 2x+1$$

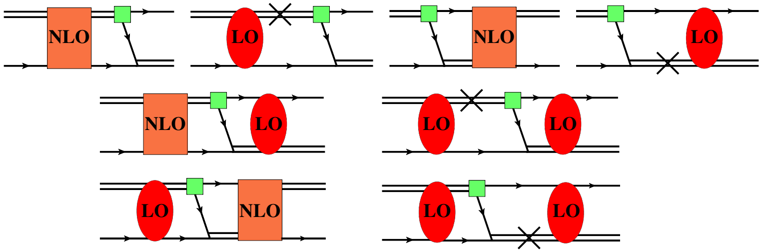
and

$$a = \frac{k^2+p^2-M_NE-i\epsilon}{kp}$$

All Projections given in (Vanasse (2012)). Agree with S to P projections in (Grießhammer, Schindler, and Springer (2012)).

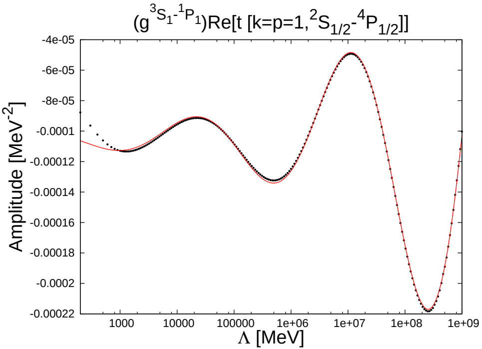
NLO 3-Body PV

NLO PV amplitude is given by type of diagrams below. NLO box is the half off shell NLO amplitude.



(Note not all diagrams given here)
As shown by (Schindler and Grießhammer (2010)) no NLO PV three-body force for *Nd* scattering should exist.

Cutoff dependence seems to suggest three-body PV not properly renormalized at NLO. New PV 3-Body force?



Cutoff dependence roughly given by

$$C\Lambda^{.2166\ldots}\sin\left(s_0\log\left(\frac{\Lambda}{\Lambda^*}\right)\right)+b$$

The asymptotic solution of the LO PC quartet P-wave is

$$t_{0,q}^{\ell=1}(q) = Bq^{-2.78334\ldots}$$

Wigner basis for amplitudes is

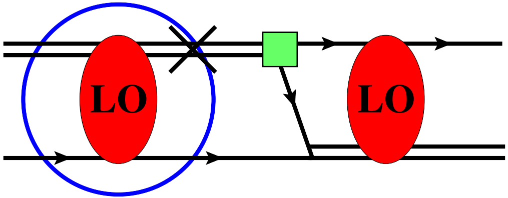
$$t_{+}(k,p) = t_{Nt\to Nt}(k,p) + t_{Nt\to Ns}(k,p)$$

$$t_{-}(k,p) = t_{Nt\to Nt}(k,p) - t_{Nt\to Ns}(k,p)$$

The asymptotic solution to the LO PC doublet S-wave is

$$t_{+}^{{}^2S_{1/2}-{}^2S_{1/2}}(q) = C\frac{\sin\left(s_0\ln\left(\frac{q}{\Lambda^*}\right)\right)}{q} + \cdots$$

Using dimensional analysis one can guess the asymptotic scaling of PV amplitude for ${}^2S_{1/2} - {}^4P_{1/2}$



$$\frac{\sin\left(s_0 \ln\left(\frac{q}{\Lambda^*}\right)\right)}{q}$$

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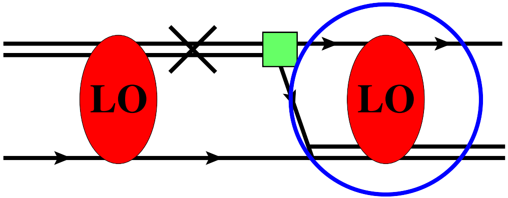

$$\frac{\sin\left(s_0 \ln\left(\frac{q}{\Lambda^*}\right)\right)}{q} q^{-2.78334}$$

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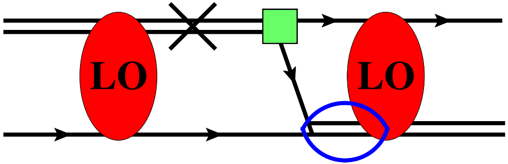
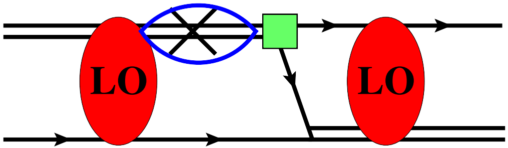


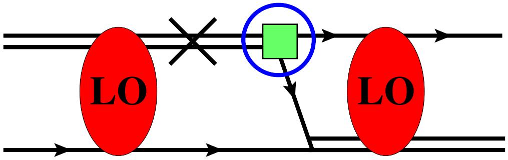
$$\frac{\sin\left(s_0 \ln\left(\frac{q}{\Lambda^*}\right)\right)}{q} q^{-2.78334} \frac{1}{q}$$

Using dimensional analysis one can guess the asymptotic scaling of PV amplitude for ${}^2S_{1/2} - {}^4P_{1/2}$



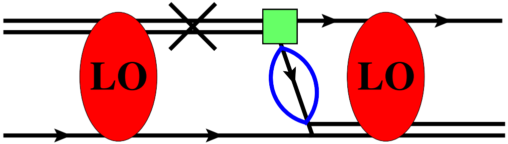
$$\frac{\sin\left(s_0 \ln\left(\frac{q}{\Lambda^*}\right)\right)}{q} q^{-2.78334} \frac{1}{q} q^0$$

Using dimensional analysis one can guess the asymptotic scaling of PV amplitude for ${}^2S_{1/2} - {}^4P_{1/2}$



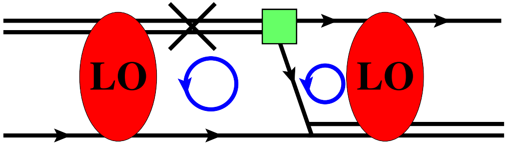
$$\frac{\sin\left(s_0 \ln\left(\frac{q}{\Lambda^*}\right)\right)}{q} q^{-2.78334} \frac{1}{q} q^0 q$$

Using dimensional analysis one can guess the asymptotic scaling of PV amplitude for ${}^2S_{1/2} - {}^4P_{1/2}$



$$\frac{\sin\left(s_0 \ln\left(\frac{q}{\Lambda^*}\right)\right)}{q} q^{-2.78334} \frac{1}{q} q^0 q \frac{1}{q^2}$$

Using dimensional analysis one can guess the asymptotic scaling of PV amplitude for ${}^2S_{1/2} - {}^4P_{1/2}$



$$\frac{\sin\left(s_0 \ln\left(\frac{q}{\Lambda^*}\right)\right)}{q} q^{-2.78334} \frac{1}{q} q^0 q \frac{1}{q^2} q^6$$

Finally one finds

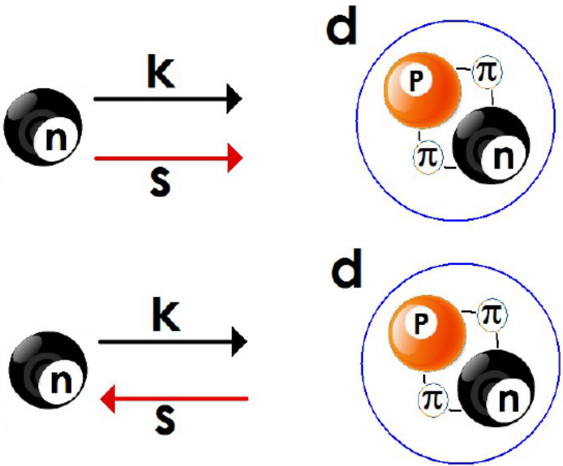
$$\frac{\sin\left(s_0\ln\left(\frac{q}{\Lambda^*}\right)\right)}{q}q^{-2.78334}\frac{1}{q}q^0q\frac{1}{q^2}q^6=\sin\left(s_0\ln\left(\frac{q}{\Lambda^*}\right)\right)\frac{q^7}{q^{6.78334}}$$
$$=q^{.2166}\sin\left(s_0\ln\left(\frac{q}{\Lambda^*}\right)\right),$$

which gives fitted numerical form of

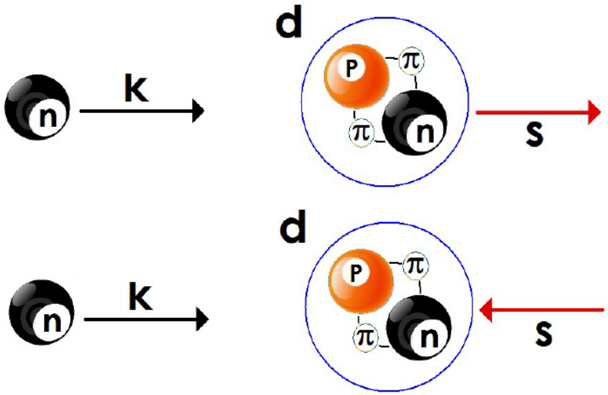
$$C\Lambda^{.2166\ldots}\sin\left(s_0\log\left(\frac{\Lambda}{\Lambda^*}\right)\right)+b.$$

Asymptotic analysis must be carried out more carefully.

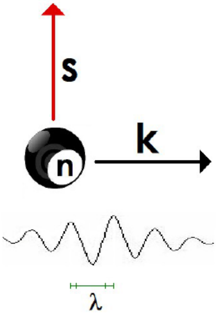
Longitudinal Beam Asymmetry

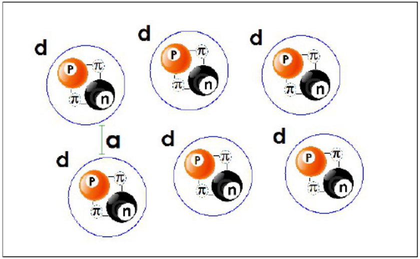


Longitudinal Target Asymmetry



Neutron Spin Rotation on Deuteron Target





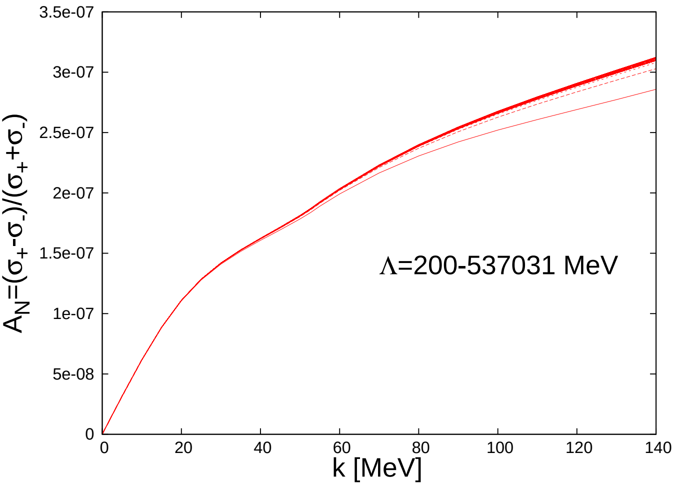
Observables are given by

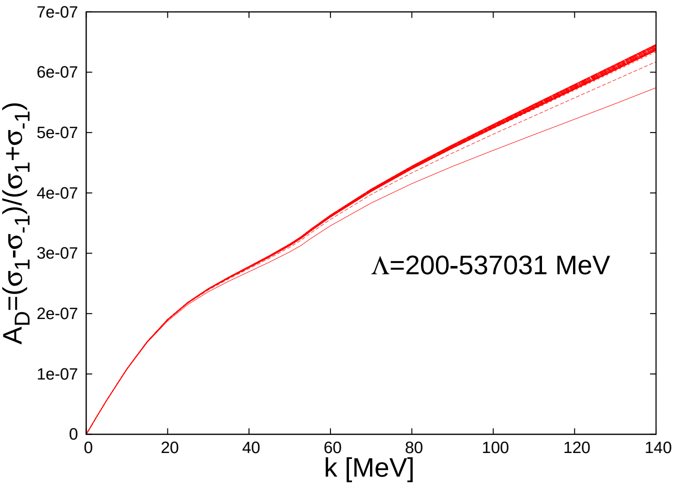
$$A_N = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \qquad A_D = \frac{\sigma_1 - \sigma_{-1}}{\sigma_1 + \sigma_{-1}}$$

$$\frac{d\phi}{dz} = -\frac{4M_N N}{27k}\mathrm{Re}\left[M^{1/2}_{1\,1/2,0\,1/2} + 2\sqrt{2}M^{1/2}_{1\,3/2,0\,1/2} - 4M^{3/2}_{1\,1/2,0\,3/2} - 2\sqrt{5}M^{3/2}_{1\,3/2,0\,3/2}\right]$$

with partial wave amplitudes defined by

$$M_{m_1',m_2';m_1,m_2} = \sqrt{4\pi}\sum_{J}\sum_{L,L'}\sum_{S,S'}\sum_{m_s,m_S'}\sum_{m_L'}\sqrt{2L+1}\,C^{m_1,m_2,m_S}_{1,1/2,S}$$
$$C^{m_1',m_2',m_S'}_{1,1/2,S'}C^{0,m_S,M}_{L,S,J}C^{m_L',m_S',M}_{L',S',J}Y^{m_L'}_{L'}(\theta,\phi)M^J_{L'S',LS}$$


3.5e-07
3e-07
2.5e-07
2e-07
1.5e-07
1e-07
5e-08
0
0
20
40
60
80
100
120
140
k [MeV]
$A_N=(\sigma_+-\sigma_-)/(\sigma_++\sigma_-)$
Λ=200-537031 MeV


7e-07
6e-07
5e-07
4e-07
3e-07
2e-07
1e-07
0
0
20
40
60
80
100
120
140
k [MeV]
$A_D=(\sigma_1-\sigma_{-1})/(\sigma_1+\sigma_{-1})$
Λ=200-537031 MeV

Spin rotation prediction in LO $\mathrm{EFT}_{\not{\pi}}$ is $1.8 \times 10^{-8}\ \mathrm{rad\ cm}^{-1}$, cutoff variation minimal

Table: Comparison of EFT calculations for spin rotation $\frac{1}{\rho}\frac{d\phi}{dz}$.

Coefficient	LO [rad $\mathrm{MeV}^{-1/2}$]	NLO [rad $\mathrm{MeV}^{-1/2}$]
$g^{{}^3S_1-{}^1P_1}$	10.4-10.7	7.2-7.8
$g^{{}^3S_1-{}^3P_1}$	20.1 - 21.1	15.3-18.7
$3g^{{}^1S_0-{}^3P_0}_{(\Delta I=0)} - 2g^{{}^1S_0-{}^3P_0}_{(\Delta I=1)}$	1.9-3.1	1.8-2.8

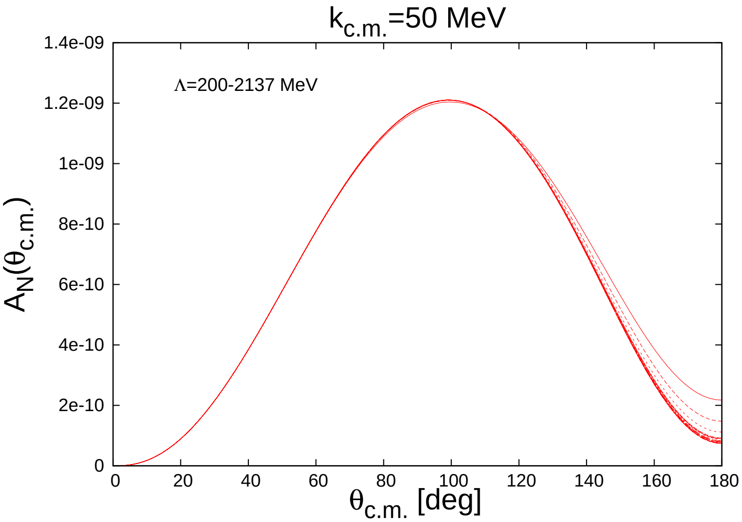
LO EFT calculation (Vanasse (2012)), NLO EFT calculation (Grießhammer, Schindler, and Springer (2012)) using partial resummation technique.

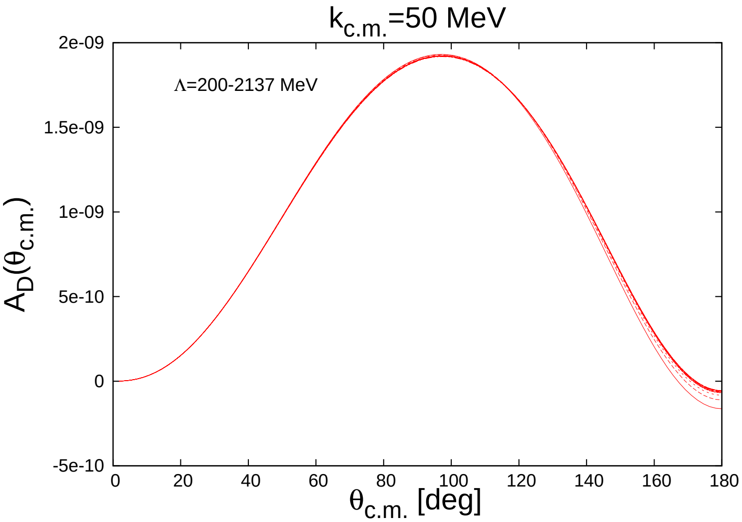
Amplitude including Coulomb effects is given by

$$\begin{aligned}M_{m_1',m_2';m_1,m_2} =& f_C(\theta)\delta_{m_2,m_2'}\delta_{m_1,m_1'}\\ &+\sqrt{4\pi}\sum_{J}\sum_{L,L'}\sum_{S,S'}\sum_{m_s,m_S'}\sum_{m_L'}\sqrt{2L+1}\,C_{1,1/2,S}^{m_1,m_2,m_S}\\ &C_{1,1/2,S'}^{m_1',m_2',m_S'}C_{L,S,J}^{0,m_S,M}C_{L',S',J}^{m_L',m_S',M}Y_{L'}^{m_L'}(\theta,\phi)M_{L'S',LS}^{J(sub)}\end{aligned}$$

where

$$M_{L'S',LS}^{J(sub)} = M_{L'S',LS}^{J}(Strong+Coulomb) - M_{L'S',LS}^{J}(Coulomb)$$


k_c.m.=50 MeV
Λ=200-2137 MeV
A_N(θ_c.m.)
θ_c.m. [deg]
1.4e-09
1.2e-09
1e-09
8e-10
6e-10
4e-10
2e-10
0
0
20
40
60
80
100
120
140
160
180


$k_{c.m.}$=50 MeV
Λ=200-2137 MeV
$A_D(\theta_{c.m.})$
$\theta_{c.m.}$ [deg]
2e-09
1.5e-09
1e-09
5e-10
0
-5e-10
0
20
40
60
80
100
120
140
160
180

Conclusions and Future Directions

- Any PV observable of interest can be calculated for nd scattering at LO in $\mathrm{EFT}_{\not{\pi}}$.
- Possible signal of PV three-body force needed at NLO. (Unfortunate)
- pd scattering via nd scattering with isospin changes and Coulomb added.
- Coulomb needs to be included in both the scattering amplitudes and corrections to two-body PV vertex.
- New perturbative technique can be used with external currents making calculations of PV in $nd \rightarrow {}^3H + \gamma$ and $pd \rightarrow {}^3He + \gamma$ feasible.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