Charge Symmetry Breaking in $pn \rightarrow d\pi^0$

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In collaboration with V. Baru, E. Epelbaum, J. Haidenbauer, C. Hanhart, A. Kudryavtsev and U.-G. Meißner

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Introduction

- Charge symmetry
  - Invariance under u and d quarks exchange – approximate symmetry of QCD
  - Explicitly broken by quark mass difference and electromagnetic effects

- Charge symmetry breaking (CSB) has numerous manifestations.
  We consider following two:
  - Neutron-proton mass difference:

$$\delta m_N = m_n - m_p = \delta m_N^{\mathrm{str}} + \delta m_N^{\mathrm{em}} = 1.293\,\mathrm{MeV}$$

  - Cross section asymmetry in $pn \to d\pi^0$
    $\delta m_N^{\mathrm{str}}$ and δm_N^{em} contribute **independently**

Our goal:
Study CSB in $pn \to d\pi^0$ to extract individual contributions $\delta m_N^{\mathrm{str}}$ and δm_N^{em} which provide important connection to other low energy processes through the chiral symmetry.

CSB Observation in pn → dπ^0

- Differential cross section expanded in Legendre polynomials

$$\frac{d\sigma}{d\Omega}(\theta) = A_0 + A_1 P_1(\cos\theta) + A_2 P_2(\cos\theta) + \cdots$$

$$\sigma = 4\pi A_0$$

- If charge symmetry is exact the differential cross section of pn → dπ^0 is symmetric about θ=90° in CM frame (i.e. $A_1 \equiv 0$)

- Any asymmetry ($A_1 \neq 0$) is due to CSB effects
- Experimentally observed value is forward-backward asymmetry $A_{\rm fb}$

$$A_{\rm fb} = \frac{A_1}{2A_0}$$

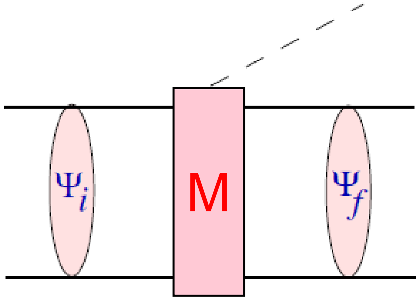
$$A_{\rm fb}^{\rm exp} = [17 \pm 8({\rm sys.}) \pm 5.5({\rm stat.})] \times 10^{-4}$$

Kinetic energy of incident neutron $T_{\rm Lab} = 279.5\ {\rm MeV}$

Excess energy $\approx 2\ {\rm MeV}$

Opper et al. (2003)
TRIUMF

Effective Field Theory of NN→NNπ



M is perturbative

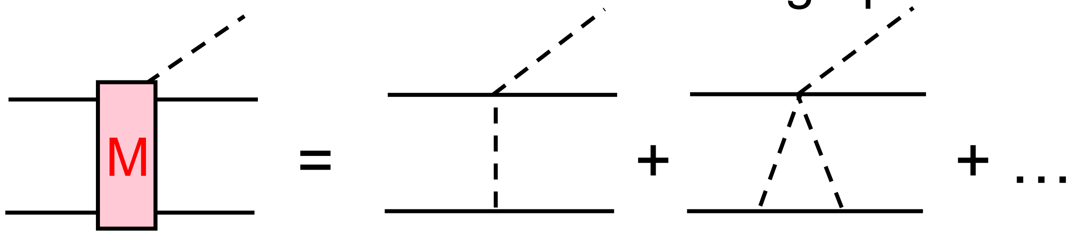
$\Psi_{i/f}$ are treated non–perturbatively

Hybrid approach Weinberg (1992)

1. Calculate transition (production) operator M
2. Convolute with non-perturbative NN wave functions

Production operator M

- Chiral perturbation theory is used to calculate M
- Expansion of M consists of **irreducible** graphs



- Special power counting for NN→NNπ due to large transferred momentum

$$p \sim \sqrt{M_\pi m_N} \gg M_\pi$$

Cohen et al. (1996); Hanhart et al. (2000)

- Expansion parameter: $\chi = \dfrac{p}{\Lambda_{\rm ChPT}} \sim \sqrt{\dfrac{M_\pi}{m_N}}$ $\qquad \Lambda_{\rm ChPT} \sim m_N \sim 1\ \mathrm{GeV}$

Leading Order CSB Effects in pn → dπ⁰

Near threshold there are two nonzero contributions to A_1:

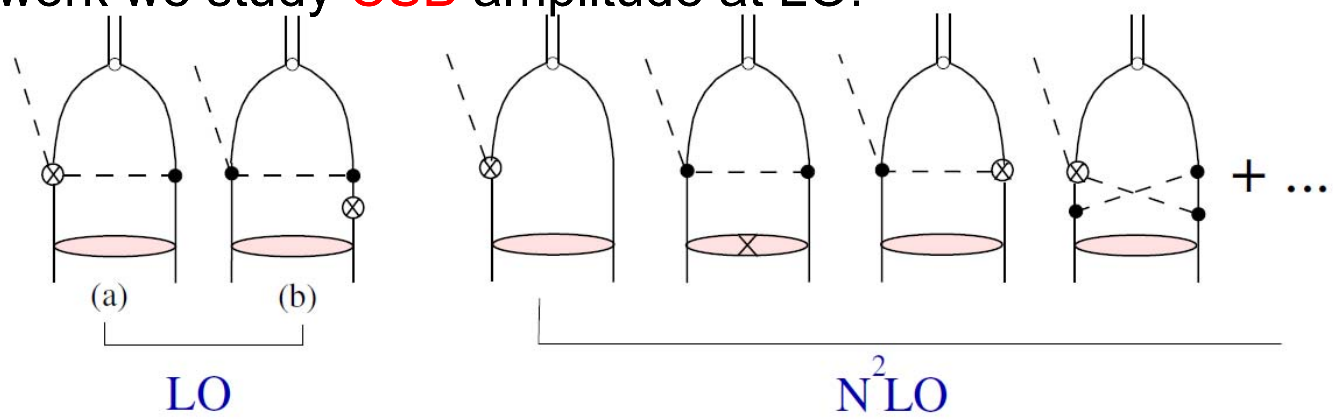
$$A_1 \propto \underbrace{M_{\mathrm{IC}}^{p\text{-wave}} \times M_{\mathrm{CSB}}^{s\text{-wave}}}_{\mathrm{LO}} + \underbrace{M_{\mathrm{CSB}}^{p\text{-wave}} \times M_{\mathrm{IC}}^{s\text{-wave}}}_{\mathrm{N^2LO}}$$

At leading order only first type should be considered:

$$A_1 \propto \mathrm{Re}\left[\left(M_{\mathrm{IC}}^{1S0\to 3S1,p} + \frac{2}{3} M_{\mathrm{IC}}^{1D2\to 3S1,p}\right) \times M_{\mathrm{CSB}}^{1P1\to 3S1,s^*}\right]$$

Isospin conserving (IC) amplitudes calculated up to and including N²LO
by Baru, Epelbaum, Haidenbauer, Hanhart, Kudryavtsev, Lensky, Meißner (2009)
See talk by V. Baru

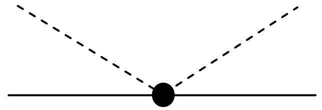
In this work we study CSB amplitude at LO:



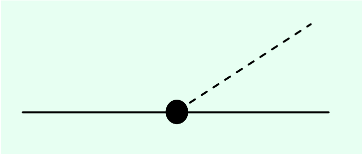
No NLO contributions

Leading Order CSB Amplitude

Effective chiral Lagrangian at LO



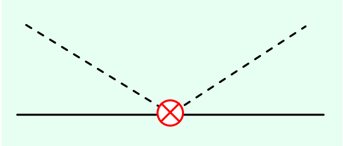
WT



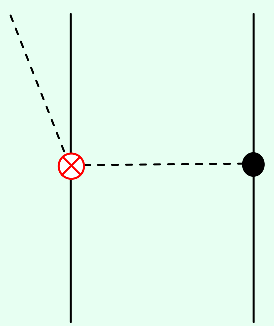
- Isospin conserving terms: $L^{(0)} = \frac{1}{4F_\pi^2} N^\dagger \tau \cdot (\dot{\pi} \times \pi) N + \frac{g_A}{2F_\pi} N^\dagger \tau \cdot \vec{\sigma} \cdot \vec{\nabla} \pi N + \cdots$

- CSB terms: $L^{(0)}_{\text{CSB}} = \frac{\delta m_N}{2} N^\dagger \tau_3 N - \frac{\delta m_N^{\text{str}}}{4F_\pi^2} N^\dagger \tau \cdot \pi \pi_3 N - \frac{\delta m_N^{\text{em}}}{4F_\pi^2} N^\dagger \left(\tau_3 \pi^2 - \tau \cdot \pi \pi_3 \right) N + \cdots$

$$\delta m_N = m_n - m_p = \delta m_N^{\text{str}} + \delta m_N^{\text{em}}$$



Leading order contributions to $M_{\text{CSB}}^{1P1 \to 3S1, s}$

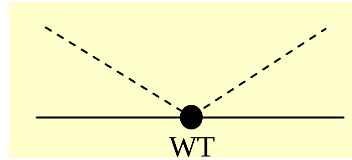


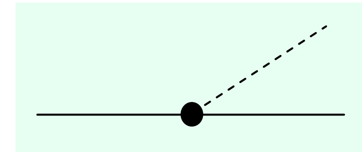
(a)

Diagram (a) was considered in previous studies
Kolck, Niskanen, Miller (2000)
Bolton, Miller (2009)

Leading Order CSB Amplitude

Effective chiral Lagrangian at LO

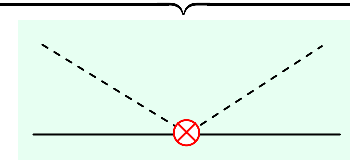




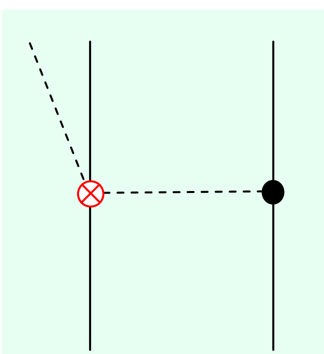
- Isospin conserving terms: $$L^{(0)} = \underbrace{\frac{1}{4F_\pi^2} N^\dagger \tau \cdot (\dot{\pi} \times \pi) N}_{} + \underbrace{\frac{g_A}{2F_\pi} N^\dagger \tau \cdot \vec{\sigma} \cdot \vec{\nabla} \pi N}_{} + \cdots$$

- CSB terms: $$L^{(0)}_{\mathrm{CSB}} = \frac{\delta m_N}{2} N^\dagger \tau_3 N \underbrace{- \frac{\delta m_N^{\mathrm{str}}}{4F_\pi^2} N^\dagger \tau \cdot \pi \pi_3 N - \frac{\delta m_N^{\mathrm{em}}}{4F_\pi^2} N^\dagger \left(\tau_3 \pi^2 - \tau \cdot \pi \pi_3 \right) N}_{} + \cdots$$

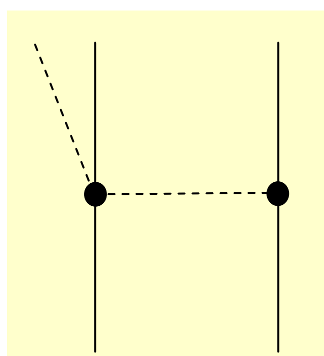
$$\delta m_N = m_n - m_p = \delta m_N^{\mathrm{str}} + \delta m_N^{\mathrm{em}}$$



Leading order contributions to $M_{\mathrm{CSB}}^{1P1 \to 3S1,s}$



(a)

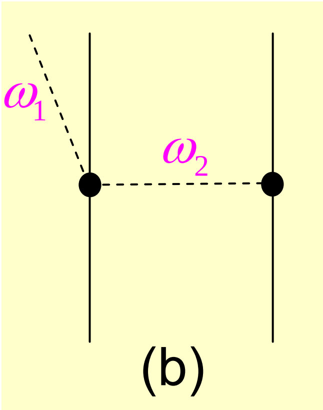


(b)

Diagram (a) was considered in previous studies
Kolck, Niskanen, Miller (2000)
Bolton, Miller (2009)

We showed that rescattering diagram (b) also contributes to LO CSB amplitude due to time dependence of WT vertex $(\dot{\pi})$

New Leading Order Contribution to CSB



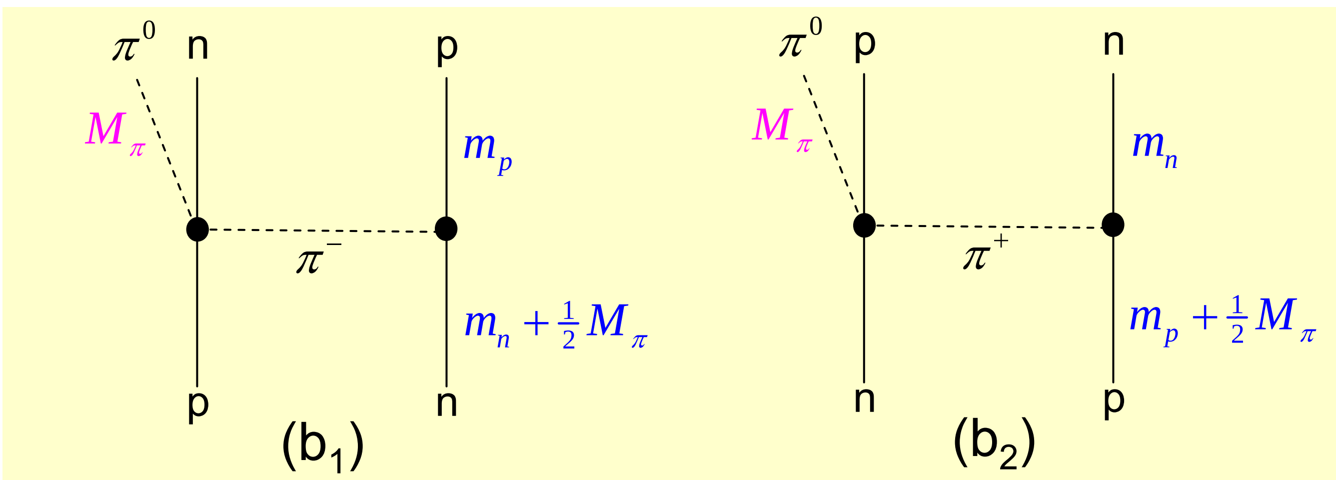
Weinberg–Tomozawa operator is time dependent

$$L_{\mathrm{WT}} = \frac{1}{4F_\pi^2} N^\dagger \tau \cdot (\dot{\pi} \times \pi) N$$

ππNN vertex is proportional to the zeroth component of pions

$$V_{\mathrm{WT}} = \frac{1}{4F_\pi^2} (\omega_1 + \omega_2) \varepsilon^{abc} \tau^c$$

Diagram (b) in particle basis:

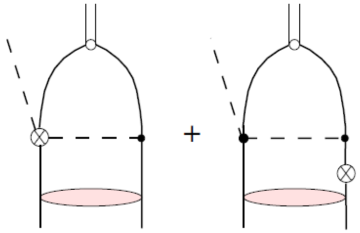


$$V_{\mathrm{WT}} = \frac{-i}{4F_\pi^2} \sqrt{2} \begin{cases} \delta m_N + \frac{3}{2} M_\pi & \text{for diagram (b}_1\text{)} \\ \delta m_N - \frac{3}{2} M_\pi & \text{for diagram (b}_2\text{)} \end{cases} \Rightarrow$$

Rescattering diagram gives $\propto \delta m_N$ contribution to LO CSB amplitude

A_{fb} at LO. Discussion and Results

$$M_{\mathrm{CSB}}^{1P1\to 3S1,s} =$$



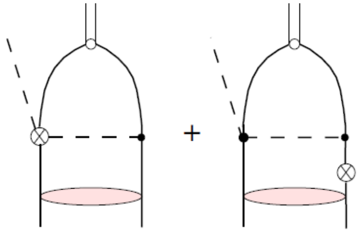
$$\propto \left(\delta m_N^{\mathrm{str}} - \frac{\delta m_N^{\mathrm{em}}}{2}\right) + \frac{\delta m_N^{\mathrm{str}} + \delta m_N^{\mathrm{em}}}{2} \propto \frac{3}{2}\delta m_N^{\mathrm{str}}$$

$$A_1 \propto \mathrm{Re}\left[\left(M_{\mathrm{IC}}^{1S0\to 3S1,p} + \tfrac{2}{3} M_{\mathrm{IC}}^{1D2\to 3S1,p}\right) M_{\mathrm{CSB}}^{1P1\to 3S1,s}\right]$$

IC p-wave amplitudes from Baru et al. (2009)

A_{fb} at LO. Discussion and Results

$$M_{CSB}^{1P1\to3S1,s} =$$



$$\propto \left(\delta m_N^{str} - \frac{\delta m_N^{em}}{2}\right) + \frac{\delta m_N^{str} + \delta m_N^{em}}{2} \propto \frac{3}{2}\delta m_N^{str}$$

$$A_1 \propto \mathrm{Re}\left[\left(M_{IC}^{1S0\to3S1,p} + \tfrac{2}{3} M_{IC}^{1D2\to3S1,p}\right) M_{CSB}^{1P1\to3S1,s}\right]$$

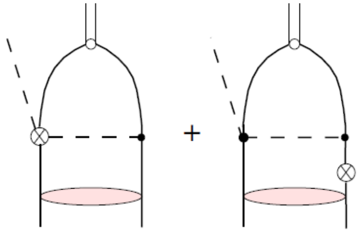
IC p-wave amplitudes from Baru et al. (2009)

- A_0 is related to total cross section $\sigma=4\pi A_0$.
- precise value extracted from pionic deuterium lifetime experiment ($\pi^- d\to nn$)

$A_0 = 1.70^{+0.03}_{-0.07}\,\mu b$ Strauch et al., PSI (2009)

$$A_{fb} = \frac{A_1}{2A_0} = (11.5 \pm 3.5)\times 10^{-4}\,\frac{\delta m_N^{str}}{\text{MeV}}$$

A_{fb} at LO. Discussion and Results

$M_{CSB}^{1P1\to 3S1,s}=$  $\propto\left(\delta m_N^{str}-\frac{\delta m_N^{em}}{2}\right)+\frac{\delta m_N^{str}+\delta m_N^{em}}{2}\propto\frac{3}{2}\delta m_N^{str}$

$$A_1\propto \mathrm{Re}\left[\left(M_{IC}^{1S0\to 3S1,p}+\tfrac{2}{3}M_{IC}^{1D2\to 3S1,p}\right)M_{CSB}^{1P1\to 3S1,s}\right]$$

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$$A_{fb}=\frac{A_1}{2A_0}=(11.5\pm 3.5)\times 10^{-4}\,\frac{\delta m_N^{str}}{\mathrm{MeV}}$$

$$A_{fb}^{exp}=[17\pm 8(\mathrm{sys.})\pm 5.5(\mathrm{stat.})]\times 10^{-4}$$

Opper et al. (2003) TRIUMF

Our result: $\delta m_N^{str}=\left(1.5\pm 0.8(\mathrm{exp.})\pm 0.5(\mathrm{th.})\right)\mathrm{MeV}$

Cottingham sum rule: $\delta m_N^{str}=2.0\pm 0.3\ \mathrm{MeV}$ Gasser, Leutwyler (1982)

Lattice QCD: $\delta m_N^{str}=2.26\pm\underbrace{0.57}_{\text{statistic}}\pm\underbrace{0.42}_{\text{input}}\pm\underbrace{0.10}_{\text{chiral extrapol.}}\ \mathrm{MeV}$ NPLQCD (2007)

Summary and Outlook

- Complete leading order calculation of CSB effect in $pn \rightarrow d\pi^0$
- New LO effect discovered
- Strong neutron-proton mass difference extracted from asymmetry data

$$\delta m_N^{\mathrm{str}} = \left(1.5 \pm 0.8(\mathrm{exp.}) \pm 0.5(\mathrm{th.})\right) \mathrm{MeV}$$

- Agreement with Cottingham sum rule and lattice QCD

Outlook

- Complete N^2LO calculation required to confirm theoretical uncertainty (loops, LECs, etc.)
- $dd \rightarrow \alpha\pi^0$ can help to constrain parameters in N^2LO calculation
  Stephenson et al. (2003), Gårdestig et al. (2004);
  Nogga et al.(2006), Fonseca et al.(2009)