$\bar{N}N$ interaction from chiral effective field theory and its application to neutron-antineutron oscillations

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(with Ulf-G. Meißner)

Outline

1. Introduction
2. Antinucleon-nucleon interaction in chiral EFT
3. Neutron-antineutron oscillations
4. Summary

Motivation

Baryon asymmetry in the universe

Standard model cannot explain observed matter-antimatter asymmetry

Baryogenesis under Sakharov conditions

- Baryon number B violation

  processes with $|\Delta B| = 1$ e.g., proton decay

  processes with $|\Delta B| = 2$ e.g., neutron-antineutron oscillations, Λ-$\bar{\Lambda}$ oscillations
- C-symmetry and CP-symmetry violation
- Interactions out of thermal equilibrium

Neutron-antineutron transition probability

Time evolution where a neutron can transform into an antineutron

$$\mathrm{i}\frac{\partial}{\partial t}\begin{pmatrix} n \\ \bar{n} \end{pmatrix} = \begin{pmatrix} E_n & \delta m \\ \delta m & E_{\bar{n}} \end{pmatrix}\begin{pmatrix} n \\ \bar{n} \end{pmatrix}$$

Probability of a free neutron oscillating to an antineutron

$$P_{n\to\bar{n}}(t) = \frac{\delta m^2}{\Delta E^2 + \delta m^2}\sin^2(\sqrt{\Delta E^2 + \delta m^2}\, t)$$

$\delta m = 1/\tau_{n-\bar{n}}$ ... $\tau_{n-\bar{n}}$ is the free neutron-antineutron oscillation time

$\Delta E = (E_n - E_{\bar{n}})/2$

for $E_n \approx E_{\bar{n}}$

$$P_{n\to\bar{n}}(t) \approx (\delta m\, t)^2 = \left(\frac{t}{\tau_{n-\bar{n}}}\right)^2$$

For bound neutrons in nuclei, the probability is

$$P_{\mathrm{nuc}}(n \to \bar{n}) = \frac{1}{T_{\mathrm{nuc}}} = \frac{1}{R\,\tau^2_{n-\bar{n}}}$$

R ... reduced lifetime, intranuclear suppression factor

Possible experimental observation

- Oscillations of neutrons to antineutrons in free space
  direct access to $\tau_{n-\bar{n}}$
- Oscillations of neutrons to antineutrons in nuclei
  1) measurement of T_{nuc}
  2) estimation of $\tau_{n-\bar{n}}$ based on a knowledge of R
  the latter can be/has to be provided by theory

  examples:
  Super-Kamiokande (K. Abe et al., PRD 103 (2021) 012008)
  lower limit on $\bar{n}$ appearance lifetime in ^{16}O: 3.6×10^{32} years
  $\Rightarrow \tau_{n-\bar{n}} > 4.7 \times 10^8$ s at 90 % C.L.
  (based on an R value from Friedman and Gal (2008))
  Sudbury Neutrino Observatory (B. Aharmim et al., PRD 96 (2017) 092005)
  lower limit on nuclear lifetime of ^{2}H: 0.118×10^{32} years
  $\Rightarrow \tau_{n-\bar{n}} > 1.23 \times 10^8$ s at 90 % C.L.
  (based on an R value from Dover, Gal, Richard (1983))

Suppression factor R in the traditional approach

C. Dover, A. Gal, J.-M. Richard, PRD 27 (1983) 1090

$$|\psi_d\rangle = \frac{u_0(r)}{r}|^3S_1\rangle + \frac{w_0(r)}{r}|^3D_1\rangle$$

NN: ψ_d ... deuteron wave function from Paris potential is used

$$-\frac{u''_{\bar{n}p}(r)}{m_N} + V_{\bar{n}p}\, u_{\bar{n}p}(r) - E_d\, u_{\bar{n}p}(r) = -\delta m\, u_0(r), \qquad V_{\bar{n}p}(r) = U_{\bar{n}p}(r) - \mathrm{i}W_{\bar{n}p}(r)$$

$$\Gamma_d = -2\int_0^\infty |u_{\bar{n}p}(r)|^2\, \mathrm{Im}\, V_{\bar{n}p}(r)\, \mathrm{d}r = -2\delta m \int_0^\infty u_0(r)\, \mathrm{Im}\, u_{\bar{n}p}(r)\, \mathrm{d}r$$

$E_d = -2.2246$ MeV ... deuteron binding energy
$\delta m = 1/\tau_{n-\bar{n}} = V_{n-\bar{n}}$ ... $n-\bar{n}$ transition potential

$$T_d = 1/\Gamma_d, \quad T_d = R\,\tau^2_{n-\bar{n}} \quad \rightarrow R = 1/(\Gamma_d\, \tau^2_{n-\bar{n}})$$

$\bar{N}N$: Dover-Richard $\bar{N}N$ potentials are used (PRC 21 (1980) 24, PRC 24 (1982) 1952)

- only S wave: $R = 2.75 \times 10^{22}$ s^{-1} (DR$_1$), $R = 2.71 \times 10^{22}$ s^{-1} (DR$_2$)
- S+D wave: $R = 2.56 \times 10^{22}$ s^{-1} (DR$_1$), $R = 2.40 \times 10^{22}$ s^{-1} (DR$_2$)

However, since 1983 ...

NN : chiral effective field theory (Weinberg, van Kolck, Epelbaum/Meißner, Entem/Machleidt, ...)

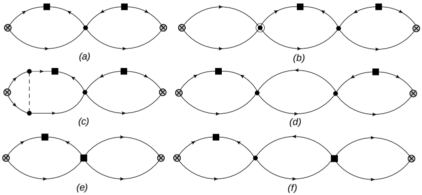
$\bar{N}N$: wealth of new low-energy data from LEAR (CERN) (E. Klempt et al., Phys. Rep. 368 (2002) 119)
partial wave analysis (D. Zhou & R.G.E. Timmermans, PRC 86 (2012) 044003)
potentials from chiral EFT (X.-W. Kang, L.-Y. Dai, J.H., U.-G. Meißner)

$\Rightarrow$ re-evaluate R with modern tools

Oosterhof, Long, de Vries, Timmermans, van Kolck, PRL 122 (2019) 172501

construct an EFT for the $|\Delta B| = 2$ interaction
calculate $n - \bar{n}$ oscillations and dinucleon decay up to NLO

Decay rate is obtained from the deuteron propagator



Kaplan-Savage-Wise resummation scheme is employed (pion exchange is treated perturbatively)

$$G(\bar{E}) = \frac{\Sigma(\bar{E})}{1 + \mathrm{i}\,\mathrm{Re}(C_0)\,\Sigma(\bar{E})} = \frac{\mathrm{i}Z_d}{\bar{E} - E_d + \mathrm{i}\Gamma_d/2} + \ldots,$$

$\Sigma(\bar{E})$ ... irreducible deuteron two-point function

Z_d ... (real) wave-function renormalization

$$\Gamma_d = \left.\frac{2\,\mathrm{Im}(\mathrm{i}\Sigma(\bar{E}))}{\mathrm{Re}(\mathrm{i}d\Sigma(\bar{E})/d\bar{E})}\right|_{\bar{E}=E_d} + \ldots$$

Effective field theory

Oosterhof, Long, de Vries, Timmermans, van Kolck, PRL 122 (2019) 172501

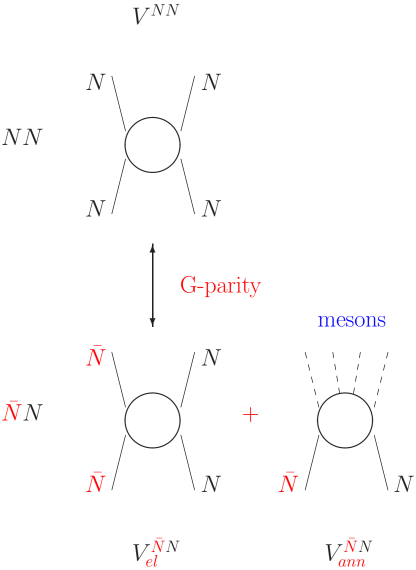
$$\Gamma_d = -\frac{m_N \,\mathrm{Im}\, a_{\bar{n}p}}{\kappa \tau^2_{n-\bar{n}}} \left[1 + \kappa \left(r_{np} + 2\,\mathrm{Re}\, a_{\bar{n}p} - \frac{g_A^2 m_N}{3\pi F_\pi^2} \frac{2 - 2\xi - 5\xi^2 + 6\xi^3}{1+2\xi} - \frac{(\kappa - \mu)\,\mathrm{Im}\,\tilde{B}_0}{\sqrt{2}\pi\,\delta m\,\mathrm{Im}\, a_{\bar{n}p}} \right) \right]$$

$$R = -\left[\frac{m_N}{\kappa} \mathrm{Im}\, a_{\bar{n}p}\ (1 + 0.40 + 0.20 - 0.13 \pm 0.4) \right]^{-1} = (1.1 \pm 0.3) \times 10^{22}\ \mathrm{s}^{-1}$$

$\tau_{n-\bar{n}}$ ... $1/\delta m$ + ...
$a_{\bar{n}p} = (0.44 - \mathrm{i}0.96)$ fm ... taken from (chiral EFT) $\bar{N}N$ potential
$r_{np} \simeq 1.75$ fm
$\kappa = \sqrt{m_N |E_d|} \simeq 45$ MeV
$\xi = \kappa / m_\pi \simeq 0.32$

μ ... renormalization scale
$\tilde{B}_0$ ... $|\Delta B| = 2$ four-baryon ($NN \to \bar{N}N$) contact term

The $\bar{N}N$ interaction



Traditional approach: meson-exchange

I) $V^{\bar{N}N}_{el}$ ... derived from an NN potential via G-parity

(Charge conjugation plus 180^o rotation around the y axis in isospin space)

$\Rightarrow$

$$\begin{aligned} V^{\bar{N}N}(\pi,\ \omega) &= -V^{NN}(\pi,\ \omega) \qquad \text{odd G} - \text{parity} \\ V^{\bar{N}N}(\sigma,\ \rho) &= +V^{NN}(\sigma,\ \rho) \qquad \text{even G} - \text{parity} \\ &\ldots \end{aligned}$$

II) $V^{\bar{N}N}_{ann}$

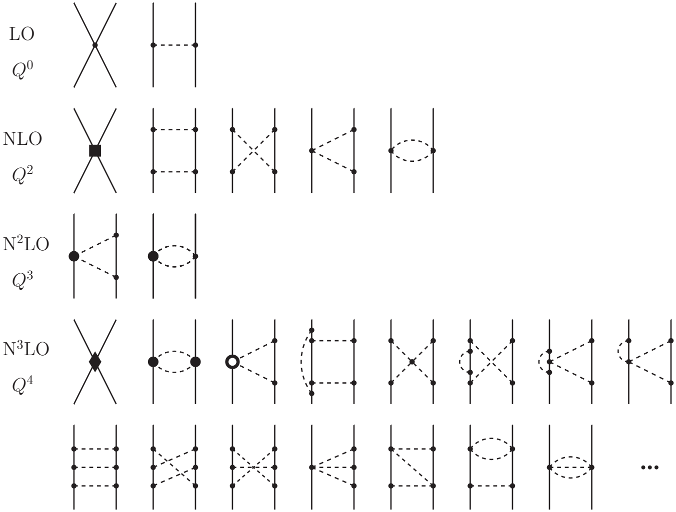
employ a phenomenological optical potential, e.g.

$V_{opt}(r) = (U_0 + iW_0)\, e^{-r^2/(2a^2)}$

with parameters U_0, W_0, a fixed by a fit to $\bar{N}N$ data

examples: Dover/Richard (1980,1982), Paris (1982,...,2009), Nijmegen (1984), Jülich (1991,1995), ...

NN in chiral effective field theory (E. Epelbaum et al.)



- $4N$ contact terms involve low-energy constants (LECs) ... parameterize unresolved short-range physics

$\Rightarrow$ need to be fixed by fit to experiments (phase shifts)

$\bar{N}N$ partial-wave analysis

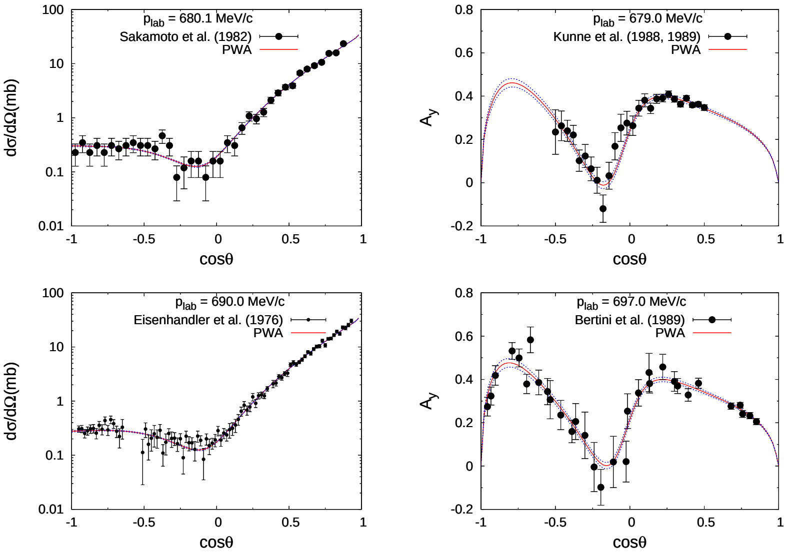
R. Timmermans et al., PRC 50 (1994) 48

- use a meson-exchange potential for the long-range part
- apply a strong absorption at short distances (boundary condition) in each individual partial wave ($\approx$ 1.2 fm)
- 30 parameters, fitted to a selection of $\bar{N}N$ data (3646!)
- However, resulting amplitudes are not explicitly given:
  no proper assessment of the uncertainties (statistical errors)
  phase-shift parameters for the $^1S_0$ and $^1P_1$ partial waves are not pinned down accurately

D. Zhou and R. Timmermans, PRC 86 (2012) 044003

- use now potential where the long-range part is fixed from chiral EFT ($\mathrm{N^2LO}$)
- somewhat larger number of $\bar{N}N$ data (3749!)
- now, resulting amplitudes and phase shifts are given!
- lowest momentum: $p_{lab} = 100$ MeV/c ($T_{lab} = 5.3$ MeV)
- highest total angular momentum: $J = 4$

$\bar{N}N$ PWA: $\bar{p}p \to \bar{p}p$



The $\bar{N}N$ interaction in chiral EFT

- $V^{NN} = \quad V_{1\pi} + V_{2\pi} + V_{3\pi} + ... + V_{cont}$
- $V^{\bar{N}N}_{el} = -V_{1\pi} + V_{2\pi} - V_{3\pi} + ... + V_{cont}$
- $V^{\bar{N}N}_{ann} = \sum_X V^{\bar{N}N\to X} \qquad X \hat{=} \pi, 2\pi, 3\pi, 4\pi, ...$

• $V_{1\pi}$, $V_{2\pi}$, ... can be taken over from chiral EFT studies of the *NN* interaction

• Xian-Wei Kang, J.H., Ulf-G. Meißner, JHEP 02 (2014) 113 (N^{2}LO)
starting point: *NN* interaction by Epelbaum, Glöckle, Meißner, NPA 747 (2005) 362

• Ling-Yun Dai, J.H., Ulf-G. Meißner, JHEP 07 (2017) 078 (N^{3}LO)
starting point: *NN* interaction by Epelbaum, Krebs, Meißner, EPJA 51 (2015) 53

• V_{cont} ... same structure as in *NN* ($\tilde{C} + C\,(p^2 + p'^2) + \ldots$). However, now the LECs have to be determined by a fit to $\bar{N}N$ data (phase shifts, inelasticites)!

no Pauli principle $\to$ more partial waves, more contact terms

• $V^{\bar{N}N}_{ann}$ has no counterpart in *NN*

empirical information: annihilation is short-ranged and practically energy-independent

$$V^{\bar{N}N}_{ann;eff} = \sum_X V^{\bar{N}N\to X} G^0_X V^{X\to\bar{N}N}, \quad V^{\bar{N}N\to X}(p, p_X) \approx p^L\,(a + b\,p^2 + \ldots); \quad p_X \approx \text{const.}$$

regularized Lippmann-Schwinger equation

$$T^{L'L}(p',p) = V^{L'L}(p',p) + \sum_{L''} \int_0^\infty \frac{dp''p''^2}{(2\pi)^3} \frac{V^{L'L''}(p',p'')\, T^{L''L}(p'',p)}{2E_p - 2E_{p''} + i\eta}$$

- $\bar{N}N$ potential up to N^{2}LO (Kang et al., 2014)
  employ the non-local regularization scheme of EGM (NPA 747 (2005) 362)
- $\bar{N}N$ potential up to N^{3}LO (Dai et al., 2017)
  employ the regularization scheme of EKM (EPJA 51 (2015) 53)

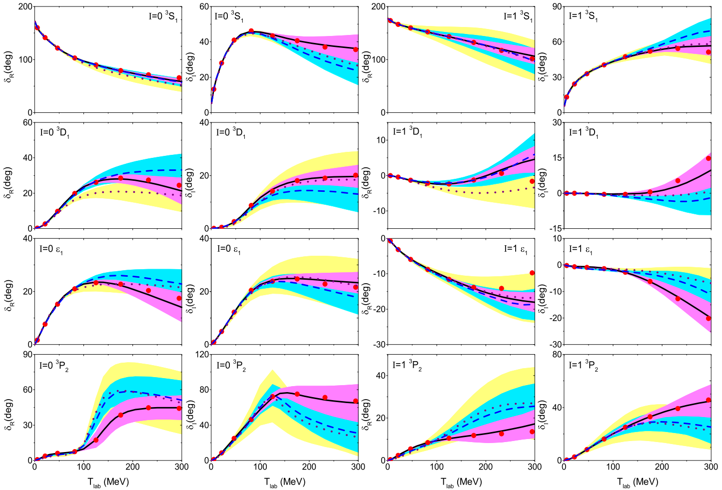
- Fit to phase shifts and inelasticity parameters in the isospin basis
  (D. Zhou, R.G.E. Timmermans, PRC 86 (2012) 044003)

- Calculation of observables is done in particle basis:
  - ⋆ Coulomb interaction in the $\bar{p}p$ channel is included
  - ⋆ the physical masses of p and n are used

$\bar{n}n$ channels opens at $p_{lab} = 98.7$ MeV/c ($T_{lab} = 5.18$ MeV)

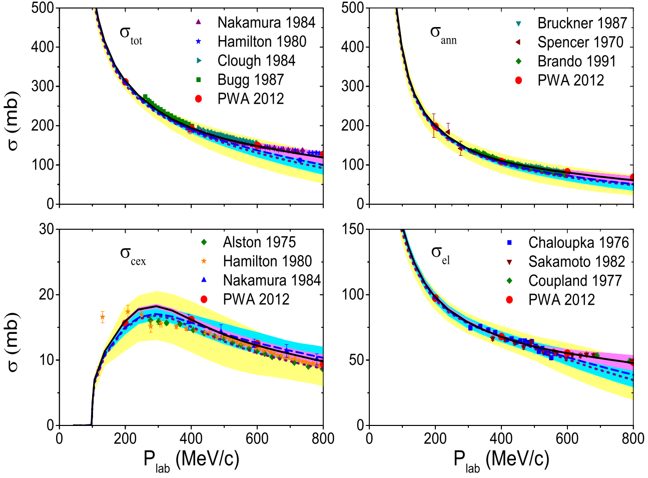
$\bar{N}N$ phase shifts

Ling-Yun Dai, J.H., Ulf-G. Meißner, JHEP 07 (2017) 078 (N^{3}LO)



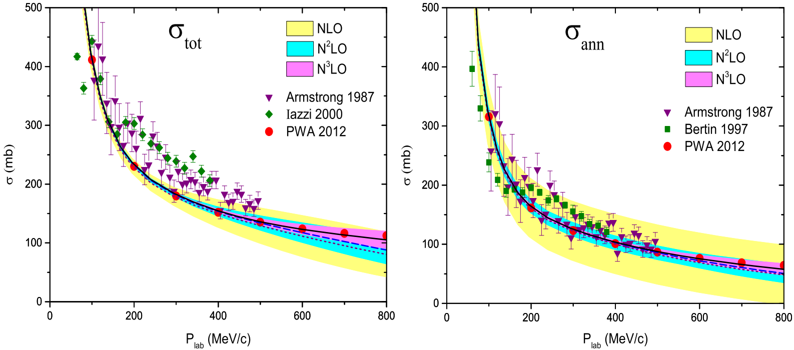
—— N^{3}LO; – – – N^{2}LO; · · · NLO (bands represent a syst. uncertainty estimate; cutoff $\mathcal{R}_c = 0.9$ fm)

Results for $\bar{p}p$ integrated cross sections



N3LO; N2LO; NLO (bands represent a systematic uncertainty estimate)

$\bar{n}p$ cross sections



Results

J.H., U.-G. Meißner, CPC 44 (2020) 033101

$$\begin{pmatrix} H_0 + V_{np} & V_{n-\bar{n}} \\ V_{n-\bar{n}} & H_0 + V_{\bar{n}p} \end{pmatrix} \begin{pmatrix} |\psi_{np}\rangle \\ |\psi_{\bar{n}p}\rangle \end{pmatrix} = (E - i\Gamma/2) \begin{pmatrix} |\psi_{np}\rangle \\ |\psi_{\bar{n}p}\rangle \end{pmatrix}$$

$$\begin{aligned} (H_0 + V_{np} - E_d)|\psi_d\rangle &= 0 \\ (H_0 + V_{\bar{n}p} - E_d)|\psi_{\bar{n}p}\rangle &\approx -V_{n-\bar{n}}|\psi_d\rangle \end{aligned}$$

$$\Gamma_d = -2\, V_{n-\bar{n}}\, \mathrm{Im}\langle\psi_d|\psi_{\bar{n}p}\rangle$$

	χEFT N^{2}LO	χEFT N^{3}LO	DR$_1$	DR$_2$
R [s^{-1}]	2.49×10^{22}	2.56×10^{22}	2.56×10^{22}	2.40×10^{22}
(Oosterhof)	$(1.1 \pm 0.3) \times 10^{22}$	$(1.2 \pm 0.3) \times 10^{22}$	$(1.4 \pm 0.4) \times 10^{22}$	$(1.3 \pm 0.3) \times 10^{22}$
$a_{\bar{n}p}$ [fm]	$0.44 - \mathrm{i}\,0.91$	$0.44 - \mathrm{i}\,0.96$	$0.87 - \mathrm{i}\,0.66$	$0.89 - \mathrm{i}\,0.71$

χEFT N^{2}LO ... X.-W. Kang, J.H., U.-G. Meißner, JHEP 02 (2014) 113
χEFT N^{3}LO ... Lingyun Dai, J.H., U.-G. Meißner, JHEP 07 (2017) 078
DR$_1$, DR$_2$ ... Dover, Gal, Richard, PRD 27 (1983) 1090

$$R = -\frac{\kappa}{m_N}\,\frac{1}{\mathrm{Im}\, a_{\bar{n}p}}\,\frac{1}{1 + 0.4 + 2\kappa\,\mathrm{Re}\, a_{\bar{n}p} - 0.13 \pm 0.4}$$

Results for R [s^{-1}]

	χEFT N^{3}LO			
$\mathcal{R}_c$ [fm]	0.8	0.9	1.0	1.1
(EFT)	2.91×10^{22}	2.71×10^{22}	2.61×10^{22}	2.57×10^{22}
(MEX)	2.87×10^{22}	2.72×10^{22}	2.61×10^{22}	2.57×10^{22}
Oosterhof LO	1.62×10^{22}			
Oosterhof NLO	$(1.2 \pm 0.3) \times 10^{22}$			
$a_{\bar{n}p}$ [fm]	$0.41 - \mathrm{i}\,0.88$	$0.42 - \mathrm{i}\,0.90$	$0.43 - \mathrm{i}\,0.91$	$0.47 - \mathrm{i}\,0.91$
$\beta\sigma_{ann}$ [mb]	34.5	35.6	36.0	36.0

$\mathcal{R}_c$ ... different regulator in χEFT N^{3}LO $\bar{N}N$ potential (Lingyun Dai et al., JHEP 07 (2017) 078)

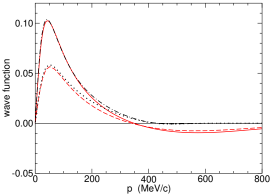
$\Rightarrow$ uncertainty $\simeq \pm 0.2 \times 10^{22}$ s^{-1}

(EFT) ... deuteron wave function from consistent χEFT N^{3}LO NN potential

(MEX) ... deuteron wave function from meson-exchange potential (J.H. et al., PRC 48 (1993) 2190)

Where does the difference come from?

- Our calculation: $|\Delta B| = 2$ four-baryon contact term is neglected
  non-perturbative aspects of NN and $\bar{N}N$ interactions are fully taken into account
- Oosterhof et al.: Kaplan-Savage-Wise resummation scheme is used
  has known deficiencies: convergence problem when tensor force of pion exchange is relevant ($^3S_1$-$^3D_1$)
  quadrupole moment of the deuteron is overestimated by 40 %
- deuteron wave function versus deuteron two-point function
  two-point function possibly inadequate for specific observables



upper curves ... $\psi_d(p)$ in the $^3S_1$ partial wave
lower curves ... $\psi_{\bar{n}p}(p)$ in the $^3S_1$ partial wave (imaginary part)
(—- N^3LO; -·-· N^2LO)

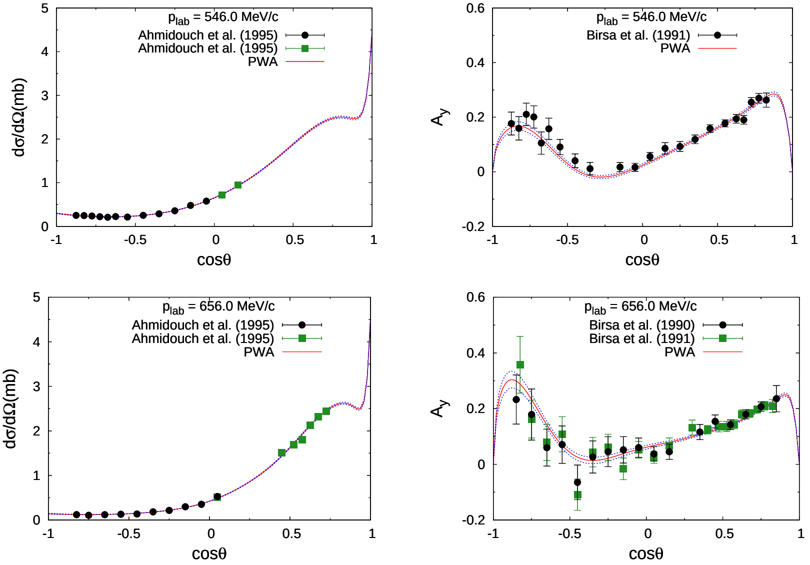
Summary

- $\bar{N}N$ interaction up to N^{3}LO in chiral effective field theory
- excellent description of $\bar{N}N$ amplitudes is achieved
- nice agreement with $\bar{p}p$ (and $\bar{p}p \to \bar{n}n$) observables for $T_{lab} \leq 250$ MeV is achieved

- Neutron-antineutron oscillatons based on up-to-date (N^{3}LO) $\bar{N}N$ (and NN) interactions in chiral EFT
- standard (leading-order) calculation of the suppression factor R for the deuteron confirms results by Dover, Gal, Richard from 1983 ($R = (2.7 \pm 0.2) \times 10^{22}$)
- discrepany to EFT calculation by Oosterhof et al. based on the Kaplan-Savage-Wise resummation scheme ($R = (1.2 \pm 0.3) \times 10^{22}$)

Backup slides

$\bar{N}N$ PWA: $\bar{p}p \to \bar{n}n$



Annihilation potential

- experimental information:
  • annihilation occurs dominantly into 4 to 6 pions
  • thresholds: for 5 pions: $\approx$ 700 MeV for $\bar{N}N$: 1878 MeV
  $\Rightarrow$ annihilation potential depends very little on energy
  • annihilation is a statistical process: individual properties of the produced particles (mass, quantum numbers) do not matter
- phenomenlogical models: bulk properties of annihilation can be described rather well by simple energy-independent optical potentials
- range associated with annihilation is around 1 fm or less
  $\rightarrow$ short-distance physics

$\Rightarrow$ describe annihilation in the same way as the short-distance physics in $V_{el}^{\bar{N}N}$, i.e. likewise by contact terms (LECs)
$\Rightarrow$ describe annihilation by a few effective (two-body) annihilation channels (unitarity is preserved!)

$$V^{\bar{N}N} = V_{el}^{\bar{N}N} + V_{ann;eff}^{\bar{N}N}; \qquad V_{ann;eff}^{\bar{N}N} = \sum_X V^{\bar{N}N\to X} G_X^0 V^{X\to\bar{N}N}$$

$$V^{\bar{N}N\to X}(p_{\bar{N}N}, p_X) \approx p_{\bar{N}N}^L (a + b\, p_{\bar{N}N}^2 + \ldots); \quad p_X \approx \text{const.}$$

$a, b, \ldots$ LECs

Contributions of V_{cont} for $\bar{N}N$ up to N^{3}LO

$V_{el}^{\bar{N}N}$

$$
\begin{aligned}
V^{L=0} &= \tilde{C}_\alpha + C_\alpha (p^2 + p'^2) + D^1_\alpha p^2 p'^2 + D^2_\alpha (p^4 + p'^4) \\
V^{L=1} &= C_\beta \, p \, p' + D_\beta \, p \, p' (p^2 + p'^2) \\
V^{L=2} &= D_\gamma \, p^2 p'^2
\end{aligned}
$$

$\tilde{C}_i$ ... LO LECs [4], C_i ... NLO LECs [+14], D_i ... N^{3}LO LECs [+30], $p = |\mathbf{p}|$; $p' = |\mathbf{p}\,'|$

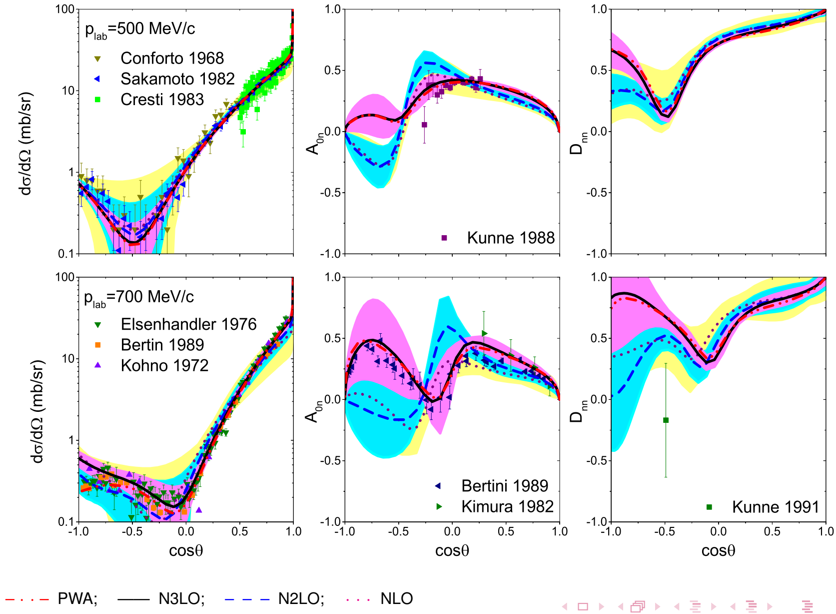
$V_{ann;eff}^{\bar{N}N}$

$$
\begin{aligned}
V^{L=0}_{ann} &= -i\,(\tilde{C}^a_\alpha + C^a_\alpha p^2 + D^a_\alpha p^4)\,(\tilde{C}^a_\alpha + C^a_\alpha p'^2 + D^a_\alpha p'^4) \\
V^{L=1}_{ann} &= -i\,(C^a_\beta p + D^a_\beta p^3)\,(C^a_\beta p' + D^a_\beta p'^3) \\
V^{L=2}_{ann} &= -i\,(D^a_\gamma)^2 p^2 p'^2 \\
V^{L=3}_{ann} &= -i\,(D^a_\delta)^2 p^3 p'^3
\end{aligned}
$$

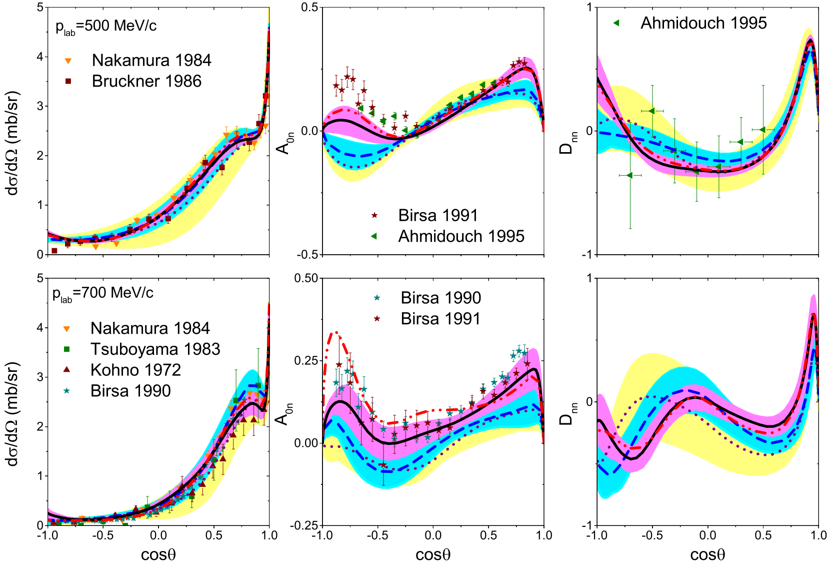
α ... ${}^1S_0$ and ${}^3S_1$
β ... ${}^3P_0$, ${}^1P_1$, and ${}^3P_1$
γ ... ${}^1D_2$, ${}^3D_2$ and ${}^3D_3$
δ ... ${}^1F_3$, ${}^3F_3$ and ${}^3F_4$

- unitarity condition: higher powers than what follows from Weinberg power counting appear!
- same number of contact terms (LECs)

$\bar{p}p \to \bar{p}p$



$\bar{p}p \to \bar{n}n$



$\bar{n}p$ annihilation cross section