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The parity-violating asymmetry in the $^3\mathbf{He}(\vec{n},p)^3\mathbf{H}$ reaction

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Summary. — The longitudinal asymmetry $A_z^{n^3\mathrm{He}}$ in the $^3\mathrm{He}(\vec{n},p)^3\mathrm{H}$ reaction is an observable directly related to parity-violating (PV) components in the nucleon-nucleon (NN) interaction. Here we study $A_z^{n^3\mathrm{He}}$ using a PV NN potential derived from an effective field theory framework at next-to-next-to-leading order, including one- and two-pion exchanges, contact interactions and relativistic corrections. This potential depends on six low-energy constants. Some of these parameters are constrained to reproduce the existing accurate measurements of the $\vec{p}$-p longitudinal asymmetry. Using these constraints we compute $A_z^{n^3\mathrm{He}}$ and study the sensitivity of such an observable to the unconstrained parameters.

PACS 11.30.Er – Charge conjugation, parity, time reversal, and other discrete symmetries.
PACS 13.75.Cs – Nucleon-nucleon interactions (including antinucleons, deuterons, etc.).
PACS 25.40.Kv – Charge-exchange reactions.

1. – Introduction

A number of experiments aimed at studying parity violation in low-energy processes involving few nucleon systems are being completed or are in an advanced stage of planning at cold neutron facilities, such as the Los Alamos Neutron Science Center, the NIST Center for Neutron Research, and the Spallation Neutron Source at Oak Ridge. The primary objective of this program is to determine the fundamental parameters of hadronic weak interactions [1], in particular the strength of the long-range part of the parity-violating (PV) nucleon-nucleon (NN) potential, mediated by one-pion exchange (OPE).

Until recently, the standard setting by which nuclear PV processes were analyzed theoretically was the use of potentials derived from the usual meson-exchange mechanism, in particular using the model proposed by Desplanques, Donoghue, and Holstein (DDH) [2].

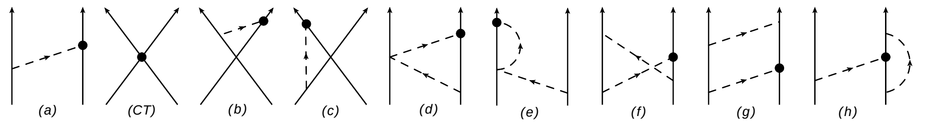

Fig. 1. – Time-ordered diagrams contributing to the PV potential (only one time ordering is given). Nucleons and pions are denoted by solid and dashed lines. The solid dot represents a PV vertex.

In recent years, a new, more systematic, approach based in a model-independent field-theoretic treatment of the nuclear forces has been vigorously pursued [3-5]. In this effective field theory (EFT) approach the pion couples to nucleons by powers of its momentum Q, and the Lagrangian describing these interactions can be expanded in powers of Q/Λ_χ, where $\Lambda_\chi \sim 1\,\mathrm{GeV}$ specifies the chiral symmetry-breaking scale. The EFT has been used to describe also the PV components in the NN interaction. Kaplan and Savage wrote in a pioneering work [6] an effective Lagrangian describing the PV interaction of pions and nucleons up to one derivative. This Lagrangian includes a "Yukawa" pion-nucleon interaction with no derivatives, multiplied by a parameter denoted as h^1_π and known as the "weak pion-nucleon" coupling constant. It gives the long-range OPE contribution to the PV NN interaction.

The PV NN potential at next-to-next-to-leading (N2LO) was derived for the first time by Zhu *et al.* [7]. This potential includes the long-range OPE component, medium-range components originating from two-pion exchange (TPE) processes, and short-range components deriving from *ten* four-nucleon contact terms (the authors of ref. [7] noted that at low energy their ten contact interactions collapse into *five* independent operators, corresponding to the five S-P low-energy PV amplitudes [8]). In a series of other works, Desplanques *et al.*, have also derived the contribution of the TPE diagrams at N2LO [9] to study, in particular, PV effects in the capture reaction $^1\mathrm{H}(\vec{n},\gamma)^2\mathrm{H}$. The expression of the TPE contribution obtained by Desplanques *et al.* is slightly different from that one reported by Zhu *et al.* [7].

We have recently derived again the PV NN potential at N2LO, in order to clarify the exact expression of the TPE contribution. Moreover, the more recent analysis of ref. [10] has shown that actually there exist only *five* independent contact terms with one derivative. We give a short summary of the properties of this PV potential in sect. **2**. It contains six unknown parameters, the pion-nucleon PV coupling constant h^1_π and five low-energy constants (LECs) In sect. **3**, we discuss the constraints of some of these LECs using the available accurate measurements of the $\vec{p}$-p longitudinal asymmetry. Finally, in the last section, we present a preliminary study of the longitudinal asymmetry in the $^3\mathrm{He}(\vec{n},p)^3\mathrm{H}$ reaction using this EFT potential. All the calculations reported in this contribution have been performed using a strong parity-conserving (PC) NN potential derived by Entem and Machleidt [11] using a chiral EFT at next-to-next-to-next-to-leading order (I-N3LO model). For $A = 4$, we have also included the three-nucleon (3N) force derived from a chiral EFT at N2LO [12], with the constants fixed in ref. [13] (N-N2LO model). The I-N3LO/N-N2LO model well describes the binding energies of ^{3}He, ^{3}H, and ^{4}He nuclei.

2. – The parity-violating potential

The potential can be constructed using time-ordered perturbation theory, following the same approach as for the PC potential described in ref. [14]. The different diagrams contributing to the PV NN potential up to order $\mathcal{O}(Q)$ are shown in fig. 1. The OPE diagram (a) gives the lowest order (LO) contribution (of order Q^{-1}). There is no contribution of order Q^0, but there are several contributions of order Q^1 (namely, at N2LO): a relativistic correction coming from diagram (a), TPE contributions coming from diagrams (d), (f), and (g), and and five contact interactions described by diagram (CT). The contributions of diagrams (b) and (c) vanish due to the integration over the loop variable, while those of diagrams (e) and (h) (vertex corrections) can be reabsorbed by a redefinition of the coupling constant h^1_π. More details on the derivation of the potential will be reported elsewhere [15].

In order to transform this potential in r-space, we have to multiply the expressions reported above by a cutoff, which is be chosen to be $f_\Lambda(k) = \exp[-(k/\Lambda)^4]$ where $\Lambda =$ 500–700 MeV is a cutoff parameter. With such a choice (a function which depends on k only), the resulting potential is local. The potential contains six unknown parameters, the pion-nucleon PV coupling constant h^1_π and five LECs C_i, $i = 1, \ldots, 5$ multiplying the contact interactions. In addition, the potential will depend on the cutoff parameter Λ needed to cut the potential at high k. A first estimate for these LECs can be obtained by comparing the chiral potential with the DDH model [2]. We have found $C_2 \approx 10 \times 10^{-7}$, while the other LECs are moreless of the order of 1×10^{-7} [15].

3. – The $\vec{p}$-p longitudinal asymmetry

There exist three accurate measurements of the angle-averaged $\vec{p}$-p longitudinal asymmetry $\overline{A}^{pp}_z(E)$, obtained at different laboratory energies E

$$\begin{aligned}
\overline{A}^{pp}_z(13.6\,\mathrm{MeV}) &= (-0.97 \pm 0.20) \times 10^{-7}, \quad \text{ref. [16]},\\
\overline{A}^{pp}_z(45\,\mathrm{MeV}) &= (-1.53 \pm 0.21) \times 10^{-7}, \quad \text{ref. [17]},\\
\overline{A}^{pp}_z(221\,\mathrm{MeV}) &= (+0.84 \pm 0.34) \times 10^{-7}, \quad \text{ref. [18]}.
\end{aligned} \tag{1}$$

Using the PV potential derived from the EFT, and taking into account the matrix elements of the different isospin operators, the longitudinal asymmetry at the end can be expressed as

$$\overline{A}^{pp}_z(E) = a_0(E) h^1_\pi + a_1(E) C'_1 + a_2(E) C_2, \tag{2}$$

where $C'_1 = C_1 + 2C_4 + 2C_5$ and $a_0(E)$, $a_1(E)$ e $a_2(E)$ are numerical coefficients independent of the values of the LECs (however, they depend on Λ). We would like to fix the three unknown parameters h^1_π, C'_1, and C_2 imposing that at the three energies the longitudinal asymmetry given in eq. (2) reproduce the experimental values given in eq. (1). However, the values of a_i at low energy scale as $\sqrt{E}$, since the longitudinal asymmetry is dominated by the contribution of S-waves. In practice, the experimental data at $E = 13.6$ MeV and $E = 45$ MeV are equivalent and the number of independent equations reduces to two.

It is therefore necessary to fix the value of one of the constant to determine the remaining two. In the following, we assume that the h^1_π value be in the "reasonable range" discussed in ref. [2]. In particular we perform the calculations for three values of the coupling constant h^1_π:

1) $h^1_\pi = 4.56 \times 10^{-7}$ ("best choice")
2) $h^1_\pi = 0$ (minimum value of the "reasonable range")
3) $h^1_\pi = 11.4 \times 10^{-7}$ (maximum value of the "reasonable range").

TABLE I. – *Coefficients C'_1 and C_2 for different values of h^1_π and Λ determined to reproduce the experimental values of $\overline{A}^{pp}_z$ at 45 and 221 MeV.*

Λ (MeV)	C'_1	C_2	C'_1	C_2	C'_1	C_2
	$h^1_\pi = 4.56 \times 10^{-7}$		$h^1_\pi = 0$		$h^1_\pi = 11.4 \times 10^{-7}$	
500	−2.15516	9.98171	−1.51765	4.00256	−3.11142	18.9504
600	−2.69957	10.03513	−2.18203	4.42237	−3.47588	18.4543
700	−4.22214	10.66532	−4.68110	5.86730	−3.53372	17.8623

The values of C'_1 and C_2, corresponding to the three choices of h^1_π and determined in order to reproduce the experimental longitudinal asymmetries at 45 and 221 MeV, are reported in table I.

4. – The ^{3}He$(\vec{n}, p)^3$H longitudinal asymmetry

For ultracold neutrons, the longitudinal asymmetry $A^{n^3\mathrm{He}}_z$ for the reaction $^3\mathrm{He}(\vec{n}, p)$ ^{3}H is given by $A^{n^3\mathrm{He}}_z = a_z \cos\theta$ [19], where θ is the angle between the outgoing proton momentum and the neutron beam direction. The coefficient a_z can be expressed in terms of products of T-matrix elements involving three PC and three PV transitions (see ref. [19] for more details). Such T-matrix elements are calculated by means of the HH method [20], using the I-N3LO/N-N2LO strong interaction model and the PV chiral potential.

In table II, we present the results of a preliminary calculation of a_z for the various choices of h^1_π and Λ, by taking the values of C'_1 and C_2 from table I, and assuming $C_1 = C'_1$ and $C_{3,4,5} = 0$. We observe that $A^{n^3\mathrm{He}}_z$ is dominated by the contribution of the (isovector) LO OPE potential. Naively, one expects that the most important contribution would come from the isoscalar operators (those multiplied by the LECs C_1 and C_2). In fact, at this energy, the reaction proceeds mainly through the close 0^+

TABLE II. – *The coefficient a_z (in units of 10^{-7}) describing the $^3\mathrm{He}(\vec{n}, p)^3\mathrm{H}$ longitudinal asymmetry (preliminary results). The calculations are performed using the I-N3LO NN plus the N-N2LO 3N potentials for the PC interaction, and the chiral PV potential model discussed in this paper for various choices of the pion-nucleon coupling constant h^1_π and the cutoff parameter Λ. The corresponding values of the LECs C_i, $i = 1, \ldots, 5$ are discussed in the text. In the columns labeled "OPE/LO" we have reported the values of a_z calculated by retaining in the PV potential only the LO OPE contribution, while in the columns labeled "FULL" we have included all terms.*

	$h^1_\pi = 4.56 \times 10^{-7}$		$h^1_\pi = 0$		$h^1_\pi = 11.4 \times 10^{-7}$	
	OPE/LO	FULL	OPE/LO	FULL	OPE/LO	FULL
500	−0.551	−0.544	0.000	+0.044	−1.377	−1.425
600	−0.554	−0.578	0.000	+0.034	−1.385	−1.497
700	−0.546	−0.584	0.000	+0.009	−1.366	−1.473

and 0^- resonances, which are considered to have total isospin $T=0$ [21]. Thus, the isoscalar operators in the PV potential should give the dominant contribution. However, the Coulomb interaction in the final state induces sizable isospin mixing configurations and, since the LO OPE term is the longest range term, at the end it gives the most important contribution, except the case where h^1_π is close to zero. The contribution of the relativistic correction to the LO OPE is always very tiny. For the case $h^1_\pi=0$, a_z is given mainly by the contribution of the isoscalar operator multiplying the LEC C_2.

Let us discuss now the dependence of a_z on the LECs $C_{3,4,5}$. Due to some cancellations between the contributions coming from the TPE and the different contact interaction terms, we have found a noticeable sensitivity to these LECs, of the order of 20%. Therefore, the measure of this observable could be very useful to extract them. From the table, we observe also that a_z does not depend very much on Λ. This dependence in some measure gives indication of the importance of high order contributions. The fact that it is found to be weak, it gives confidence that the PV potential at N2LO represents a good description of the NN PV potential.

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