Effective Field Theory Calculation of $nd$ Radiative Capture at Thermal Energies

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Abstract

The cross section for the thermal neutron capture by the deuteron is calculated with pionless Effective Field Theory (EFT). No new Three-Nucleon forces are needed up to next-to-next-to-leading order in order to achieve cut-off independent results, besides those fixed by the triton binding energy and Nd scattering length in the triton channel. The cross-section is accurately determined to be $\sigma_{\text{tot}} = [0.503 \pm 0.003] \text{mb}$. At zero energies, the magnetic $M1$-transition gives the dominant contribution and is calculated up to next-to-next-to-leading order ($N^2\text{LO}$). Close agreement between the available experimental data and the calculated cross section is reached. We demonstrate convergence and cutoff independence order by order in the low-energy expansion.

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I. INTRODUCTION

The study of the three-body nuclear system involving neutron radiative capture by deuteron has been investigated in theoretical and experimental works over the past years. The experimental result of this process has most accurately been measured by Jurney, et.al. [1]. The value of \(0.508 \pm 0.015\) (mb) for the cross section was resulted for 2200 m/sec neutrons.

Rapid progress has been made in the theoretical study of the \(Nd \rightarrow ^3H\gamma\) reaction such as the \(p-d\) and \(n-d\) radiative capture. At such energies a magnetic dipole (\(M_1\)) transition is almost entirely participated. These reactions were studied in plane wave (Born) approximation by Friar et al. [2]. In these investigations the authors employed their configuration-space Faddeev calculations of the helium wave function, with inclusion of three-body forces and pion exchange currents. More recently a rather detailed investigation of such processes has been performed by Viviani et al. [3,19]. In their calculations the quite accurate three-nucleon bound- and continuum states were obtained in the variational pair-correlated hyperspherical method from a realistic Hamiltonian model with two- nucleon and three-nucleon interactions.

They obtained in Ref. [3] the cross section from Argonne \(v_{14}\) two-nucleon and Urbana VIII three-nucleon interactions(\(AV14/UVIII\)), also from Argonne \(v_{18}\) two-nucleon and Urbana IX three-nucleon interactions(\(AV18/UIX\)) and including \(\Delta\) admixtures. Cross section values were found 0.600 (mb) and 0.578 (mb) which overestimate the experimental value by 18% and 14% value, respectively, see table 2. It should be noted, however, that the explicit, non-perturbative inclusion of \(\Delta\)-isobar degrees of freedom in the nuclear wave function are found to be in significantly better agreement with experiment than those obtained from perturbative (\(\Delta_{PT}\)) estimates. This shows that these results for this very-low energy observable are sensitive to details of the short-range part of the interaction. recent calculation using manifestly gauge-invariant currents reduced the spread [19], but the result including three-body currents, 0.558 mb, still over-predicts the cross-section by 10%. Model-dependent currents associated with the \(\Delta(1232)\) were identified as source of the discrepancy. Thus, the question remains how such details of short-range Physics can so severely influence a very-long-range reaction with maximal energies of less than 10 MeV.

During the last few years, nuclear Effective Field Theory (EFT) has been applied to two-, three-, and four-nucleon systems, see e.g. [4, 5, 6, 7, 8, 9, 10]. The pionless Effective Field Theory would be an ideal tool to calculate low-energy cross sections in a model-independent way and to possibly reduce the theoretical errors by a systematic, model-independent calculation with an a-priori estimate of the theoretical uncertainties. An example of a precise calculation is the reaction \(np \rightarrow \gamma d\), which is relevant to big-bang nucleosynthesis (BBN). The cross section for this process was computed to 1% error for center of mass energies \(E \lesssim 1\text{MeV}\) [11,12,13].

We have suggested a method for computation of neutron-deuteron radiative capture for extremely low energy (\(20 \leq E \leq 200\) Kev) with pionless EFT [15], where with this formalism, we can estimate errors in a perturbative expansion up to \(N^2\)LO within a few percent of the ENDF values [16].

The purpose of the present paper is to study the cross section for radiative capture of
neutrons by deuterons $nd \rightarrow \gamma^3H$ at zero energies with pionless EFT. At these energies, the magnetic $M_1$-transition gives the dominant contribution. The $M_1$ amplitude is calculated up to next-to-next-to-leading order (N$^2$LO) with insertion of three body force. Results show less than 1% deviation from the available experimental data at zero energy (0.0253 eV).

This article is organized as follows. In the next section, a brief description of the formalism and its input for total cross section of the neutron-deuteron radiative capture will be presented. We discuss the theoretical errors, tabulation of the calculated cross section in comparison with the other theoretical approaches and the most recent data [1] in section III. Finally, Summary and conclusions follow in Section IV.

II. NEUTRON-DEUTERON SCATTERING IN TRITON CHANNEL AND RADIATIVE CAPTURE

The $^2S_{1/2}$ channel to which $^3\text{He}$ and $^3\text{H}$ belong is qualitatively different from the other three-nucleon channels because all three nucleons can occupy the same points in space. Consequently, $^2S_{1/2}$ describes the preferred mode for $nd \rightarrow ^3H\gamma$ and $pd \rightarrow ^3H\gamma$. The three-nucleon Lagrangean is well-known and will not be repeated here, see e.g. [14,18] for details.

The derivation of the integral equation describing neutron-deuteron scattering has also been discussed before, see e.g. [7,18]. We present here only the results. The integral equation is solved numerically by imposing a cut-off $\Lambda$. In that case, a unique solution exists in the $^2S_{1/2}$-channel for each $\Lambda$ and vanishing three-body force, but no unique limit as $\Lambda \rightarrow \infty$. As long-distance phenomena must however be insensitive to details of the short-distance physics (and in particular of the regulator chosen), Bedaque et al. [6,7,14,18] showed that the system must be stabilized by a three-body force

$$
H(E;\Lambda) = \frac{2}{\Lambda^2} \sum_{n=0}^{\infty} H_{2n}(\Lambda) \left( \frac{ME + \gamma_i^2}{\Lambda^2} \right)^n = \frac{2H_0(\Lambda)}{\Lambda^2} + \frac{2H_2(\Lambda)}{\Lambda^4} (ME + \gamma_i^2) + \ldots .
$$

which absorbs all dependence on the cut-off as $\Lambda \rightarrow \infty$. It is analytical in $E$ and can be obtained from a three-body Lagrangean, employing a three-nucleon auxiliary field analogous to the treatment of the two-nucleon channels [14]. Contrary to the terms without derivatives, there are different, inequivalent three-body force terms with two derivatives, but only one of them, $H_2$, is enhanced over its naive dimensional estimate, mandating its inclusion at N$^2$LO [14,20]. Neutron-deuteron scattering amplitude including the new term generated by the two-derivative three-body force is shown schematically in Fig.1. Two amplitudes get mixed: $t_s$ describes the $d_t + N \rightarrow d_s + N$ process, and $t_t$ describes the $d_t + N \rightarrow d_t + N$ process, where $d_s$ ($d_t$) is an auxiliary field of two nucleons in a relative singlet-S (triplet-S) wave.
\[
t_s(p, k) = \frac{1}{4} \left[ 3K(p, k) + 2H(E, \Lambda) \right] + \frac{1}{2\pi} \int_0^\Lambda dq \, q^2 \left[ D_s(q) \left[ K(p, q) + 2H(E, \Lambda) \right] t_s(q) \right] \\
+ \mathcal{D}_t(q) \left[ 3K(p, q) + 2H(E, \Lambda) \right] t_t(q)
\]

\[
t_t(p, k) = \frac{1}{4} \left[ K(p, k) + 2H(E, \Lambda) \right] + \frac{1}{2\pi} \int_0^\Lambda dq \, q^2 \left[ D_t(q) \left[ K(p, q) + 2H(E, \Lambda) \right] t_t(q) \right] \\
+ \mathcal{D}_s(q) \left[ 3K(p, q) + 2H(E, \Lambda) \right] t_s(q)
\] (2)

where \( \mathcal{D}_{s,t}(q) = \mathcal{D}_{s,t}(E - \frac{q^2}{2M}, q) \) are the propagators of the auxiliary fields \( d_{s,t} \), and \( K \) the propagator of the exchanged nucleon, projected into the S-wave. For the spin-triplet S-wave channel, one determines the two-nucleon interaction up to N²LO by the deuteron binding momentum \( \gamma_t = 45.7025 \text{ MeV} \) and effective range \( \rho_t = 1.764 \text{ fm} \). Because there is no real bound state in the spin singlet channel of the two-nucleon system, its free parameters are better determined by the scattering length \( a_s = 1/\gamma_s = -23.714 \text{ fm} \) and the effective range \( r_s = 2.73 \text{ fm} \) at zero momentum.

The neutron-deuteron \( J = 1/2 \) phase shifts \( \delta \) is determined by the on-shell amplitude \( t_t(k, k) \), multiplied with the wave function renormalisation

\[
T(k) = Zt_t(k, k) = \frac{3\pi}{M} \frac{1}{k \cot \delta - i} .
\] (3)

At thermal energies, the reaction proceeds through S-wave capture predominantly via a magnetic dipole transition, \( M_t^{LSJ} \), where \( L=0 \), \( S=1/2,3/2 \) and \( i=1 \). To obtain the spin structure, which corresponds to a definite value of \( J \) for the entrance channel, it is necessary to build special linear combinations of products \( \vec{D}N \) and \( \vec{\sigma} \times \vec{D}N \), with \( J^P = \frac{1}{2}^+ \) or \( J^P = \frac{3}{2}^+ \), and \( \vec{D} \) the deuteron spin-one field, see [15] for details.

\[
\vec{\phi}_{1/2} = (i\vec{D} + \vec{\sigma} \times \vec{D})N \text{ and } (2i\vec{D} - \vec{\sigma} \times \vec{D})N .
\]

For both possible magnetic dipole transitions with \( J^P = \frac{1}{2}^+ \) (amplitude \( g_1 \)) and \( J^P = \frac{3}{2}^+ \)
(amplitude $g_3$) we can write:

$$g_1: \ t^\dagger (i \vec{D} \cdot e^3 \times \vec{k} + \vec{\sigma} \times \vec{D} \cdot \vec{e}^3 \times \vec{k}) N,$$

$$g_3: \ t^\dagger (i \vec{D} \cdot e^3 \times \vec{k} + \vec{\sigma} \times \vec{D} \cdot \vec{e}^3 \times \vec{k}) N. \quad (4)$$

The contribution of the electric transition $E_1^{LSJ}$ for energies of less than 60 KeV to the total cross section is very small. Therefore, the electric quadrupole transition $E_2^{0(3/2)(3/2)}$ from the initial quartet state will not be considered at thermal energies. The $M_1$ amplitude receives contributions from the magnetic moments of the nucleon and dibaryon operators coupling to the magnetic field, which are described by the Lagrange density

$$\mathcal{L}_B = \frac{e}{2M_N} N^\dagger (k_0 + k_1 \tau^3) \vec{\sigma} \cdot \vec{B} + e \frac{L_1}{M_N \sqrt{r^{(1S_0)}r^{(1S_1)}}} d_{i3}^j d_{s3} B_j + H.C. \quad (5)$$

where $k_0 = 1/2(k_p + k_n) = 0.4399$ and $k_1 = 1/2(k_p - k_n) = 2.35294$ are the isoscalar and isovector nucleon magnetic moment in nuclear magnetons, respectively. The NLO-coefficient $L_1$ is fixed at its leading non-vanishing order to the thermal cross section [11].

FIG. 2: Some diagrams for adding photon-interaction to the Faddeev equation up to N$^2$LO. Wavy line shows photon and small circles show magnetic photon interaction. For $L_1$ vertices, see eq.(7); $H_2$:three- body force, see eq.(3). Remaining notation as in Fig. 1

The radiative capture cross section $nd \rightarrow ^3H\gamma$ at very low energy is given by

$$\sigma = \frac{2}{9} \frac{\alpha}{v_{rel}} \frac{p^3}{4M_N^2} \sum_{iLSJ} |\tilde{\chi}_{iLSJ}|^2 , \quad (6)$$

where

$$\tilde{\chi}_{iLSJ} = \sqrt{\frac{6\pi}{p\mu_N}} \sqrt{4\pi \chi_{iLSJ}}, \quad (7)$$

with $\chi$ stands for either E or M and $\mu_N$ is in nuclear magneton and p is momentum of the incident neutron in the center of mass.

We now turn to the Faddeev integral equation to be used in the $M_1$ calculation. We solve the Faddeev equation for nd-scattering and also for the triton bound state to some order (e.g. LO), then we take these Faddeev amplitudes and sandwich the photon-interactions with
nucleons between them when the photon kernel is expanded to the same order. This process will be done separately for NLO and N^2LO. Finally the wave function renormalization in each order will be done.

The diagrams in Fig. 3 represent contributions of electromagnetic interaction with nucleon, deuteron, four-nucleon-magnetic-photon operator described by a coupling between the ^3S_1-dibaryon and ^1S_0-dibaryon and a magnetic photon. As mentioned in the introduction, in another paper [15], we have presented detailed schematic of these diagrams in neutron-deuteron radiative capture for (20 ≤ E ≤ 200 keV) up to N^2LO.

The last diagrams in Fig. 3 with insertion of a photon to the N^2LO three-nucleon force H_2 vertex is not M_1 and we know that M_1 contribution is the dominant contribution at very low energy and especially for zero energy. Its contribution should therefore be very tiny. Because the leading three-nucleon force H_0 has no derivatives, it is not affected by the minimal substitution p → p − eA. But the parameter H_2 is the strength of the three-nucleon interaction with two derivatives. Naturally for the energy range near zero momentum, insertion of photon to H_2 vertices for momentum p ∼ 0.025eV and M_1 transition, could be neglected. H_2 is necessary in neutron-deuteron scattering to improve cut-off independence but is defined such that it does not contribute at zero momentum. Contributions of a photon coupling to H_2 are however indeed negligible at zero energy.

### III. NEUTRON-DEUTERON RADIATIVE CAPTURE RESULTS AT ZERO ENERGY

We numerically solved the Faddeev integral equation up to N^2LO. We used ℏc = 197.327 MeV fm, a nucleon mass of M = 938.918 MeV, for the NN triplet channel a deuteron binding energy (momentum) of B = 2.225 MeV (γ_d = 45.7066 MeV), a residue of Z_d = 1.690(3), for the NN singlet channel an ^1S_0 scattering length of a_s = −23.714 fm , L_1 ∼ −4.5 fm by fixing at its leading non-vanishing order by the thermal cross section.

As in Ref. [20], we can determine which three-body forces are required at any given order, and how they depend on the cutoff.

Low-energy observables must be insensitive to the cut-off, namely to any details of short-distance physics in the region above the break-down scale of the pion-less EFT, set approximately by the pion-mass. It was found in Ref. [20] that no additional three-nucleon forces are necessary to render a renormalisable amplitude at N^2LO in this process, besides those needed already in nucleon-deuteron scattering: H_0 and H_2. At N^2LO , where we saw that H_2 is required, we checked this by varying the cut-off between 150 and 500 MeV. This is a reasonable estimate of the errors of our calculation due to higher-order effects. As seen in Fig. 3, in the thermal energy range the cutoff variation is very small and decreases steadily as we increase the order of the calculation and it is of the order of (k/Λ)^n, (γ/Λ)^n, where n is the order of the calculation and Λ = 150 MeV is the smallest cutoff used ( see Table I and Fig. 3). Also, errors due to cutoff variation is decreasing when the order of calculation is increased up to N^2LO.

We determined the two-nucleon parameters from the deuteron binding energy, triplet effective range (defined by an expansion around the deuteron pole, not at zero momentum), the singlet scattering length, effective range (defined by expanding at zero momentum), and
two body capture process (obtained with comparison between experimental data and theoretical results for \( np \to d\gamma \) process at zero energy \[12\]). We fix the three-body parameters as follows: because we defined \( H_2 \) such that it does not contribute at zero momentum scattering, one can first determine \( H_0 \) from the \( ^2S_\frac{1}{2} \) scattering length \( a_3 = (0.65 \pm 0.04) \) fm \[17\]. At LO and NLO, this is the only three-body force. At \( N^2LO \), \( H_2 \) is required. It is determined by the triton binding energy \( B_3 = 8.48 \) MeV. Finally, we solve by insertion of the potential at a given order in the integral equation and iteration of kernel.

The cross section for neutron-deuteron radiative capture as function of the center-of-mass energy up to \( N^2LO \) is shown in Fig. 4. We also show single point that shows the available experimental results for this cross section at 0.025 eV \[1\].

Table II shows Comparison between results of different models-dependent, model-independent EFT and experiment, for neutron radiative capture by deuteron up to \( N^2LO \),
FIG. 4: The cross section for neutron radiative capture by deuteron as function of the center-of-
mass kinetic energy $E$ in MeV. The short dashed, long dashed and solid line correspond to the con-
tribution of $M_1$ capture cross section up to LO, NLO and $N^2$LO, respectively. Single point 
shows experimental results for this cross section at 0.025 eV.

TABLE II: Comparison between different theoretical results for Neutron radiative capture by 
deuteron at zero energy (0.0253 ev). Last row shows our EFT result. The last line quotes deviation 
between data and theory, if it is larger than the theoretical or experimental uncertainty.

| Theory                          | $\sigma$ (mb) | deviation from exp. |
|--------------------------------|---------------|---------------------|
| AV14/VIII (IA+MI+MD) [3]       | 0.509         |                     |
| AV18/IX (IA+MI+MD) [3]         | 0.489         | 4%                  |
| AV14/VIII(IA+MI+MD+$\Delta_{PT}$) [3] | 0.658       | 29%                 |
| AV18/IX(IA+MI+MD+$\Delta_{PT}$) [3] | 0.631       | 24%                 |
| AV14/VIII(IA+MI+MD+$\Delta$) [3] | 0.600         | 18%                 |
| AV18/IX(IA+MI+MD+$\Delta$) [3] | 0.578         | 14%                 |
| AV18/IX (gauge inv.) [19]      | 0.523         | 3%                  |
| AV18/IX (gauge inv. + 3N-current) [19] | 0.556     |                     |
| EFT(LO)                        | 0.485         | 5%                  |
| EFT(NLO)                       | 0.496         |                     |
| EFT($N^2$LO)                   | 0.503 ± 0.003 |                     |
| Experiment [1]                 | 0.508 ± 0.015 |                     |

at zero energy (0.0253 ev). The calculations by Viviani et al. [3, 19] shows sensitivity to
short-range physics namely to details of including the physics of the Delta and pion-exchange currents. The calculation of Ref. [19] with manifestly gauge-invariant current operators is quite sensitive to including meson-exchange three-nucleon currents. One might therefore have been tempted to conclude that a new three-nucleon force is also needed in the pionless EFT. As shown above, this is not the case: There are no new three-nucleon forces besides those already fixed in nd scattering at the same order. The contribution from the photon coupling to a three-nucleon force is negligible in our calculation. As our result is model-independent and universal, any model with the same input must – within the accuracy of our calculation – lead to the same result. Our inputs are the first two terms of the effective-range expansion in the singlet- and triplet-S wave of NN scattering, the proton and neutron magnetic moments, the triton binding energy and nd scattering length in the doublet-S-wave, and finally the thermal cross section of the reaction np → dγ (determining $L_1$). More work is needed to understand why the potential-model calculations [3,19] have the same input but do not seem to reproduce the same result.

Addressing convergence of the EFT calculation, we notice that the contributions which are characterized as higher-order in the power-counting are indeed small: The LO result is 0.485 mb, with NLO adding 0.011 mb, and N$^2$LO another 0.007 mb. Cut-off dependence is negligible. The typical size of the expansion parameter in the pion-less EFT is about $\gamma_t/m_\pi \approx 1/3$. We therefore estimate the uncertainty from leaving out corrections at N$^{3}$LO and higher as about 1/3 of the N$^2$LO correction or 0.003 mb.

IV. CONCLUSION

The cross section for radiative capture of neutrons by deuterons nd → $\gamma^3H$ at zero energies with was calculated pionless Effective Field Theory, the unique, model independent and systematic low-energy version of QCD for processes involving momenta below the pion mass. We applied pionless EFT to find numerical results for the $M_1$ contributions. Incident thermal neutron energies have been considered for this capture process. At these energy our calculation is dominated by only S-wave state and magnetic transition $M_1$ contribution. The $M_1$ amplitude is calculated up to Next-to-Next to leading order N$^2$LO. Three-Nucleon forces are needed up to N$^2$LO order for cut-off independent results. The triton binding energy and nd scattering length in the triton channel have been used to fix them. Hence the cross-section is in total determined as $\sigma_{tot} = [0.485(LO) + 0.011(NLO) + 0.007(N^2LO)] = [0.503 \pm 0.003] mb$. It converges order by order in low energy expansion. It is also cut-off independent at this order. We notice that our calculation has a systematic uncertainty from higher-order terms which is now smaller than the experimental error-bar.
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