Two-Pion Exchange Currents in Photodisintegration of the Deuteron

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Content

- Chiral Effective Field Theory (ChEFT)
- Electromagnetic current operators within ChEFT
- Calculations of polarization observables in photodisintegration of the deuteron
- Conclusions and outlook
Forces and currents

• Many models
• A lot of experience gained

Problem of consistence: we need a good theory!

Chiral Effective Field Theory

Forces  Currents

Experimental data
Forces and Currents

The LO nucleon-nucleon potential is given by one pion exchange (OPE) and contact terms.

\[ V_{LO} = V_{\text{cont}} + V_{1\pi} \]

The NLO corrections are due to one and two-pion exchanges (TPE) as well as new contact interactions. The N2LO and N3LO include corrections with many-pion exchanges and contact interactions in higher orders.

\[ V_{NLO} = V_{\text{cont}} + V_{1\pi} + V_{2\pi} \]

The current operator must be consistent with the nucleon-nucleon interaction.

The effective operator for two-nucleon (2N) system is a sum of the single nucleon operators and two-nucleon operator:

\[ j^{\mu}_{2N} = j^{\mu}(1) + j^{\mu}(2) + j^{\mu}(1, 2) \].
Two-nucleon electromagnetic currents

\[ j^\mu(1, 2) = j^\mu_{\text{mec}}(1, 2) + j^\mu_{\text{cont}}(1, 2) \]

\[ j^\mu_{\text{mec}}(1, 2) = j^\mu_{\pi}(1, 2) + j^\mu_{2\pi}(1, 2) + \ldots \]

Two-pion exchange (TPE) currents in NLO arise from many complicated processes

Results by S. Kölling, E. Epelbaum et al. ('09) using the method of unitary transformation

Rederived:
- single-nucleon current operators
- one-pion exchange current operators

Derived:
- (long-ranged) two-pion exchange current operators containing no free parameters

Work in progress:
- contact terms

How do we apply the long-ranged two-pion exchange current operators?

We get contributions to:

- $0^{th}$ component of the current operator (charge density) $j^0$
- Vector components of the current operator $j$

The most general expression for the current and the charge density in momentum space is given by:

$$j^0 = \sum_{\alpha=1}^{5} \sum_{\beta=1}^{8} f^\beta_s (\vec{q}_1, \vec{q}_2) T_\alpha O^\beta; \quad \vec{j} = \sum_{\alpha=1}^{5} \sum_{\beta=1}^{24} f^\beta (\vec{q}_1, \vec{q}_2) T_\alpha \vec{O}^\beta$$

$q_1 = p'_1 - p_1 = p' - p + \frac{1}{2} k$
$q_2 = p'_2 - p_2 = p - p' + \frac{1}{2} k$
$k = q_1 + q_2$
For the photodisintegration of the deuteron, we work with the following operators:

\[
\begin{align*}
O^3 &= \tilde{q}_1 \times \tilde{\sigma}_2 + \tilde{q}_2 \times \tilde{\sigma}_1 \\
O^4 &= \tilde{q}_1 \times \tilde{\sigma}_2 - \tilde{q}_2 \times \tilde{\sigma}_1 \\
O^5 &= \tilde{q}_1 \times \tilde{\sigma}_1 + \tilde{q}_2 \times \tilde{\sigma}_2 \\
O^6 &= \tilde{q}_1 \times \tilde{\sigma}_2 - \tilde{q}_2 \times \tilde{\sigma}_2 \\
O^7 &= \tilde{q}_1 (\tilde{q}_1 \cdot \tilde{q}_2 \times \tilde{\sigma}_2) + \tilde{q}_2 (\tilde{q}_1 \cdot \tilde{q}_2 \times \tilde{\sigma}_1) \\
O^8 &= \tilde{q}_1 (\tilde{q}_1 \cdot \tilde{q}_2 \times \tilde{\sigma}_2) - \tilde{q}_2 (\tilde{q}_1 \cdot \tilde{q}_2 \times \tilde{\sigma}_1) \\
O^9 &= \tilde{q}_2 (\tilde{q}_1 \cdot \tilde{q}_2 \times \tilde{\sigma}_2) + \tilde{q}_1 (\tilde{q}_1 \cdot \tilde{q}_2 \times \tilde{\sigma}_1) \\
O^{10} &= \tilde{q}_2 (\tilde{q}_1 \cdot \tilde{q}_2 \times \tilde{\sigma}_2) - \tilde{q}_1 (\tilde{q}_1 \cdot \tilde{q}_2 \times \tilde{\sigma}_1)
\end{align*}
\]

\[
O^2 = \tilde{q}_1 - \tilde{q}_2
\]

\[
T_2 = (\tau_1 - \tau_2)_3 \\
T_3 = (\tau_1 \times \tau_2)_3
\]

Working with *Mathematica* is quite important!

For example:

\[
f_2^8(q_1,q_2) = \frac{eg_A^2\pi}{2F^4_{\pi}} \left[ 8\pi q_1^2 (q_1^2 - 2M^2) I^{(d+4)}_{(3,1,2)} - g_A^2 M^2 I^{(d+2)}_{(2,1,2)} + 192\pi^2 g_A^2 q_1^2 I^{(d+6)}_{(4,1,2)} - 64\pi^2 g_A^2 q_1 q_2 z I^{(d+6)}_{(3,2,2)} + 8\pi g_A^2 I^{(d+4)}_{(2,1,2)} + (g_A^2 - 1) I^{(d+2)}_{(2,1,0)} + 16\pi (g_A^2 - 1) I^{(d+4)}_{(3,1,0)} \right] - (1 \leftrightarrow 2),
\]

where

\[
z = \hat{q}_1 \cdot \hat{q}_2
\]

functions \(I^{(d)}(v_1,v_2,v_3)\) correspond to the three-point functions.

Two nucleon reactions

The formalism requires knowledge of the consistent potentials and electromagnetic currents.

\[ V_{2N}, \quad j^\mu \]

\[ |\Psi_{\text{bound}}\rangle \quad |\Psi_{\text{scatt}}^\text{pn}\rangle = (1 + G_0 t) |\text{pn}\rangle \]

\[ t = V_{2N} + V_{2N} G_0 t \]

\( G_0 \) – the free propagator of two nucleon

\( t \) – satisfies the Lippmann – Schwinger equation

\[ N_\mu \equiv \langle \Psi_{\text{scatt}}^\text{pn} | j^\mu | \Psi_{\text{bound}} \rangle \]

All calculations were made with the chiral potentials and currents. The AV18 potential and the corresponding currents were used as the reference calculation.

For a given chiral N2LO NN potential we produce: the deuteron wave function and matrix elements of the t-operator.
Photodisintegration of the deuteron

Calculations of polarization observables for two photon energies.

For polarized deuteron target we have

\[
\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_0 \sum_{kq} (-1)^q t_{kq} T_{k-q}(\theta)
\]

We calculated the following observables:

- Deuteron analyzing powers: \(T_{20}, T_{21}, T_{22}\)
- Photon analyzing power \(\Sigma_l\)
- Differential cross-sections
Results for the deuteron tensor analyzing powers for the photon energy bin 25 - 45 MeV

Results for the deuteron tensor analyzing powers for the photon energy bin 45 - 65 MeV

Experimental data from
Results for the deuteron tensor analyzing powers for the photon energy bin 65 - 100 MeV

Results for the photon analyzing power at three energies 30, 60 and 100 MeV

Results for the differential cross section for three photon energies 30, 60 and 100 MeV

Experimental data from
Conclusions and outlook

- ChEFT has become a standard tool in nuclear physics – it offers a consistent picture of nuclear forces and nuclear current operators.
- Chiral 2N and 3N potentials are already used for studying the structure of nuclei and nuclear reactions.
- We used results of ChEFT to compute electromagnetic reactions with few nucleon systems. In particular, we considered low energy photodisintegration reaction.
- We compared predictions based on this approach to the results obtained within a more traditional framework, where the high precision nucleon-nucleon potential AV18 and the current operator including meson exchange currents consistent with this force is employed.
- We have shown results for the unpolarized cross sections and various polarization observables.
- The main aim of our work is to create a complete framework for the description of two- and three-nucleon processes including many-body electromagnetic currents and forces in the ChEFT approach.
Thank you for your attention!
How we proceed

For deuteron one needs:

\[ N^\mu \equiv < \tilde{p}_0 \left| \left( 1 + t \left( \frac{p_0^2}{m} + i\varepsilon \right) G_0 \left( \frac{p_0^2}{m} + i\varepsilon \right) \right) j_{2N}^\mu (k) \right| \phi_d > \]

How do we do PWD?

\[ < p'(l's') ; t'm_t \mid j_{\alpha\beta} (k \mid \hat{z}) \mid p(ls) jm; tm_t > = \]

\[ \int d\hat{p}' \int d\hat{p} \sum_{m_{l'}} C(l's' ; m_{l'}, m' - m_{l'}, m') Y_{l'm_{l'}}^* (\hat{p}') \]

\[ \sum_{m_l} C(lsj ; m_l, m - m_l, m) Y_{lml} (\hat{p}) f_{\alpha\beta} (q_1, q_2, \hat{q}_1 \cdot \hat{q}_2) \]

\[ < t'm_t \mid T_\alpha \mid tm_t > < s'm' - m_l \mid O_\beta (\tilde{q}_1, \tilde{q}_2) \mid sm - m_l > , \]

\[ m' = m' (m, \beta) \]

\[ m_{t'} = m_t \]
All integrals, in particular spin and isospin matrix elements:

\[
\sum_{m_{l'}} C(l's'; m'_{l'}, m'-m'_{l'}, m') Y^*_{l'm_{l'}} (\hat{p}')
\]

\[
\sum_{m_{l'}} C(lsj; m_{l'}, m-m_{l'}, m) Y_{l m_{l'}} (\hat{p}) f_{\alpha\beta} (q_1, q_2, \hat{q}_1 \cdot \hat{q}_2)
\]

\[
< t' m_{l'} | T_\alpha | t m_t > < s' m'-m_{l'} | O_\beta (\bar{q}_1, \bar{q}_2) | s m-m_{l} >
\]

are prepared using *Mathematica*

For a given set of quantum numbers: \( \{ l', s', j', t', l, s, j, m, t, m_t \} \)
we identify all non-zero cases and produce a Fortran code (again using *Mathematica*) to get the integrals calculated on a parallel machine.