A02: Pion production in chiral EFT

PIs: Hans-Werner Hammer and Robert Roth

Jonas Braun

Institut für Kernphysik

3rd Workshop of the SFB 1245, 4-6 July 2018

TECHNISCHE UNIVERSITÄT DARMSTADT

SFB 1245

Neutral Pion Photoproduction on ^{3}He

TECHNISCHE UNIVERSITÄT DARMSTADT

- calculate **threshold π^0 photoproduction** at LO in χEFT
- extraction of **neutron S-wave amplitude** from ^{3}He calculation
- hadron physics motivation $\rightarrow$ ^{3}He as a **neutron-like** target
- **counterintuitive** ChPT prediction [Bernard et al., 1996, Bernard et al., 2001]

$$E_{0+}^{\pi^0 p} = -1.16 \times 10^{-3} / M_{\pi^+} \qquad E_{0+}^{\pi^0 n} = +2.13 \times 10^{-3} / M_{\pi^+}$$

Neutral Pion Photoproduction on ^{3}He

- calculate **threshold π^0 photoproduction** at LO in χEFT
- extraction of **neutron S-wave amplitude** from ^{3}He calculation
- hadron physics motivation $\rightarrow$ ^{3}He as a **neutron-like** target
- **counterintuitive** ChPT prediction [Bernard et al., 1996, Bernard et al., 2001]

$$E_{0+}^{\pi^0 p} = -1.16 \times 10^{-3} / M_{\pi^+} \qquad E_{0+}^{\pi^0 n} = +2.13 \times 10^{-3} / M_{\pi^+}$$

- **threshold amplitude:** $\langle M_{J'} | \hat{O} | M_J \rangle = 2i\, E_{0+} \left(\vec{\epsilon}_{\lambda,T} \cdot \vec{J}_{M_{J'}, M_J} \right)$
- calculate matrix element numerically with **Monte Carlo** integration
- sensitivity of threshold S-wave cross section **a_0 to $E_{0+}^{\pi^0 n}$** ?

Neutral Pion Photoproduction on ^{3}He

- **sensitivity to $E_{0+}^{\pi^0 n}$ for ^{3}He:** $$a_0 = \frac{|\vec{k}|}{|\vec{q}|}\frac{d\sigma}{d\Omega}\Big|_{\vec{q}=0} = \left|E_{0+}\right|^2$$
- E_{0+}^{theo} is **12% below** experimental value

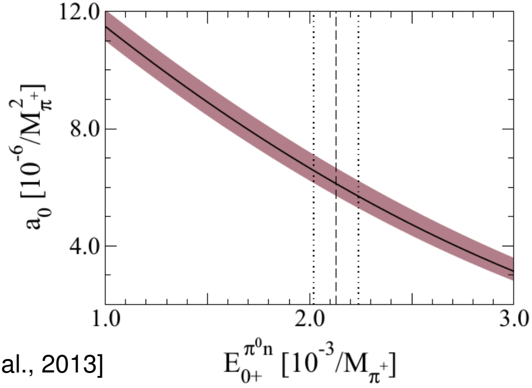
nuclear S-wave multipole:

$E_{0+}^{theo} = (-2.8 \pm 0.2) \times 10^{-3}/M_{\pi^+}$

[Lenkewitz et al., 2013]

$E_{0+}^{exp} = (-2.48 \pm 0.11) \times 10^{-3}/M_{\pi^+}$

[Argan et al., 1988]



[Lenkewitz et al., 2013]

Neutral Pion Photoproduction off light nuclei

TECHNISCHE UNIVERSITÄT DARMSTADT

- nuclear physics motivation to further **test ChPT**

  $\rightarrow$ use **IT-NCSM approach** to calculate wave function of light nuclei

- initially wanted to use Monte Carlo integration

  $\rightarrow$ 1N- and 2N-**density matrices** from IT-NCSM results more convenient

- χEFT amplitudes in plane wave basis

  $\rightarrow$ need **basis transformation** to HO basis

Neutral Pion Photoproduction off light nuclei

TECHNISCHE UNIVERSITÄT DARMSTADT

- nuclear physics motivation to further **test ChPT**
  $\rightarrow$ use **IT-NCSM approach** to calculate wave function of light nuclei
- initially wanted to use Monte Carlo integration
  $\rightarrow$ 1N- and 2N-**density matrices** from IT-NCSM results more convenient
- χEFT amplitudes in plane wave basis
  $\rightarrow$ need **basis transformation** to HO basis
- evaluate expectation value by tracing over matrices

$$\langle \Psi_f | \hat{O} | \Psi_i \rangle = Tr \left(\mathbf{UOU}^\dagger \rho_{\Psi_f \Psi_i} \right)$$

$$U = \langle SP_{HO} | SP_{PW} \rangle := \langle (nlm) m_s m_t | \vec{k} m_s m_t \rangle = i^l \Phi_{nl}(k) Y^*_{lm}(\Omega_k)$$

One-Nucleon Magnetic Moment

TECHNISCHE UNIVERSITÄT DARMSTADT

- consistency check by comparison of **magnetic moments**

$$\mu^{1N}\vec{J}_{M_{J'},M_J} = \left\langle M_{J'} \left| \vec{\sigma}_1 \left(\mu_S + \tau_1^z \mu_V\right) \right| M_J \right\rangle_\Psi = \mathrm{Tr}\left(U O_M^{1N} U^\dagger \rho^{(1N)}_{M_{J'},M_J} \right)$$

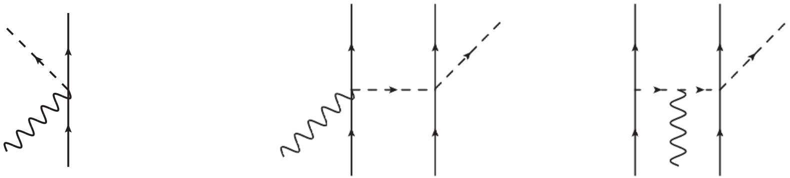
	μ^{1N} $[\mu_N]$	
nucl	density	literature
^{3}H	2.67(4)	2.58(4) [1]
^{3}He	-1.86(5)	-1.81(3) [1]

[1] [Lenkewitz et al., 2013]

- results in **good agreement** $\rightarrow$ different NN interactions
- **uncertainties** mainly from deviation of different M_J combinations

Neutral Pion Photoproduction off light nuclei

- one-, two-, three- and A-nucleon contributions at **different orders** in χEFT
- **at LO:** one- and two-nucleon contributions



- reproduce ^{3}He & ^{3}H results with IT-NCSM wave functions
- **straightforward extension** to other light nuclei
- compare results with **experiments**

One-Nucleon Neutral Pion Photoproduction

TECHNISCHE UNIVERSITÄT DARMSTADT

- compare **one-nucleon π^0-production amplitudes** for different nuclei

	E_{0+}^{1N} $[10^{-3}/M_{\pi^+}]$	
nucl	density	literature
^{2}H	0.39(3)	0.36 [1]
^{3}H	-1.00(5)	-0.93(3) [2]
^{3}He	1.77(5)	1.71(3) [2]
^{6}Li	0.22(3)	
^{7}Li	-0.94(5)	
^{9}Be	1.40(5)	

[1] [H. Krebs, 2000]

[2] [Lenkewitz et al., 2013]

- with given wave function, calculation at **small cost** for arbitrary nuclei
  $\rightarrow$ workstation sufficient
- at threshold, only contribution if **$J \neq 0$**

Two-Nucleon Neutral Pion Photoproduction

TECHNISCHE UNIVERSITÄT DARMSTADT

- two-nucleon contribution **same order** as one-nucleon part
- same approach, but **significantly higher** computing time
  $\rightarrow$ need two-body density matrices
  $\rightarrow$ two-particle model space grows quadratically with number of s.-p. states
  $\rightarrow$ matrix dimensions increase by **power of four**

Two-Nucleon Neutral Pion Photoproduction

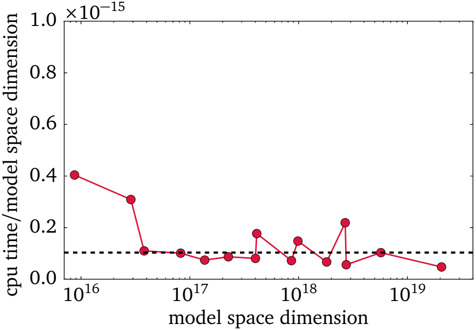
- two-nucleon contribution **same order** as one-nucleon part
- same approach, but **significantly higher** computing time

  $\rightarrow$ need two-body density matrices

  $\rightarrow$ two-particle model space grows quadratically with number of s.-p. states

  $\rightarrow$ matrix dimensions increase by **power of four**

$\Rightarrow$ calculate two-nucleon part at **Lichtenberg-Cluster**



Summary & Outlook

TECHNISCHE UNIVERSITÄT DARMSTADT

Summary

- threshold pion photoproduction at LO in χEFT
- one- and two-nucleon contributions
- extension to arbitrary nuclei straightforward
- further test of ChPT

SFB 1245

DFG Deutsche Forschungsgemeinschaft

HGS-HIRe for FAIR
Helmholtz Graduate School for Hadron and Ion Research

Summary & Outlook

TECHNISCHE UNIVERSITÄT DARMSTADT

Summary

- threshold pion photoproduction at LO in χEFT
- one- and two-nucleon contributions
- extension to arbitrary nuclei straightforward
- further test of ChPT

SFB 1245

DFG Deutsche Forschungsgemeinschaft

HGS-HIRe for FAIR
Helmholtz Graduate School for Hadron and Ion Research

Outlook

- calculate two-nucleon part at Lichtenberg-Cluster
- motivate experiments (MAMI)
- consider P-wave contributions close to threshold

References

TECHNISCHE UNIVERSITÄT DARMSTADT

Bernard, V., Kaiser, N., and Meissner, U.-G.
Z. Phys., C70:483–498.

Bernard, V., Kaiser, N., and Meissner, U.-G.
Eur. Phys. J., A11:209–216.

Lenkewitz, M., Epelbaum, E., Hammer, H. W., and Meissner, U. G.
Eur. Phys. J., A49:20.

Argan, P. et al.
Phys. Lett., B206:4.
[Erratum: Phys. Lett.B213,564(1988)].

Bernard, V., Kaiser, N., and Meissner, U.-G.
Phys. Lett., B383:116–120.

Charged Pion Photoproduction off light nuclei

TECHNISCHE UNIVERSITÄT DARMSTADT

- **same diagrams** as for neutral pion production
- however, **at LO only one-nucleon contribution** from Kroll-Ruderman term
  $\rightarrow$ first two-nucleon contribution at NLO
- pion-production amplitudes off proton and neutron **larger in magnitude** [Bernard et al., 1996]

$$E_{0+}^{\pi^- p} = -31.7 \times 10^{-3}/M_{\pi^+} \qquad E_{0+}^{\pi^+ n} = 27.6 \times 10^{-3}/M_{\pi^+}$$

- **different** incoming and outgoing nucleus
  $\rightarrow$ only **bound states** possible for IT-NCSM calculations
  $\rightarrow$ both nuclei spins must be **unequal zero**