Pion absorption from the lowest atomic orbital in ^{2}H, ^{3}He and ^{3}H

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LENPIC

Outline

- Introduction: elements of formalism
- Results on pion absorption in ^2H, ^3He and ^3H
- Conclusions and outlook

Introduction

Efficient momentum-space nonrelativistic framework to deal with nucleon-deuteron scattering and many electroweak processes has been constructed and tested:
Phys. Rept. 274, 107 (1996); Phys. Rept. 415, 89 (2005);
Eur. Phys. J. A24, 31 (2005)

Calculations performed with semi-phenomenological 2N potentials (Argonne V18, Nijmegen I and II, CD Bonn) and 3N potentials (Tucson-Melbourne, Urbana IX) and recently with 2N and 3N chiral potentials by E. Epelbaum *et al.* from the Bonn/Bochum group

Introduction

Methods developed originally for elastic and inelastic electron scattering, photodisintegration, and later applied to neutrino induced reactions, muon capture and radiative pion capture are now used to investigate the following processes

$$\pi^- + d \rightarrow n + n$$

$$\pi^- + {}^3\mathrm{He} \rightarrow d + n$$

$$\pi^- + {}^3\mathrm{He} \rightarrow p + n + n$$

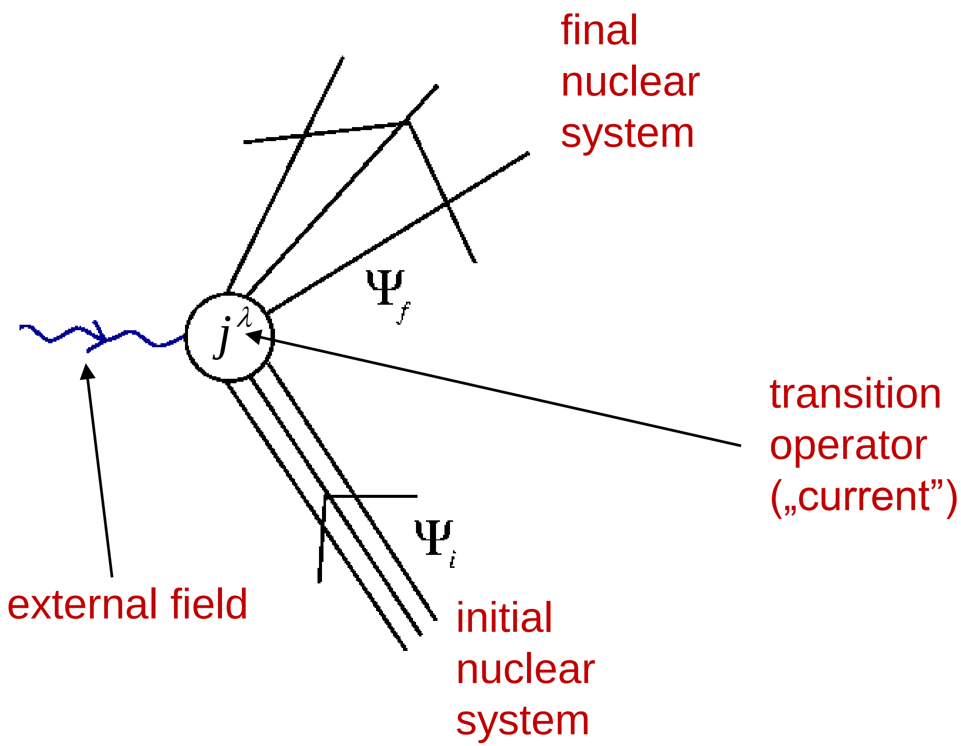
$$\pi^- + {}^3\mathrm{H} \rightarrow n + n + n$$

These processes combine information from several areas (pionic atoms, nuclear interactions, mechanisms of pion production and absorption) and are studied with nuclear forces and transition operators stemming from ChEFT

J. Golak *et al*., Phys. Rev. C **106**, 064003 (2022)

Formalism

interaction of nuclear system with external probe



$$N^\lambda = \left\langle \Psi_{f\, m_f} \middle| j^\lambda \middle| \Psi_{i\, m_i} \right\rangle$$

essential dynamical quantity

Formalism *(cont.)*

Dynamical ingredients (1): 2N and 3N Hamiltonians

$$H_{2N} = H_0^{2N} + V_{12}$$

$$H_{3N} = H_0^{3N} + V_{23} + V_{13} + V_{12} + V_{123} \equiv H_0^{3N} + V_1 + V_2 + V_3 + V_4$$

$$\equiv H_0^{3N} + V_1 + V_2 + V_3 + \underbrace{V_4^{(1)} + V_4^{(2)} + V_4^{(3)}}_{V_4}$$

used to generate nuclear bound and scattering states contain 2N and 3N potentials

Formalism *(cont.)*

Dynamical ingredients (2): nuclear single-nucleon, 2N and 3N transition operators („currents")

$$j_{2N} = j_1 + j_2 + j_{12}$$

$$j_{3N} = j_1 + j_2 + j_3 + j_{12} + j_{23} + j_{13} + j_{123}$$

$$\equiv j_1 + j_{23} + j_2 + j_{13} + j_3 + j_{12} + \underbrace{j_{123}^{(1)} + j_{123}^{(2)} + j_{123}^{(3)}}_{j_{123}}$$

$$\equiv \underbrace{j_1 + j_{23} + j_{123}^{(1)}}_{j(1)} + \underbrace{j_2 + j_{13} + j_{123}^{(2)}}_{j(2)} + \underbrace{j_3 + j_{12} + j_{123}^{(3)}}_{j(3)}$$

describe interactions of an external probe with a nuclear system

Formalism *(reactions with* ^{2}H*)*

$$H_{2N}\left|\psi_d\right\rangle = E_d\left|\psi_d\right\rangle$$

deuteron state with $E_d < 0$

$$\cancel{N^{\lambda}_{elas} \equiv \left\langle \psi'_d \right| j^{\lambda}_{2N} \left|\psi_d\right\rangle}$$

elastic channel does not exist for negative pion absorption

$$N^{\lambda} \equiv \left\langle \psi^{(-)} \right| j^{\lambda}_{2N} \left|\psi_d\right\rangle = {}_a\!\left\langle \vec{p}_o \right| \left(1 + t_{12}(E)G_0^{2N}(E)\right) j^{\lambda}_{2N} \left|\psi_d\right\rangle$$

break-up channel

$$H_{2N}\left|\psi^{(-)}\right\rangle = E\left|\psi^{(-)}\right\rangle, \qquad E = \frac{p_0^2}{m} > 0$$

internal 2N energy

$$t_{12}(E) = V_{12} + t_{12}(E)G_0^{2N}(E)V_{12}$$

Lippmann-Schwinger equation

$$G_0^{2N}(E) \equiv \lim_{\varepsilon\to 0^+}\frac{1}{E + i\varepsilon - H_0^{2N}}$$

free 2N propagator

Formalism *(reactions with* ^{3}He *and* ^{3}H*)*

$$H_{3N} \left| \Psi \right\rangle = E_b \left| \Psi \right\rangle$$

3N bound state with $E_b < 0$ generated by the Faddeev equation

$$N^{\lambda} = \left\langle \Psi' \right| j_{3N}^{\lambda} \left| \Psi \right\rangle$$

elastic or quasielastic channel with initial and final bound states does not exist for negative pion absorption

$$N^{\lambda} = \left\langle \Psi_f^{(-)} \right| j_{3N}^{\lambda} \left| \Psi_i \right\rangle$$

two-body or three-body break-up channel with final scattering states

$$\left| \Psi_f^{(-)} \right\rangle = \lim_{\varepsilon \to 0^+} \frac{-i\varepsilon}{E - i\varepsilon - H_{3N}} \left| \phi_f \right\rangle$$

formal definition including the channel state

Formalism *(reactions with* ^{3}He *and* ^{3}H*)*

Operators in 3N space:

(1) 3N force decomposed as

$$V_4 = V_4^{(1)} + V_4^{(2)} + V_4^{(3)}$$

$V_4^{(i)}$ is symmetric under the exchange of nucleons j and k, i≠j≠k≠i

(2) free 3N propagator

$$G_0^{3N}(E) \equiv \lim_{\varepsilon \to 0^+} \frac{1}{E + i\varepsilon - H_0^{3N}}$$

(3) 2N off-shell t-matrix generated via LSE:

$$t_{23} = V_{23} + V_{23}\, G_0^{3N}\, t_{23}$$

(4) permutation operator:

$$P = P_{12} P_{23} + P_{13} P_{23}$$

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Formalism *(reactions with* ^{3}He *and* ^{3}H*)*

Auxiliary equation for $\left| U^{\lambda} \right\rangle \equiv \left| U(j^{\lambda}(1), E_{c.m.}, Q) \right\rangle$

3N internal energy

magnitude of the three momentum transfer

$$\left| U^{\lambda} \right\rangle = \left\{ t_{23}\, G_0^{3N} + \frac{1}{2}\left(1+P\right) V_4^{(1)}\, G_0^{3N} \left(1 + t_{23}\, G_0^{3N}\right) \right\} \left(1+P\right) j^{\lambda}(1) \left| \Psi_{i m_i} \right\rangle$$

$$+ \left\{ t_{23}\, G_0^{3N}\, P + \frac{1}{2}\left(1+P\right) V_4^{(1)}\, G_0^{3N} \left(1 + t_{23}\, G_0^{3N}\right) P \right\} \left| U^{\lambda} \right\rangle$$

Formalism *(reactions with* ^{3}He *and* ^{3}H*)*

Quadratures

$$N_{Nd}^{\lambda} = \left\langle \phi_{Nd} \left| \left(1+P\right) j^{\lambda}(1) \right| \Psi_{i m_i} \right\rangle + \left\langle \phi_{Nd} \left| P \right| U^{\lambda} \right\rangle$$

$$N_{3N}^{\lambda} = \left\langle \phi_{3N} \left| \left(1+P\right) j^{\lambda}(1) \right| \Psi_{i m_i} \right\rangle + \left\langle \phi_{3N} \left| t_{23}\, G_0^{3N} \left(1+P\right) j^{\lambda}(1) \right| \Psi_{i m_i} \right\rangle$$
$$+ \left\langle \phi_{3N} \left| P \right| U^{\lambda} \right\rangle + \left\langle \phi_{3N} \left| t_{23}\, G_0^{3N} P \right| U^{\lambda} \right\rangle$$

are used to obtain nuclear matrix elements for arbitrary exclusive kinematics !

Semi-exclusive and inclusive observables are calculated by integrations
over suitable phase space domains.

Formalism *(reactions with* ^{3}He *and* ^{3}H*)*

Substantial simplifications for $V_4^{(1)} \to 0$

$$\left| U^{\lambda} \right\rangle = t_{23}\, G_0^{3N} \left(1+P\right) j^{\lambda}(1) \left| \Psi_{i\, m_i} \right\rangle + t_{23}\, G_0^{3N}\, P \left| U^{\lambda} \right\rangle$$

$$N_{Nd}^{\lambda} = \left\langle \phi_{Nd} \right| \left(1+P\right) j^{\lambda}(1) \left| \Psi_{i\, m_i} \right\rangle + \left\langle \phi_{Nd} \right| P \left| U^{\lambda} \right\rangle$$

$$N_{3N}^{\lambda} = \left\langle \phi_{3N} \right| \left(1+P\right) j^{\lambda}(1) \left| \Psi_{i\, m_i} \right\rangle + \left\langle \phi_{3N} \right| \left(1+P\right) \left| U^{\lambda} \right\rangle$$

$$\left| \phi_{Nd} \right\rangle = \left| \psi_d \right\rangle \left| \vec{q}_0 \right\rangle$$

$$\left| \phi_{3N} \right\rangle = \left| \vec{p} \right\rangle_a \left| \vec{q} \right\rangle$$

two- and three-body
channel states

Formalism (*cont.*)

Nuclear states for $\left| \Psi_i \right\rangle$ **and** $\left| \Psi_f \right\rangle$

^{2}H, 2N scattering states,
3N bound states (^{3}H , ^{3}He), 3N scattering states (d+n, pnn, nnn)
built from the chiral semilocal momentum space
(SMS) 2N potentials up to N4LO+ [1] and the N2LO 3N forces [2]

[1] P. Reinert, H. Krebs, and E. Epelbaum, Eur. Phys. J. A **54**, 86 (2018)
[2] P. Maris *et al*., (LENPIC Collaboration), Phys. Rev. C **103**, 054001 (2021)

Formalism (*cont.*)

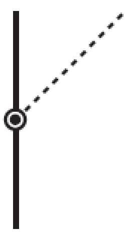
Pion absorption operator $j^{\lambda} \to \rho$

Important role played by the momentum scale $p \approx \sqrt{M_{\pi} M}$ associated with real pion production resulted in a modification of the chiral power counting as compared to the standard framework used to describe few-nucleon reactions below pion-production threshold.
New counting scheme - momentum counting scheme (MCS) describes the threshold charge pion production data well already at leading order (LO)

$\to$ LO-MCS

single-nucleon (SN) contributions in ρ

single-nucleon
isospn lowering
operator

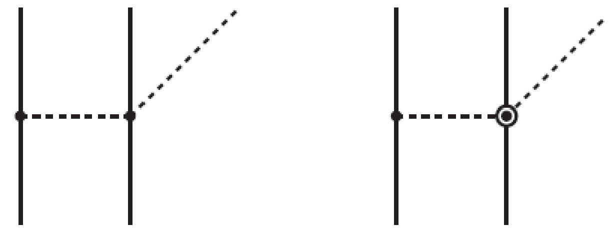


$$\langle \mathbf{p}' | \rho(1) | \mathbf{p} \rangle = -\frac{g_A M_\pi}{\sqrt{2} F_\pi} \frac{(\mathbf{p}' + \mathbf{p}) \cdot \boldsymbol{\sigma}_1}{2M} (\boldsymbol{\tau}_1)_-$$

V. Bernard, N. Kaiser, and U.-G. Meißner, Int. J. Mod. Phys. E **4**, 193 (1995)

Formalism (*cont.*)

two-nucleon (2N) contributions in ρ



$$\langle \mathbf{p}_1' \, \mathbf{p}_2' | \rho(1,2) | \mathbf{p}_1 \, \mathbf{p}_2 \rangle =$$

$$(v(k_2)\mathbf{k}_2 \cdot \boldsymbol{\sigma}_2 - v(k_1)\mathbf{k}_1 \cdot \boldsymbol{\sigma}_1)\frac{i}{\sqrt{2}}[(\boldsymbol{\tau}_1 \times \boldsymbol{\tau}_2)_x - i(\boldsymbol{\tau}_1 \times \boldsymbol{\tau}_2)_y]$$

$$\mathbf{k}_1 = \mathbf{p}_1' - \mathbf{p}_1, \, \mathbf{k}_2 = \mathbf{p}_2' - \mathbf{p}_2$$

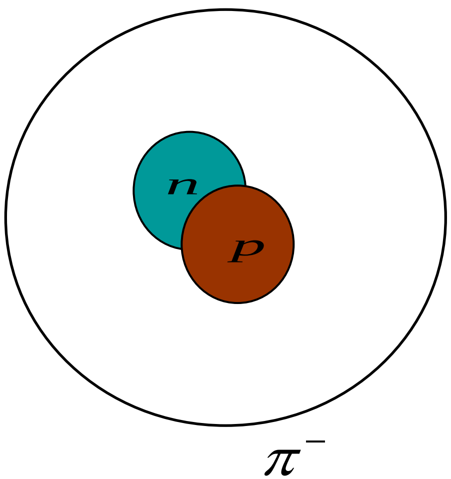
two-nucleon isospn lowering operator

$$v(k) = \frac{1}{(2\pi)^3} \frac{g_A M_\pi}{4F_\pi^3} \frac{1}{M_\pi^2 + k^2}.$$

V. Lensky, V. Baru, J. Haidenbauer, C. Hanhart, A. E. Kudryavtsev, and U.-G. Meißner, Eur. Phys. J. A **27**, 37 (2006)

Formalism (*cont.*)

Pion absorption from the lowest K-shell of the pionic atom



$$\psi_K(r) \equiv \psi_{100}(r) = \sqrt{\frac{(ZM'\alpha)^3}{\pi}}\, e^{-ZM'\alpha r}$$

$$M' \equiv \frac{M_\pi M_Z}{M_\pi + M_Z}$$ reduced mass

$$E_1 = -\frac{Z^2\alpha^2 M'}{2}$$ negligible for *Z=1,2* when compared to the pion or nucleon mass

Pion brings energy to the nuclear system but the initial and final total nuclear momenta are ZERO!
Total angular momentum of the nuclear system is conserved.
Parity is changed !

Pion absorption in ^{2}H

$$\pi^- + d \rightarrow n + n$$

$\vec{p}_1$ $\vec{p}_2$

$$\Gamma_{nn} = \frac{(\alpha\, M_d')^3\, c\, M_n\, p_0}{2M_{\pi^-}} \underbrace{\int d\hat{\mathbf{p}}_0}_{4\pi} \frac{1}{3} \sum_{m_1, m_2, m_d} |N_{nn}(m_1, m_2, m_d)|^2$$

$$\vec{p}_0 = \vec{p}_1$$

$$N_{nn}(m_1, m_2, m_d) = \overbrace{{}^{(-)}\langle \mathbf{p}_0 m_1 m_2\, \mathbf{P}_f = 0|}^{\text{2n scattering state}}\rho|\phi_d m_d\, \mathbf{P}_i = 0\rangle,$$

magnetic quantum numbers

relative momentum

The final 2n system is in ***only one*** partial-wave state: ***l=1, s=1, j=1***

Pion absorption in ^{2}H

PWD of $\rho(1)$ in 2N basis

$$\langle p(ls)jm_j\,;tm_t\,\mathbf{P}_f|\rho(1)|\phi_d\,m_d\,\mathbf{P}_i\rangle =$$

$$\delta_{t,1}\,\delta_{m_t,-1}\,\langle 1\;-1|(\boldsymbol{\tau}_1)_-|00\,\rangle \sum_{m_l} c(l,\,s,\,j;m_l,m_j-m_l,m_j)$$

$$\times \sum_{l_d=0,2}\sum_{m_{l_d}} c(l_d,1,1;m_{l_d},m_d-m_{l_d},m_d) \sum_{m_1} c\left(\frac{1}{2},\frac{1}{2},s;m_1,m_j-m_l-m_1,m_j-m_l\right)$$

$$\times \sum_{\mu_1} c\left(\frac{1}{2},\frac{1}{2},1;\mu_1,m_d-m_{l_d}-\mu_1,m_d-m_{l_d}\right)$$

$$\times\;\delta_{m_j-m_l-m_1,m_d-m_{l_d}-\mu_1}\int d\hat{\mathbf{p}}\,Y^*_{l\,m_l}(\hat{\mathbf{p}})\,Y_{l_d\,m_{l_d}}\left(\widehat{\mathbf{p}-\frac{1}{2}\mathbf{Q}}\right)\varphi_{l_d}\left(\left|\mathbf{p}-\frac{1}{2}\mathbf{Q}\right|\right)$$

$$\times\left\langle\frac{1}{2}m_1\left|\left\langle\mathbf{p}+\frac{1}{2}\mathbf{P}_f\right|\rho(1)\left|\mathbf{p}-\frac{1}{2}\mathbf{P}_f+\mathbf{P}_i\right\rangle\right|\frac{1}{2}\mu_1\right\rangle,$$

$$\langle p(11)1m_j;1-1\,\mathbf{P}_f=0|\rho(1)|\phi_d\,m_d\,\mathbf{P}_i=0\rangle$$

$$=\delta_{m_j,m_d}\,\frac{g_A M_\pi}{2\sqrt{2}MF_\pi}\,p\,\frac{2\varphi_0(p)+\sqrt{2}\varphi_2(p)}{\sqrt{3}}.$$

Pion absorption in ^{2}H

PWD of $\rho(1,2)$ in 2N basis

$$\left\langle p'(l's')\,j'm_{j'}\left|\rho(1,2)^{spin}\right|p(ls)\,jm_j\right\rangle =$$

$$\delta_{j,j'}\,\delta_{m_j,m_{j'}}\,\delta_{s,1}\,\delta_{s',1}\,12\pi\sqrt{2}\,(-1)^j \begin{Bmatrix} l & l' & 1 \\ 1 & 1 & j \end{Bmatrix}$$

$$\times \sum_{a_1+a_2=1} (p')^{a_1}\, p^{a_2}\, (-1)^{a_2} \sum_w (2w+1)\,(-1)^w\, g_w(p',p)$$

$$\times \begin{Bmatrix} l & l' & 1 \\ a_1 & a_2 & w \end{Bmatrix} c(w,a_1,l';0,0,0)\, c(w,a_2,l;0,0,0),$$

$$g_w(p',p) = \int_{-1}^{1} dx\, P_w(x)\, v\left(\sqrt{(p')^2+p^2-2pp'x}\right),$$

This result is used also for pion absorption in ^{3}He and ^{3}H !

Pion absorption in ^{2}H

Predictions with the LO-MCS transition operator

		Absorption rate Γ_{nn} in 10^{15} s^{-1}			
		SN		SN+2N	
Chiral order in nuclear w.f.	Λ (MeV)	PW	Full	PW	Full
LO	450	0.0593	0.0883	3.541	3.613
NLO	450	0.0001	0.0135	2.221	2.059
N^{2}LO	450	0.0158	0.0039	1.827	1.433
N^{3}LO	450	0.0155	0.0087	1.836	1.237
N^{4}LO	450	0.0131	0.0091	1.850	1.243
N^{4}LO$^+$	400	0.0028	0.0125	2.057	1.484
N^{4}LO$^+$	450	0.0142	0.0070	1.836	1.292
N^{4}LO$^+$	500	0.0305	0.0032	1.644	1.224
N^{4}LO$^+$	550	0.0460	0.0007	1.508	1.247

Expt. $1.306^{+0.026}_{-0.055}$

deduced from the $p + p \to \pi^+ + d$
reaction at threshold

PW vs. Full=PW+rescattering

SN vs. SN+2N transition operator

Pion absorption in ^{3}He and ^{3}H

PWD of $\rho(1)$ in 3N basis

$$\left\langle pq\alpha\, \mathbf{P}_f = 0 | \rho(1) \middle| \Psi\, m_b\, ; \frac{1}{2} m_{T_b}\, \mathbf{P}_i = 0 \right\rangle =$$

$$\frac{g_A M_\pi \sqrt{6}}{M F_\pi}\, q\, \delta_{m_T, m_{T_b}-1}\, \delta_{J,\frac{1}{2}}\, \delta_{m_J, m_b} \sqrt{(2\lambda+1)}\, (-1)^{I+\frac{1}{2}}$$

$$\times\ (-1)^t \begin{Bmatrix} 1 & \frac{1}{2} & \frac{1}{2} \\ t & T & \frac{1}{2} \end{Bmatrix} c\left(1, \frac{1}{2}, T; -1, m_{T_b}, m_{T_b} - 1\right)$$

$$\times \sum_{\alpha_b} \delta_{l,l_b}\, \delta_{s,s_b}\, \delta_{j,j_b}\, \delta_{t,t_b}\, \delta_{I,I_b}\, \phi_{\alpha_b}(p,q)$$

$$\times\ \sqrt{(2\lambda_b+1)}\, c(\lambda, \lambda_b, 1; 0, 0, 0) \begin{Bmatrix} \lambda & \lambda_b & 1 \\ \frac{1}{2} & \frac{1}{2} & I \end{Bmatrix},$$

Pion absorption in ^{3}He: two-body breakup

$$\pi^- + {}^3\mathrm{He} \to d + n$$

$$\longleftarrow \vec{p}_n \qquad \vec{p}_d \longrightarrow$$

$$\rho_{3N} = \rho(1) + \rho(2) + \rho(3) + \rho(1,2) + \rho(2,3) + \rho(3,1) + \cancel{\rho(1,2,3)}$$

$$\Gamma_{\rm nd} = \mathcal{R}\, \frac{16\left(\alpha^3 M'_{^3\mathrm{He}}\right)^3 c\, M q_0}{9 M_{\pi^-}} \underbrace{\int d\hat{\mathbf{q}}_0}_{4\pi} \frac{1}{2} \sum_{m_n, m_d, m_{^3\mathrm{He}}} \left| N_{\rm nd}(m_n, m_d, m_{^3\mathrm{He}}) \right|^2$$

correction due to
final volume of the
nuclear charge

$$\vec{q}_0 = \vec{p}_n$$

$$N_{\rm nd}(m_n, m_d, m_{^3\mathrm{He}}) \equiv \overbrace{{}^{(-)}\langle \Psi_{\rm nd}\, m_n\, m_d\, \mathbf{P}_f = 0}^{\text{nd scattering state}} | \rho_{3N} | \Psi_{^3\mathrm{He}}\, m_{^3\mathrm{He}}\, \mathbf{P}_i = 0 \rangle$$

magnetic quantum
numbers

Pion absorption in ^{3}He: two-body breakup

nuclear forces at N^{4}LO$^+$

	Absorption rate Γ_{nd} in 10^{15} s^{-1}			
Λ (MeV)	Calc. (1)	Calc. (2)	Calc. (3)	Calc. (4)
400	8.3158	0.0172	3.6566	3.028
450	6.6961	0.0231	2.5466	2.089
500	5.4398	0.0666	1.9909	1.595
550	4.6015	0.1840	1.8029	1.371

(1) PWIAS-(SN+2N)-(2NF+3NF)

(2) Full-SN-(2NF+3NF)

(3) Full-(SN+2N)-2NF

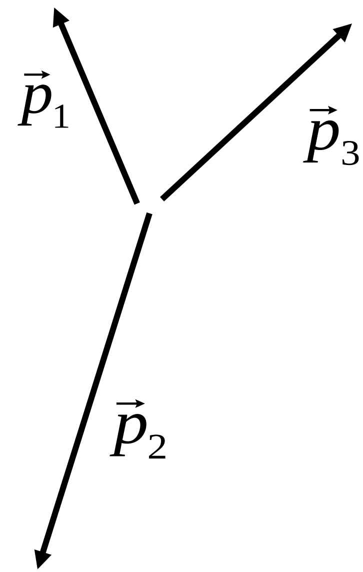
(4) Full-(SN+2N)-(2NF+3NF)

3NF effects

SN vs. SN+2N transition operator

Pion absorption in ^{3}He: three-body breakup

$$\pi^- + {}^3\mathrm{He} \rightarrow p + n + n$$



$$\Gamma_{\mathrm{pnn}} = \mathcal{R}\, \frac{16\left(\alpha\, M'_{^3\mathrm{He}}\right)^3 c\, M}{9 M_{\pi^-}} \int d\hat{\mathbf{q}} \int_0^{2\pi} d\phi_p \int_0^{\pi} d\theta_p \sin\theta_p$$
$$\times \int_0^{p_{\max}} dp\, p^2 \sqrt{\frac{4}{3}(M E_{pq} - p^2)}\, \frac{1}{2}$$
$$\times \sum_{m_1, m_2, m_3, m_{^3\mathrm{He}}} |N_{\mathrm{pnn}}(m_1, m_2, m_3, m_{^3\mathrm{He}})|^2$$

$$\vec{q} = \vec{p}_1$$
$$\vec{p} = \frac{1}{2}\left(\vec{p}_2 - \vec{p}_3\right)$$

Integrals $\int d\hat{\mathbf{q}} \int_0^{2\pi} d\phi_p$ yield 8π !

Pion absorption in ^{3}He: three-body breakup

Total absorption rates

nuclear forces at N^{4}LO$^+$

	Absorption rate Γ_{pnn} in 10^{15} s^{-1}			
Λ (MeV)	Calc. (1)	Calc. (2)	Calc. (3)	Calc. (4)
400	38.378	0.675	16.346	15.686
450	35.212	0.612	13.237	12.733
500	32.343	0.601	11.849	11.367
550	30.170	0.650	12.039	11.421

3NF effects

SN vs. SN+2N transition operator

(1) PWIAS-(SN+2N)-(2NF+3NF)

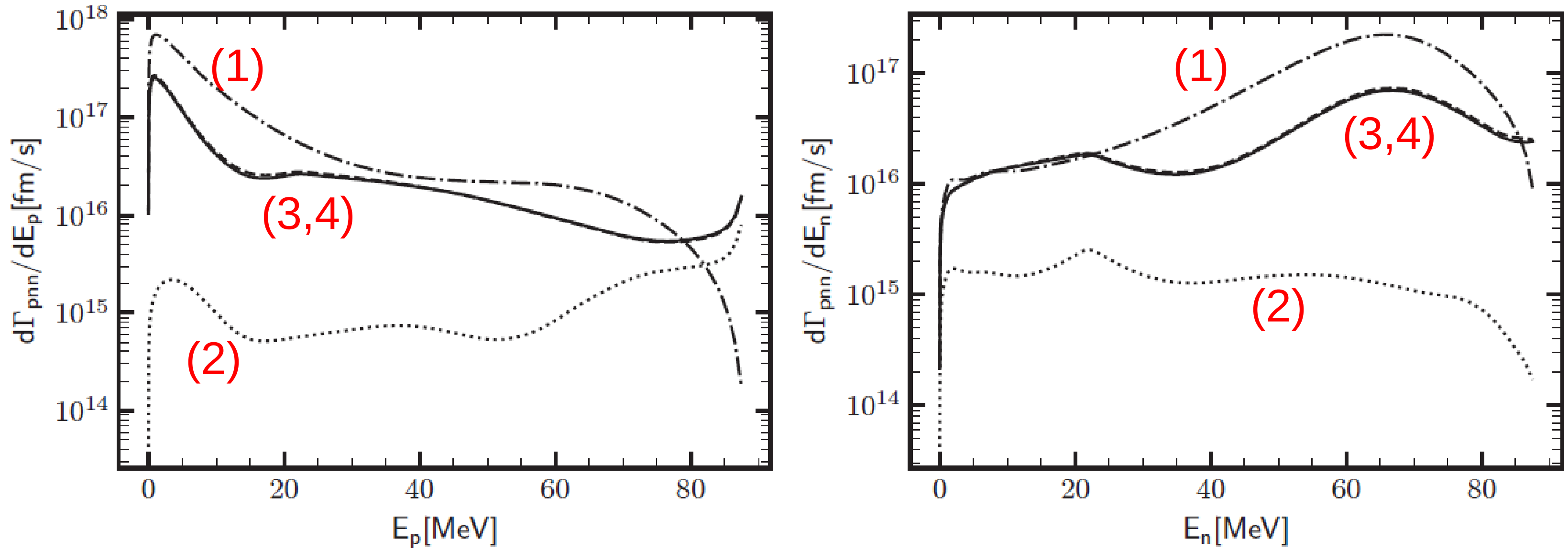
(2) Full-SN-(2NF+3NF)

(3) Full-(SN+2N)-2NF

(4) Full-(SN+2N)-(2NF+3NF)

Pion absorption in ^{3}He: three-body breakup

Differential absorption rates



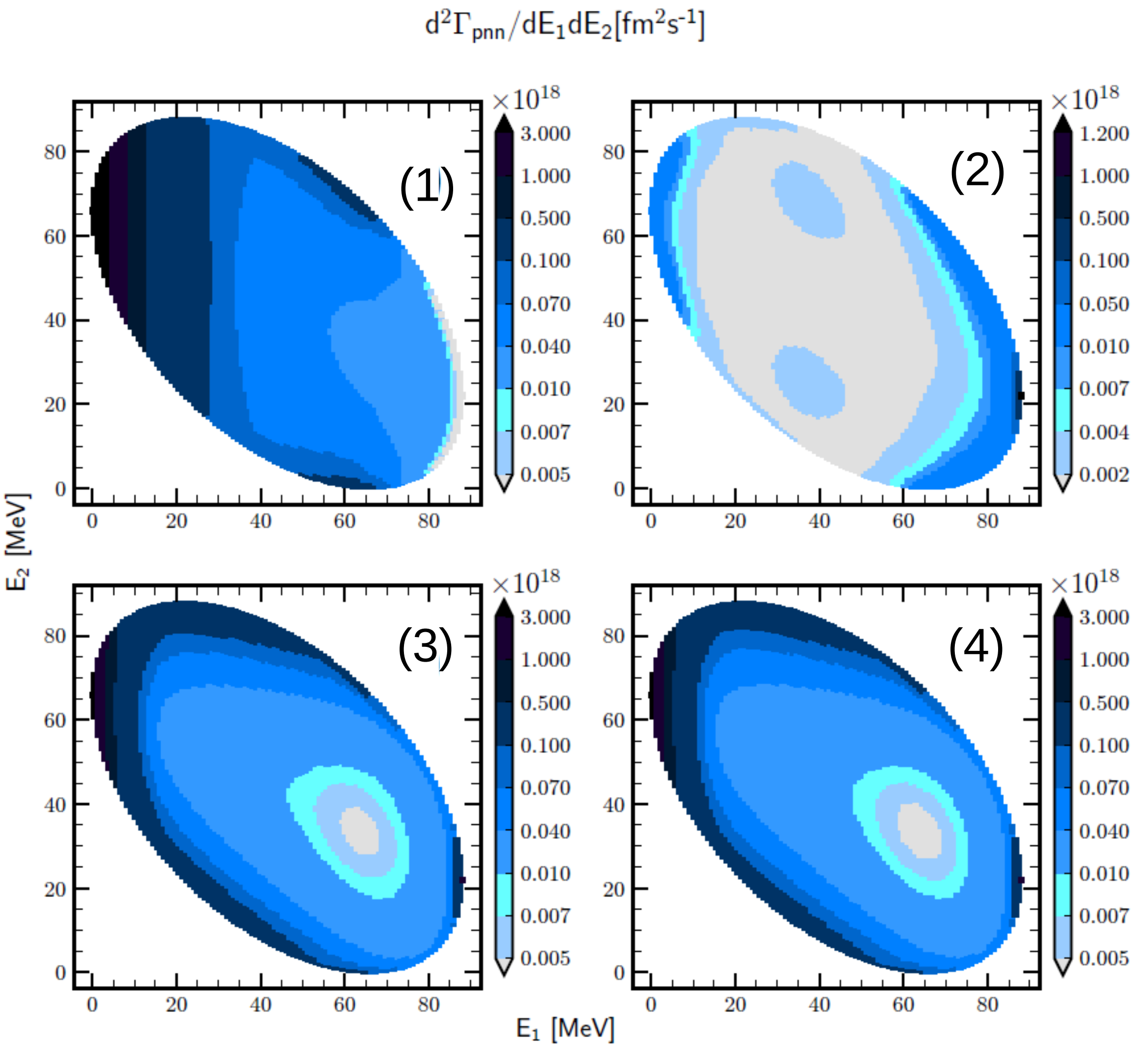
(1) PWIAS-(SN+2N)-(2NF+3NF)

(2) Full-SN-(2NF+3NF)

(3) Full-(SN+2N)-2NF

(4) Full-(SN+2N)-(2NF+3NF)

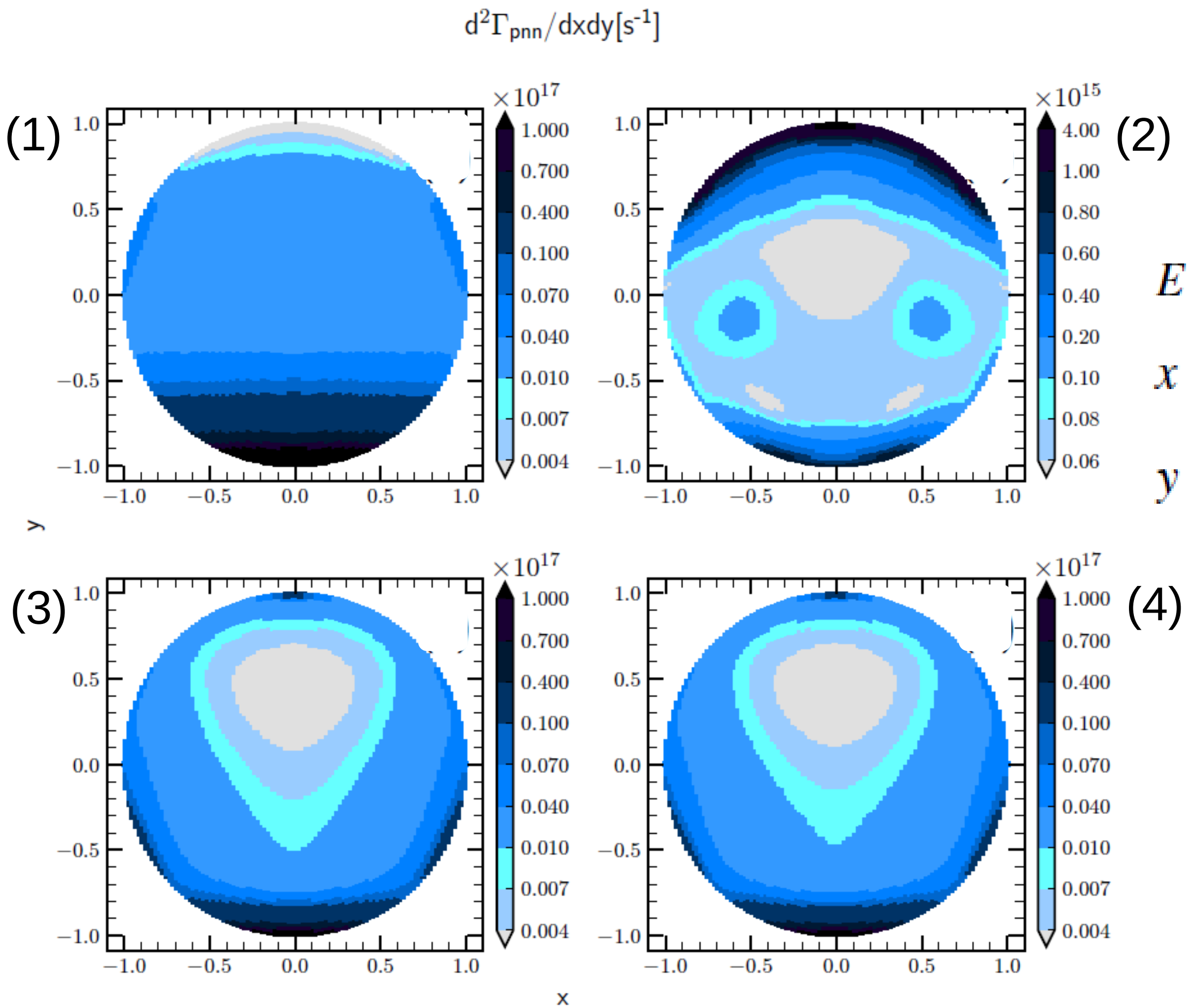
Pion absorption in ^{3}He: three-body breakup



Standard Dalitz plots

Nucleon 1 is a proton

Pion absorption in ^{3}He: three-body breakup



Modified Dalitz plots

$$E = E_1 + E_2 + E_3$$

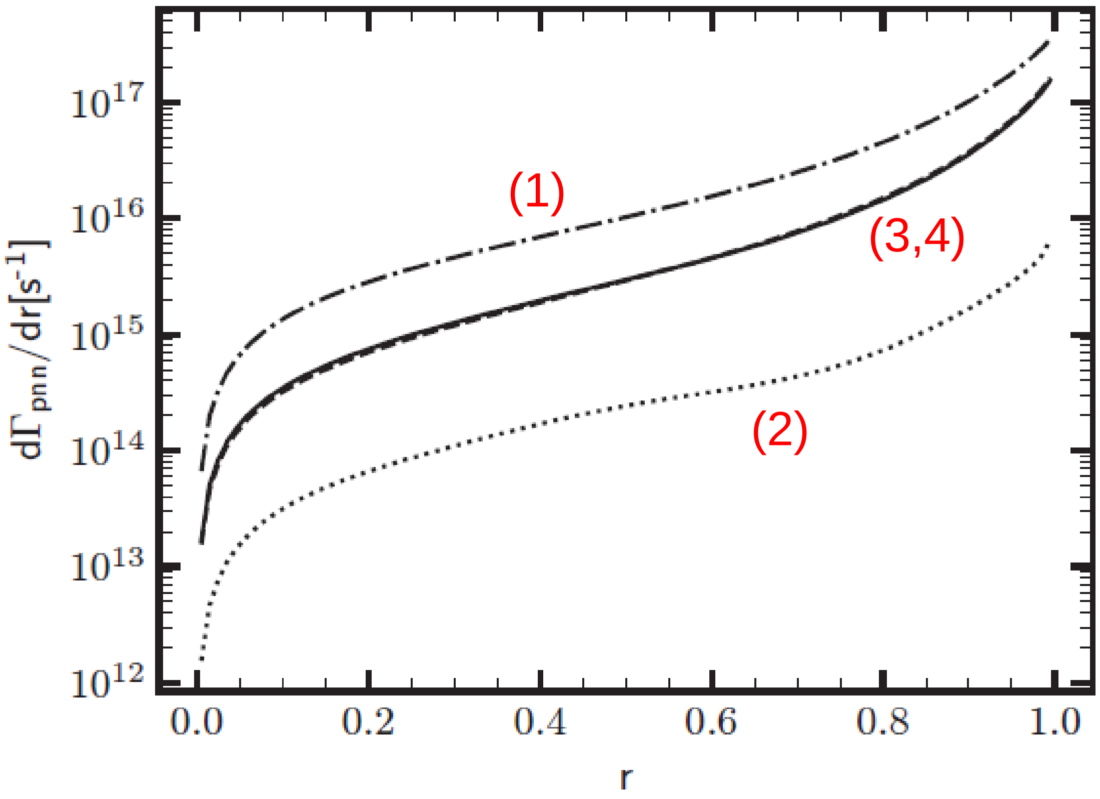
$$x = \sqrt{3}\,(E_1 + 2E_2 - E)/E,$$

$$y = (3E_1 - E)/E,$$

$$x = r\cos\Phi$$

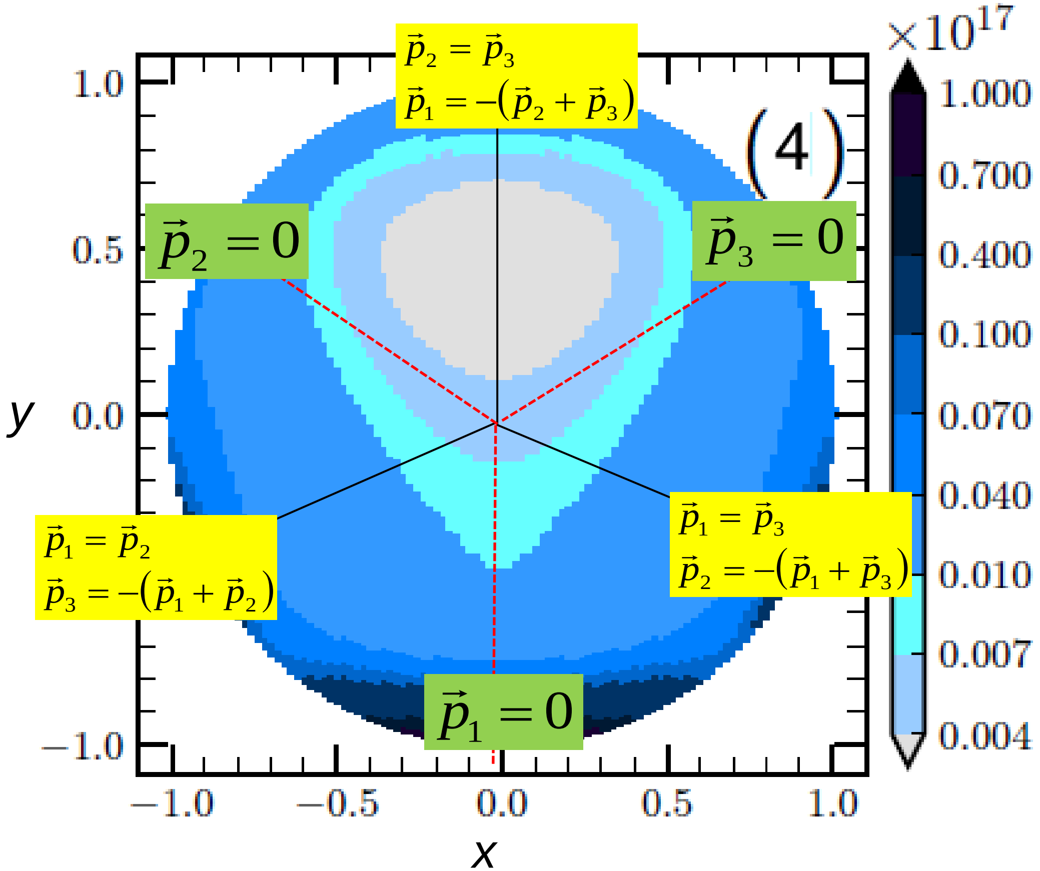
$$y = r\sin\Phi$$

Pion absorption in ^{3}He: three-body breakup



Main contributions come from regions with r close to 1

Pion absorption in ^{3}He: three-body breakup



FSI and *QFS*

$$E = E_1 + E_2 + E_3$$

$$x = \sqrt{3}\,(E_1 + 2E_2 - E)/E,$$

$$y = (3E_1 - E)/E,$$

Pion absorption in ^{3}He: three-body breakup

Normalized predictions for four regions in the pnn phase space obtained with Full-(SN+2N)-(2NF+3NF) dynamics

	Normalized absorption rates Γ_i			
Λ (MeV)	I_1	I_2	I_3	I_4
400	0.804	0.152	0.029	0.016
450	0.797	0.152	0.032	0.019
500	0.792	0.152	0.035	0.021
550	0.793	0.151	0.036	0.020
Gotta *et al.* (expt.)	0.844	0.099	0.033	0.023

D. Gotta *et al.*, Phys. Rev. C **51**, 469 (1995)

Pion absorption in ^{3}He: theoretical uncertinties

Full-(SN+2N)-(2NF+3NF) dynamics

$$\Gamma_{\rm nd} = \left(2.0^{+1.0}_{-0.6} \pm 1.6\right) \times 10^{15}\ {\rm s}^{-1}$$

$$\Gamma_{\rm pnn} = \left(12.8^{+2.9}_{-1.4} \pm 10.2\right) \times 10^{15}\ {\rm s}^{-1}$$

$$\Gamma_{\rm nd} + \Gamma_{\rm pnn} = \left(14.8^{+3.9}_{-2.0} \pm 11.8\right) \times 10^{15}\ {\rm s}^{-1}$$

truncation of the chiral expansion at LO-MCS

average and spread from cutoff Λ variation

$$\Gamma^{\rm exp.}_{\rm nd} = (6.8 \pm 1.9) \times 10^{15}\ {\rm s}^{-1}$$

$$\Gamma^{\rm exp.}_{\rm pnn} = (24.7 \pm 6.5) \times 10^{15}\ {\rm s}^{-1}$$

$$\Gamma^{\rm exp.}_{\rm nd+pnn} = (29.0 \pm 7.3) \times 10^{15}\ {\rm s}^{-1}$$

Pion absorption in ^{3}H: three-neutron breakup

Total absorption rates

nuclear forces at N^{4}LO$^+$

	Absorption rate Γ_{nnn} in 10^{15} s^{-1}			
Λ (MeV)	Calc. (1)	Calc. (2)	Calc. (3)	Calc. (4)
400	2.352	0.086	1.360	1.375
450	2.264	0.074	1.103	1.110
500	2.179	0.065	0.999	1.002
550	2.120	0.057	1.056	1.061

3NF effects

(1) PWIAS-(SN+2N)-(2NF+3NF)

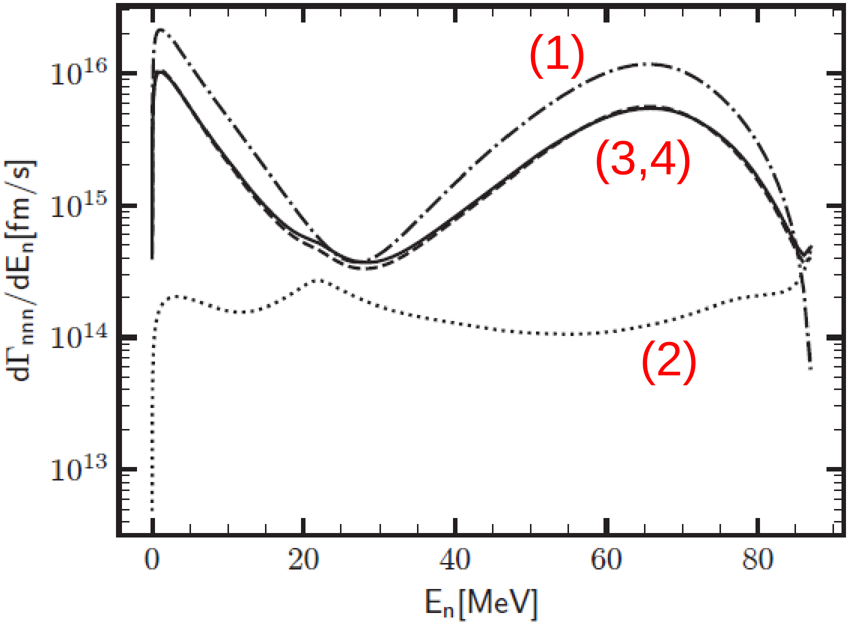
(2) Full-SN-(2NF+3NF)

(3) Full-(SN+2N)-2NF

(4) Full-(SN+2N)-(2NF+3NF)

SN vs. SN+2N transition operator

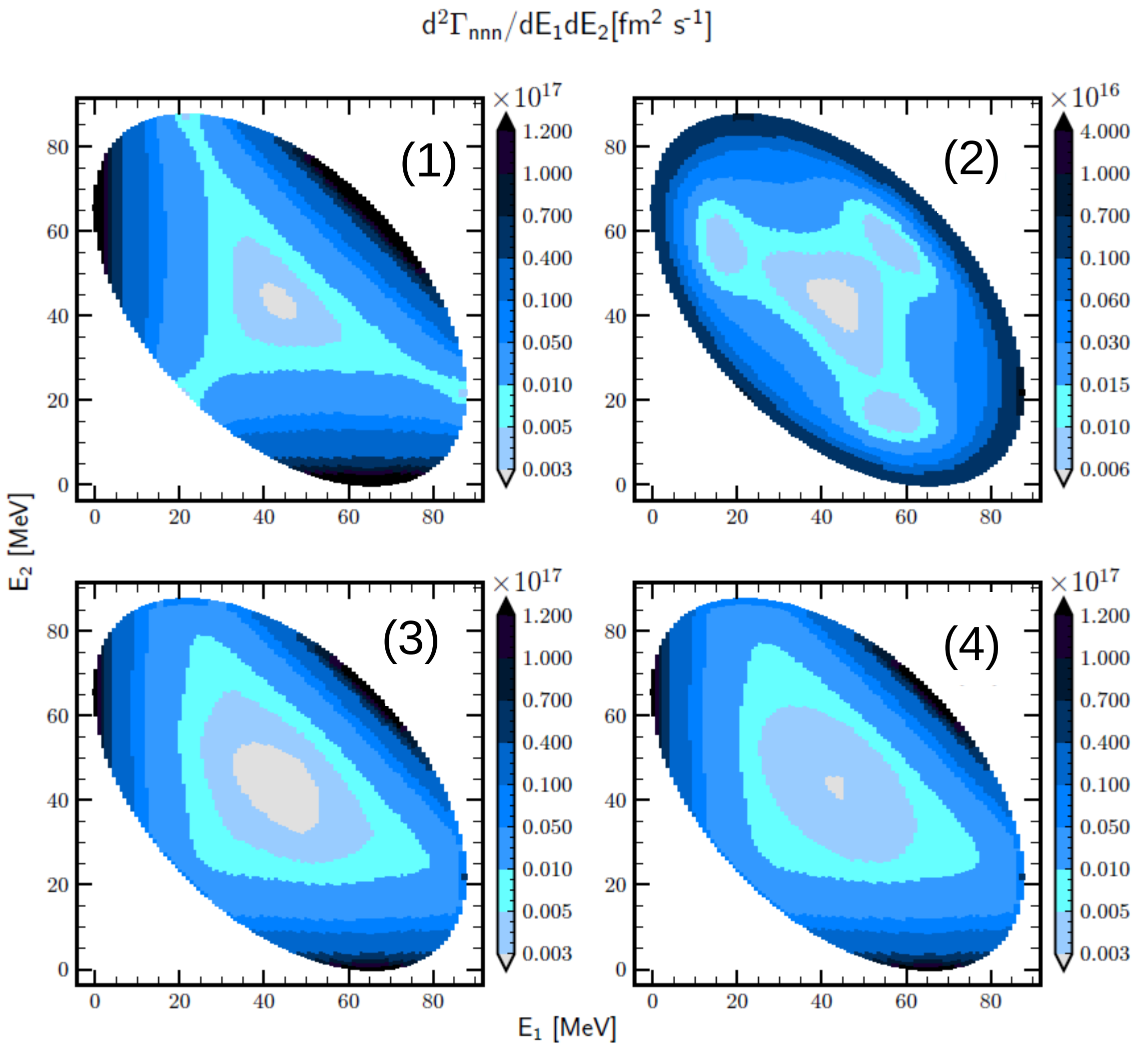
Pion absorption in ^3H: three-neutron breakup



$$\Gamma_{\mathrm{nnn}} = \left(1.1^{+0.2}_{-0.1} \pm 0.9\right) \times 10^{15}\ \mathrm{s}^{-1}$$

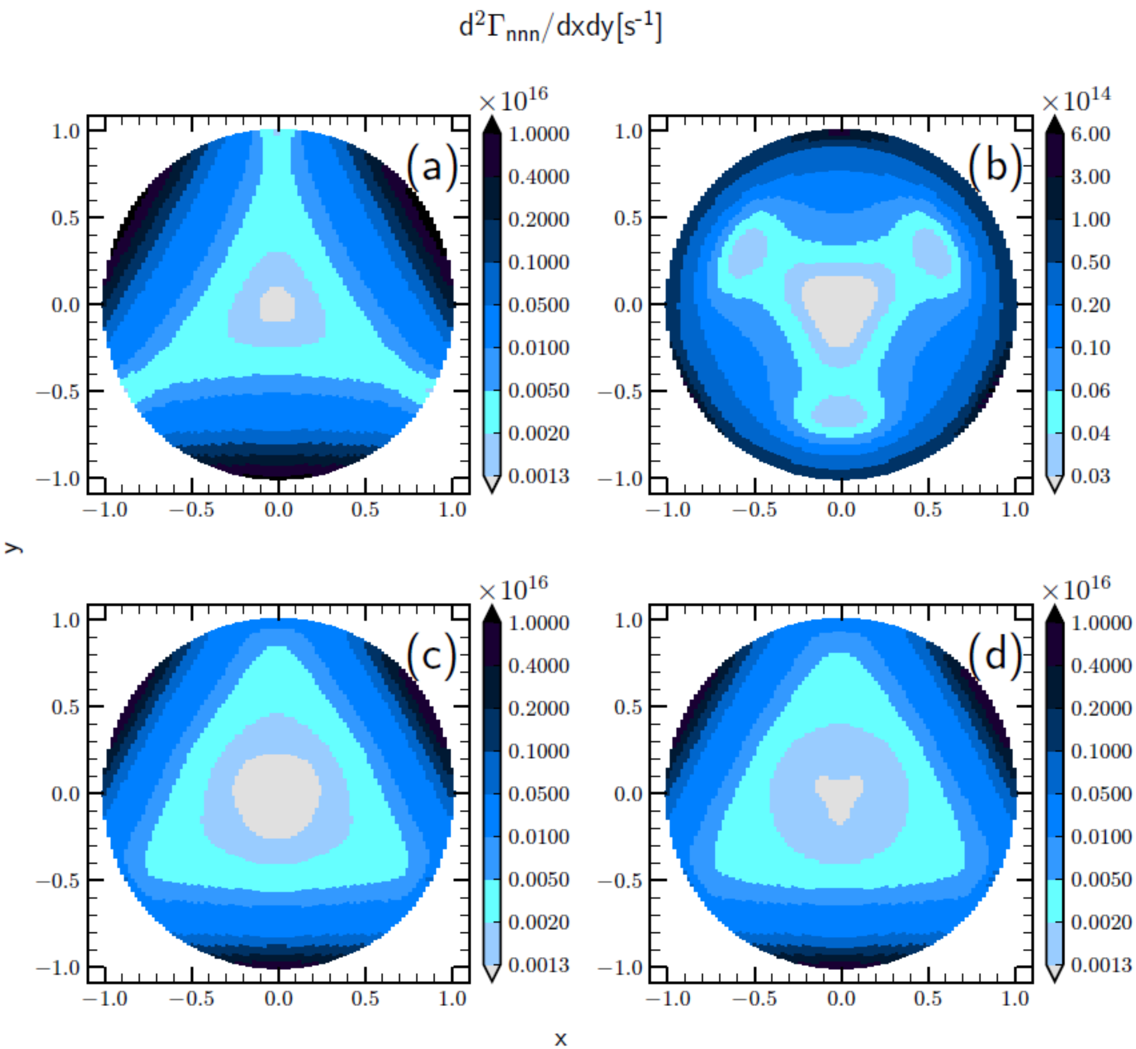
Full-(SN+2N)-(2NF+3NF) dynamics

Pion absorption in ^{3}H: three-neutron breakup



Standard Dalitz plots

Pion absorption in ^{3}H: three-neutron breakup



Modified Dalitz plots: additional symmetry

Conclusions and outlook

- A very robust momentum space framework to deal with many electroweak processes has been applied to pion absorption processes
- First results with the chiral SMS nuclear forces (N^4LO^+, N^2LO) and absorption operators (LO-CMS) for ^2H, ^3He and ^3H under full inclusion of final-state interactions have been calculated
- Calculations confirm the decisive role of the 2N absorption mechanisms
- Final-state interactions are also very important
- Our theoretical results for Γ_{nn} show a very good agreement with experimental data from the hadronic ground-state broadening in pionic deuterium as well as with the previous EFT calculations
- Predicted absorption rates Γ_{nd} and Γ_{pnn} in 3He are smaller than the experimental data; normalized predictions for Γ_{pnn} in four phase-space regions are in rough agreement with the data
- Room for improvement: consistent 2N and 3N potentials as well as transition operators should be used for all absorption reactions at sufficiently high chiral order
- New data would be very welcome !

Better transition operators badly needed !

PHYSICAL REVIEW C **98**, 054001 (2018)

Radiative pion capture in ^{2}H, ^{3}He, and ^{3}H

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The $\pi^- + {}^2\mathrm{H} \to \gamma + n + n$, $\pi^- + {}^3\mathrm{He} \to \gamma + {}^3\mathrm{H}$, $\pi^- + {}^3\mathrm{He} \to \gamma + n + d$, $\pi^- + {}^3\mathrm{He} \to \gamma + n + n + p$, and $\pi^- + {}^3\mathrm{H} \to \gamma + n + n + n$ capture reactions are studied with the AV18 two-nucleon potential and the Urbana IX three-nucleon potential. We provide for the first time realistic predictions for the differential and total capture rates for all these processes, treating consistently the initial and final nuclear states. Our results are based on the single-nucleon Kroll-Ruderman-type transition operator and concentrate on the full treatment of the nuclear final state interactions. They are compared with older theoretical predictions and experimental data.

DOI: 10.1103/PhysRevC.98.054001

Better transition operators badly needed !

PHYSICAL REVIEW C **90**, 024001 (2014)

Break-up channels in muon capture on ^{3}He

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The $\mu^- + {}^2\mathrm{H} \to \nu_\mu + n + n$, $\mu^- + {}^3\mathrm{He} \to \nu_\mu + {}^3\mathrm{H}$, $\mu^- + {}^3\mathrm{He} \to \nu_\mu + n + d$, and $\mu^- + {}^3\mathrm{He} \to \nu_\mu + n + n + p$ capture reactions are studied with various realistic potentials under full inclusion of final-state interactions. Our results for the two- and three-body break-up of ^{3}He are calculated with a variety of nucleon-nucleon potentials, among which is the AV18 potential, augmented by the Urbana IX three-nucleon potential. Most of our results are based on the single-nucleon weak-current operator. As a first step, we tested our calculation in the case of the $\mu^- + {}^2\mathrm{H} \to \nu_\mu + n + n$ and $\mu^- + {}^3\mathrm{He} \to \nu_\mu + {}^3\mathrm{H}$ reactions, for which theoretical predictions obtained in a comparable framework are available. Additionally, we have been able to obtain for the first time a realistic estimate for the total rates of the muon capture reactions on ^{3}He in the break-up channels: 544 s^{-1} and 154 s^{-1} for the $n + d$ and $n + n + p$ channels, respectively. Our results are compared with the most recent experimental data, finding a rough agreement for the total capture rates, but failing to reproduce the differential capture rates.

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Thank you !