Electroinduced ^{3}He breakup as a tool to study three-body systems

J.Golak[1], H.Witała[1], W.Glöckle[2],
H.Kamada[3], A.Nogga[4] and R.S.[1]
[1]Jagiellonian University
[2]Ruhr-Universität
[3]Kyushu Institute of Technology
[4]Institute für Kernphysik, Jülich

- Introduction
  - Faddeev scheme
  - The electromagnetic current operator
- Results for unpolarized $^3He(e,e'N_1N_2)N_3$ process.
- Results for $^3\vec{H}e(e,e'\vec{p})d$ and $^3\vec{H}e(e,e'\vec{d})p$
- Results for $^3\vec{H}e(\vec{e},e'p)d$ and $^3\vec{H}e(\vec{e},e'N_1N_2)N_3$
- Summary

Electrodisintegration of ^{3}He

The most important aims:

- understanding of the underlying dynamics
  - role of final state interactions
  - role of meson exchange currents
  - neutron and proton formfactors
  - role of three-nucleon force
- precise information on ^{3}He wave function, like momentum and spin dependent momentum distribution

Theoretical description:

All observables are given through $N_\mu \equiv \langle \Psi_f \mid j_\mu \mid \Psi_i \rangle$

$$
\begin{aligned}
{}^{Nd}\langle \Psi_f \mid j_\mu \mid \Psi_i \rangle &= \langle \Phi_1^{Nd} \mid (1+P) j_\mu \mid \Psi_i \rangle \\
&+ \langle \Phi_1^{Nd} \mid P \mid U_\mu \rangle
\end{aligned}
$$

where

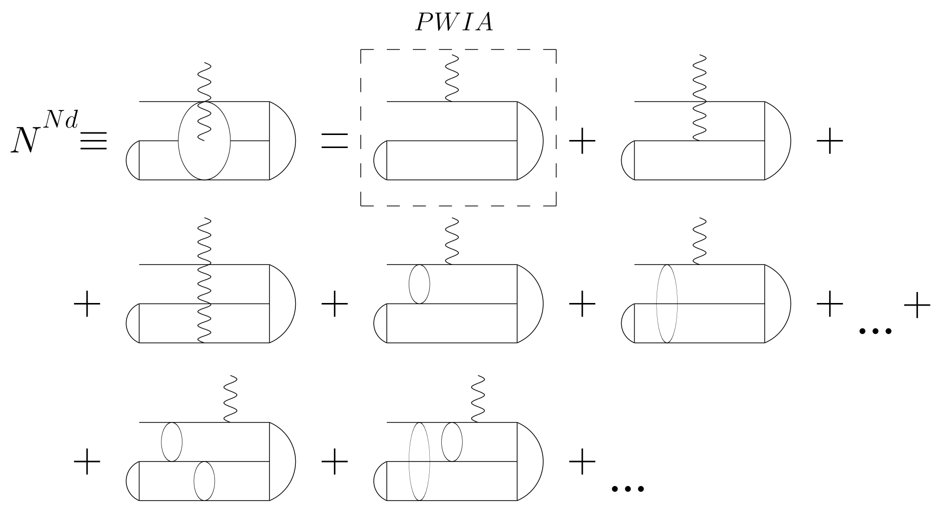
$$
\begin{aligned}
\mid U_\mu \rangle &= [t_1 G_0 + \frac{1}{2}(1+P) V_4^{(1)} G_0 (1 + t_1 G_0)] \\
& \quad (1+P) j_\mu \mid \Psi_i \rangle \\
&+ [t_1 G_0 P + \frac{1}{2}(1+P) V_4^{(1)} G_0 (1 + t_1 G_0) P] \mid U_\mu \rangle
\end{aligned}
$$

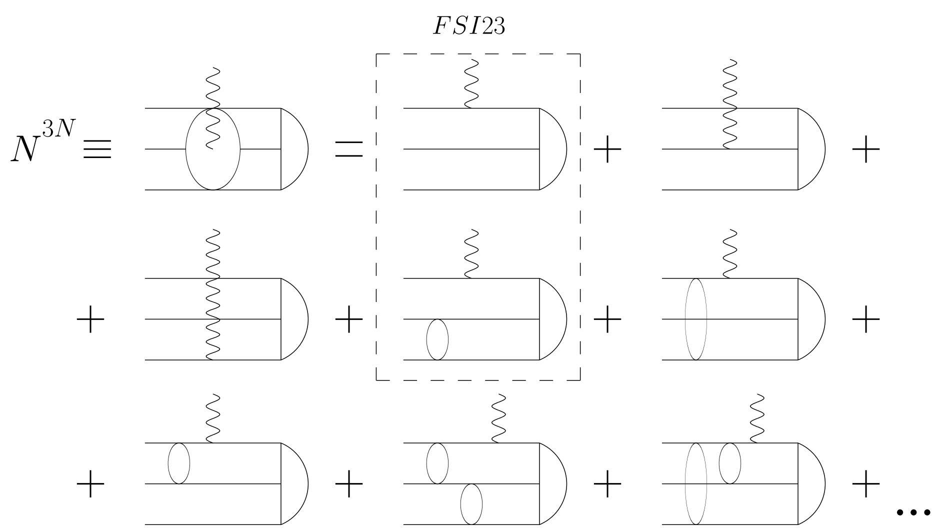
$$
\begin{aligned}
G_0 &\equiv (E - H_0 + i\epsilon)^{-1} \\
t_1 &= V_{23} + V_{23} G_0 V_{23} + \ldots \\
P &\equiv P_{12} P_{23} + P_{13} P_{32}
\end{aligned}
$$

$V_4^{(1)}$ - part of 3N force

$$
\begin{aligned}
{}^{3N}\langle \Psi_f \mid j_\mu \mid \Psi_i \rangle &= \langle \Phi_1^{3N} \mid (1+P) j_\mu \mid \Psi_i \rangle \\
&+ \langle \Phi_1^{3N} \mid (1+P) j_\mu \mid U_\mu \rangle
\end{aligned}
$$

Diagrammatic approach for two- and three-body breakup





The nuclear current operator: j_μ

1. Single nucleon current j_μ^1
2. Direct inclusion of meson exchange currents

$$j_\mu = j_\mu^1 + \underbrace{j_\mu^{2,\pi} + j_\mu^{2,\rho}}_{MEC}$$

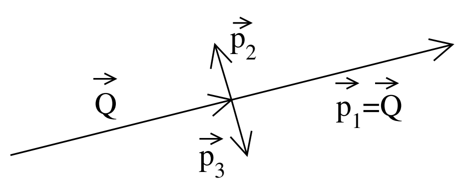
Predictions for ^{3}He(e,e'N$_1$N$_2$)N$_3$: relative momentum distribution in ^{3}He measured with proton and neutron knockout

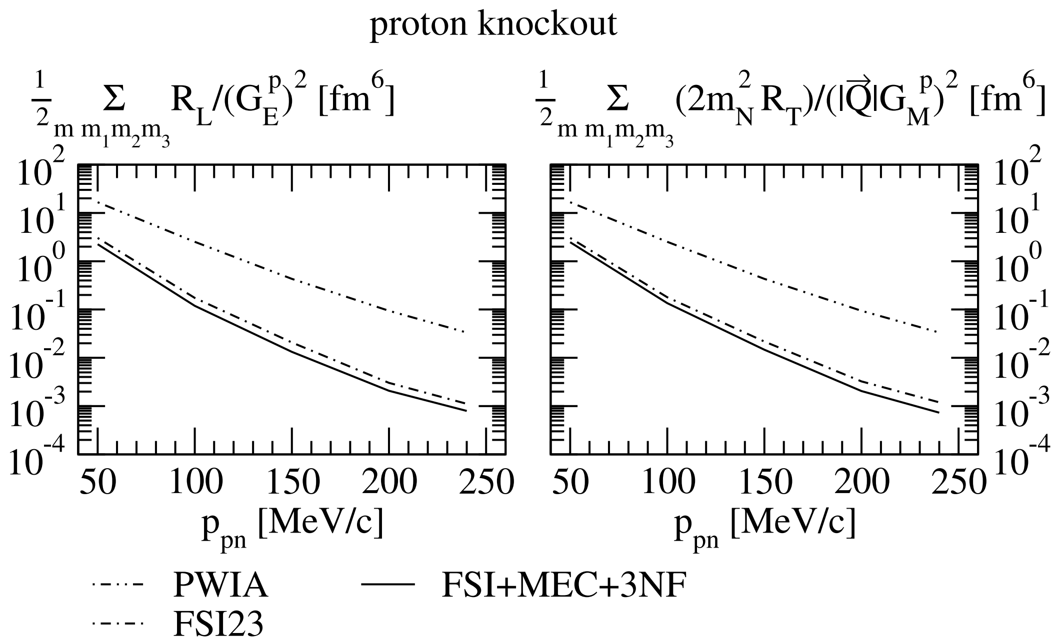
$$C(p) = 3 \sum_{m} \sum_{m_1,m_2,m_3} \left|\Psi(\vec{p},\vec{q}=0)\right|^2 .$$

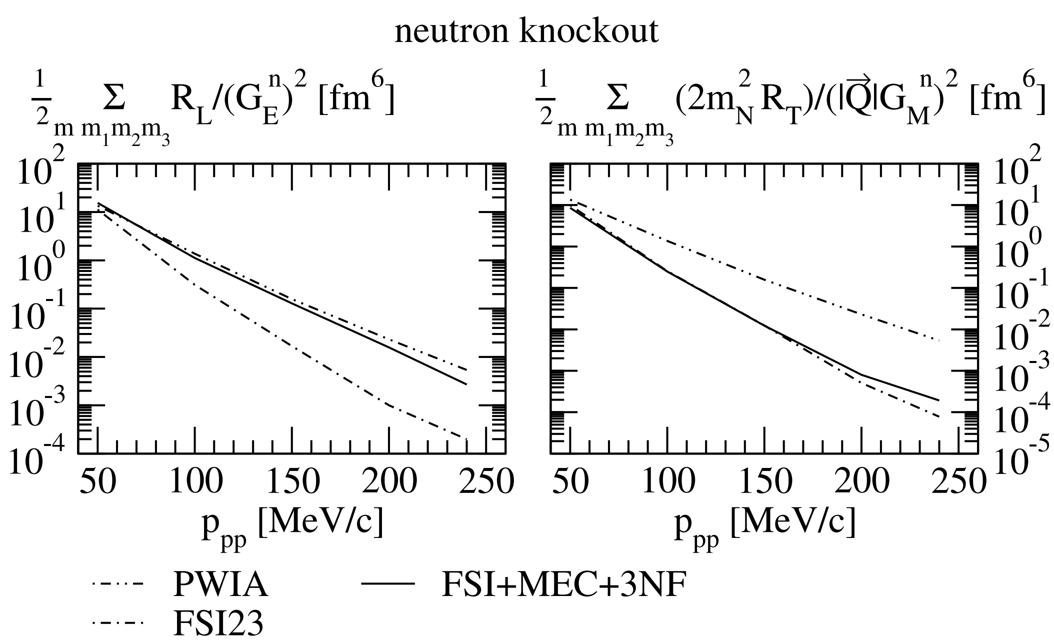
In PWIA

$$C(p) = \frac{1}{2} \sum_{m} \sum_{m_1,m_2,m_3} R_L^{PWIA}/G_E^2$$

$$C(p) = \frac{1}{2} \sum_{m} \sum_{m_1,m_2,m_3} 2m_N^2 \, R_T^{PWIA}/\left(\vec{Q}^2 \, G_M^2\right)$$




proton knockout
1/2 Σ_{m m1m2m3} R_L/(G_E^p)^2 [fm^6]
1/2 Σ_{m m1m2m3} (2m_N^2 R_T)/(|Q|G_M^p)^2 [fm^6]
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
50
100
150
200
250
p_pn [MeV/c]
PWIA
FSI23
FSI+MEC+3NF


neutron knockout
1/2 Σ_{m m1m2m3} R_L/(G_E^n)^2 [fm^6]
1/2 Σ_{m m1m2m3} (2m_N^2 R_T)/(|Q|G_M^n)^2 [fm^6]
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
50
100
150
200
250
p_pp [MeV/c]
PWIA
FSI23
FSI+MEC+3NF

Predictions for $^3\vec{H}e(e,e'\vec{p})d$, $^3\vec{H}e(e,e'\vec{d})p$ - spin dependent distribution of pd clusters

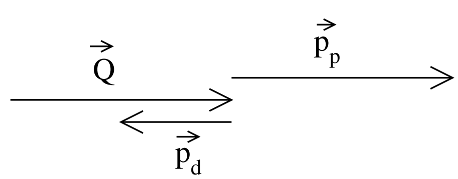
$$\begin{aligned}
\mathcal{Y}(m,m_d,m_p;\vec{q}_0) &\equiv \left\langle \Psi m \middle| |\phi_d m_d\rangle |\vec{q}_0 \, \frac{1}{2} m_p\rangle \langle \vec{q}_0 \, \frac{1}{2} m_p| \langle \phi_d m_d| \middle| \Psi m \right\rangle \\
&= | \sum_{\lambda=0,2} Y_{\lambda, m-m_d-m_p}(\hat{q}_0) C(1 I_\lambda \frac{1}{2}; m_d, m-m_d, m) \\
&\quad C(\lambda \frac{1}{2} I_\lambda; m-m_d-m_p, m_p, m-m_d) H_\lambda(q_0)|^2
\end{aligned}$$

$I_0 = \frac{1}{2}, I_2 = \frac{3}{2}$ and the auxiliary quantity $H_\lambda(q_0)$ is

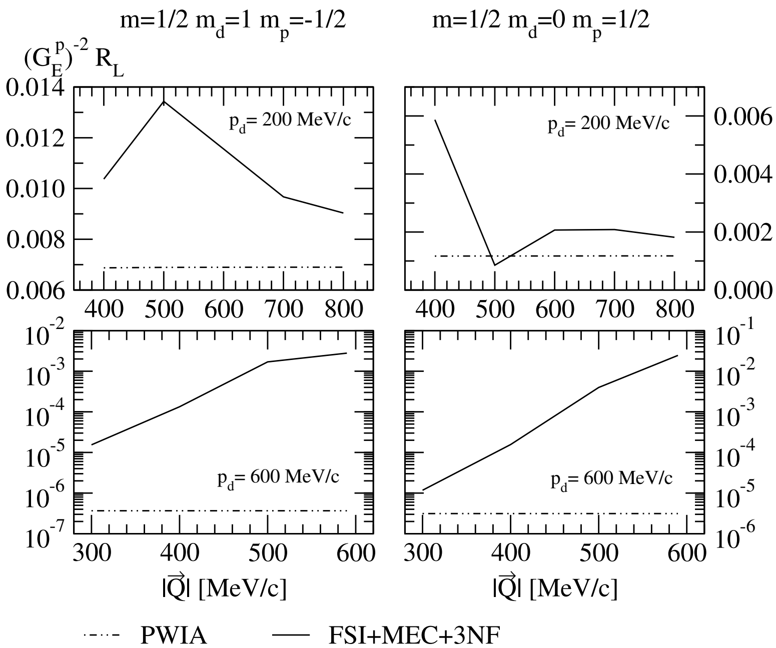
$$H_\lambda(q_0) \equiv \sum_{l=0,2} \int_0^\infty dp \, p^2 \, \phi_l(p) \, \langle p q_0 \alpha_{l\lambda} | \Psi \rangle \ \ , \ \lambda = 0,2$$

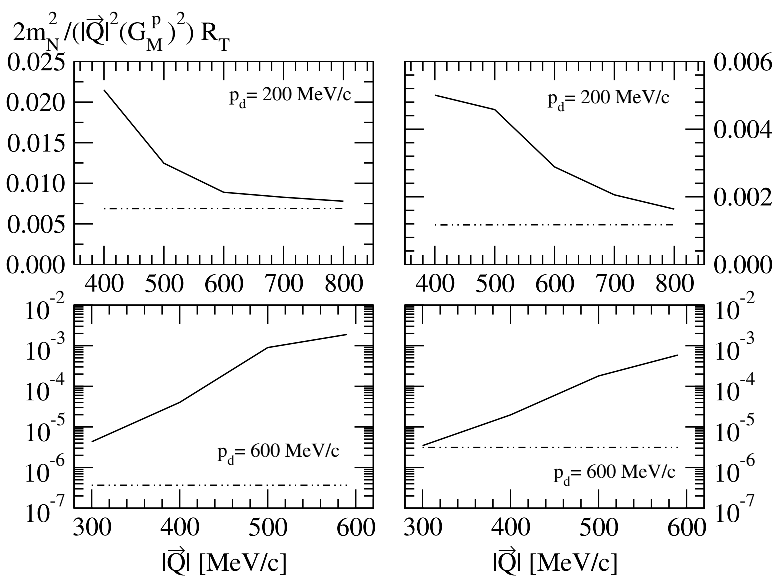
Under PWIA assumption and for parallel kinematics:
only $R_L(N_\mu^{PWIA})$ and $R_T(N_\mu^{PWIA})$ contribute to σ
On the other hand

$$\mathcal{Y}(m,m_d,m_p;\vec{q}_0) \sim N_\mu^{PWIA}$$



Predictions for $^3\vec{H}e(e,e'\vec{p})d$ and $^3\vec{H}e(e,e'\vec{d})p$ spin dependent momentum distribution- R_L, R_T





→ PWIA is sufficient for small deuteron momenta and $|\vec{Q}| \to \infty$.

Asymmetries in ${}^3\vec{H}e(\vec{e}, e'p)d$ process

$$A(\vec{S}) \equiv \frac{\sigma(\vec{S}, h=+1) - \sigma(\vec{S}, h=-1)}{\sigma(\vec{S}, h=+1) + \sigma(\vec{S}, h=-1)}$$

$\vec{S}$ -initial ^{3}He spin direction

in PWIA and assuming parallel kinematics ($\vec{p}_p \parallel \vec{Q}$)

$$A_\parallel \equiv A(\theta^\star = 0, \phi^\star = 0) = \frac{\left(G_M^p\, Q\right)^2\ v_{T'}}{2\left(G_E^p\right)^2\ M^2\, v_L + \left(G_M^p\, Q\right)^2\ v_T}\ P_1$$

$$A_\perp \equiv A(\theta^\star = \frac{\pi}{2}, \phi^\star = 0) = \frac{-2\sqrt{2}\, G_E^p\, G_M^p\, M\, Q\, v_{TL'}}{2\left(G_E^p\right)^2\ M^2\, v_L + \left(G_M^p\, Q\right)^2\ v_T}\ P_2$$

where

$$P_1 \equiv \frac{H_0(q)^2 + 4\sqrt{2}\, H_0(q)\, H_2(q) - H_2(q)^2}{3\left(H_0(q)^2 + H_2(q)^2\right)}$$

$$P_2 \equiv \frac{H_0(q)^2 - 2\sqrt{2}\, H_0(q)\, H_2(q) + 2\, H_2(q)^2}{3\left(H_0(q)^2 + H_2(q)^2\right)}.$$

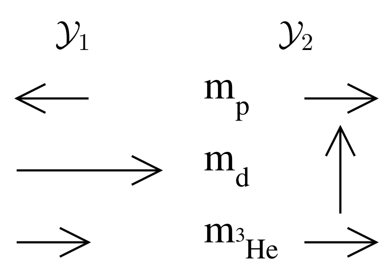
In addition

$$P_1 = \frac{\mathcal{Y}_1 - \mathcal{Y}_2}{\mathcal{Y}_1 + \mathcal{Y}_2},$$

$$P_2 = \frac{\mathcal{Y}_3 + \mathcal{Y}_4 - \mathcal{Y}_5}{\mathcal{Y}_3 + \mathcal{Y}_4 + \mathcal{Y}_5},$$

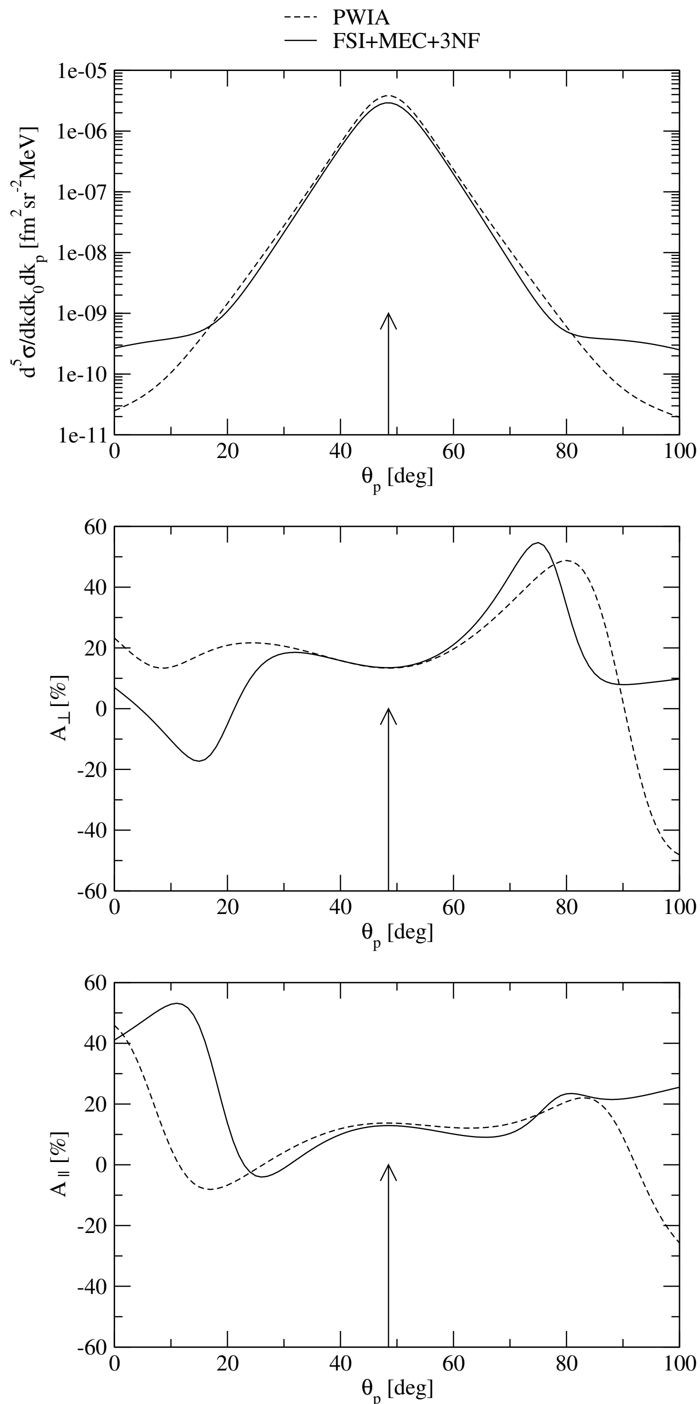
where $\mathcal{Y}_i$ are spin dependent momentum distributions for different spin projections combinations.

P_1 and P_2 are related $2P_2 = 1 - P_1$.

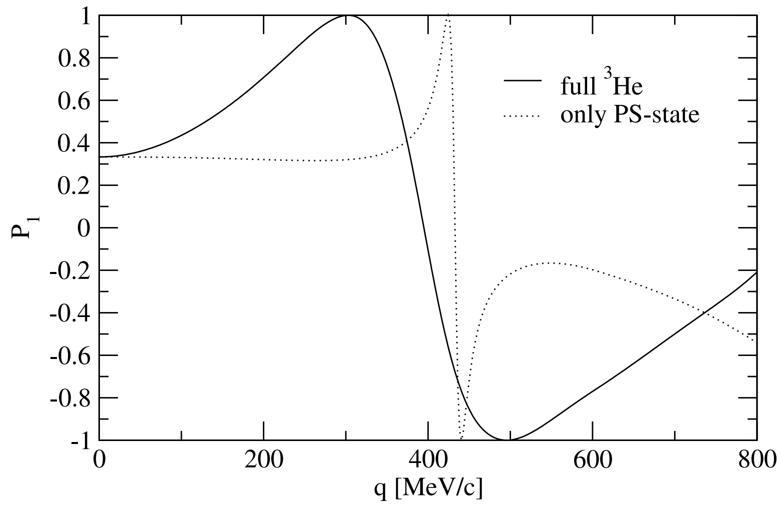


Asymmetries in $^3\vec{H}e(\vec{e}, e'p)d$ process

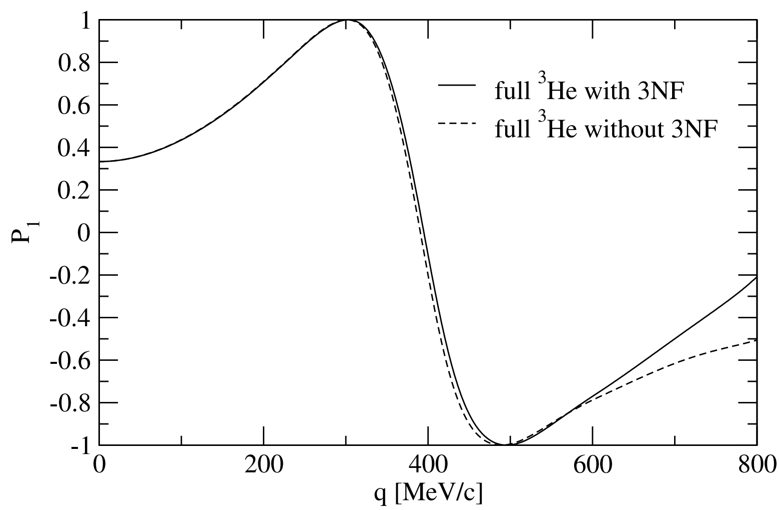
E MeV	θ_e deg	ω MeV	Q MeV/c	θ_Q deg	q^2 (GeV/c)^2	p_d MeV/c
735	50	179	569	48.5	0.29	5



→ PWIA is sufficient near $\theta_p = 48.5°$.



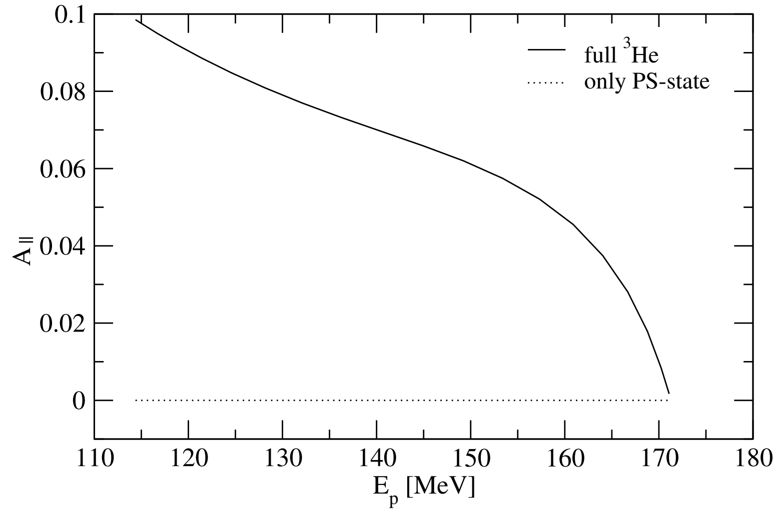
→ Principal S-state is sufficient only for small q.

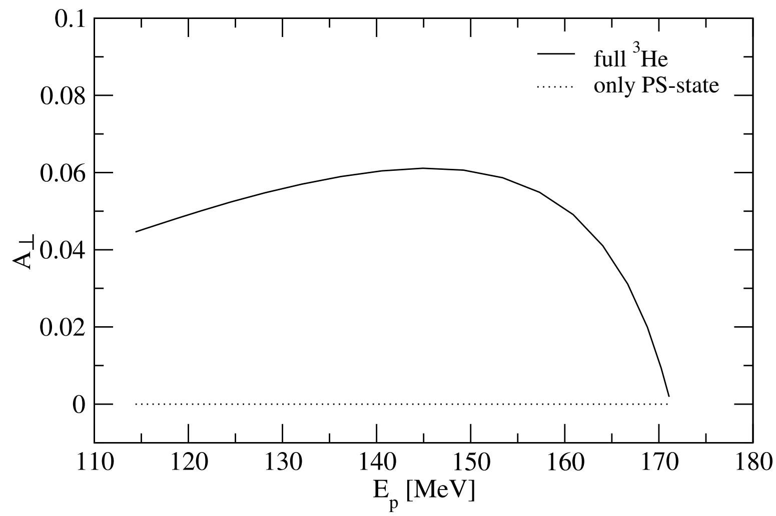


→ no 3N force action for $q < 600$ MeV/c

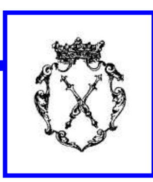
Asymmetries in $^3\vec{H}e(\vec{e}, e'p)pn$ process

PWIA and principal S-state $\rightarrow A(\vec{S}) = 0$

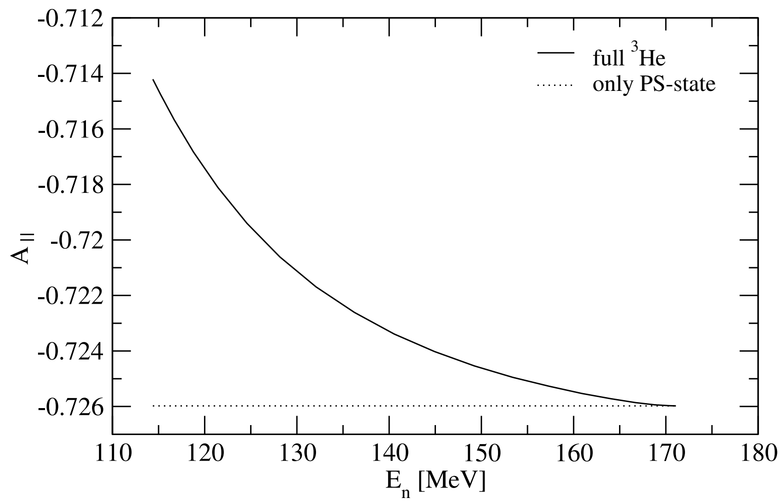


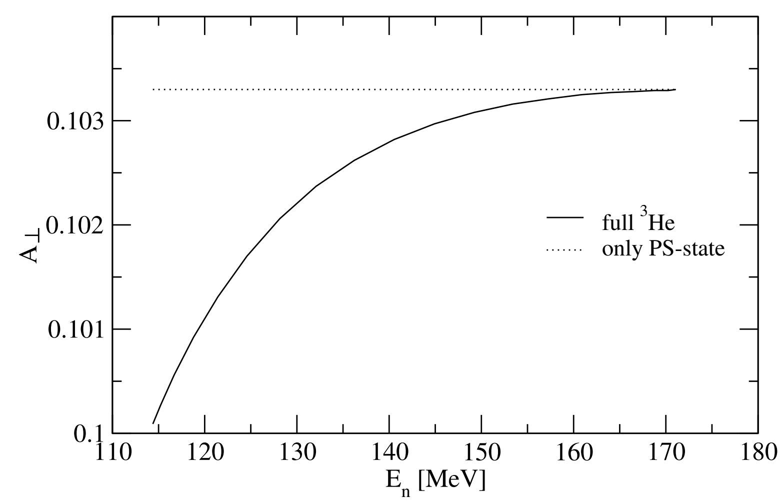


$\rightarrow$ in PWIA, principal S-state is not sufficient except $E_p \approx 170$ MeV.



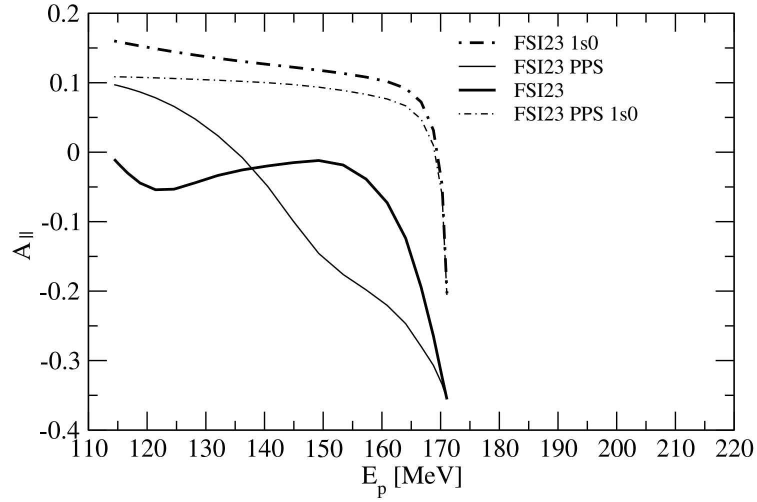
Asymmetries in $^3\vec{H}e(\vec{e}, e'n)pp$ process





$\rightarrow$ in PWIA, principal S-state is sufficient for $E_n > 140$ MeV.

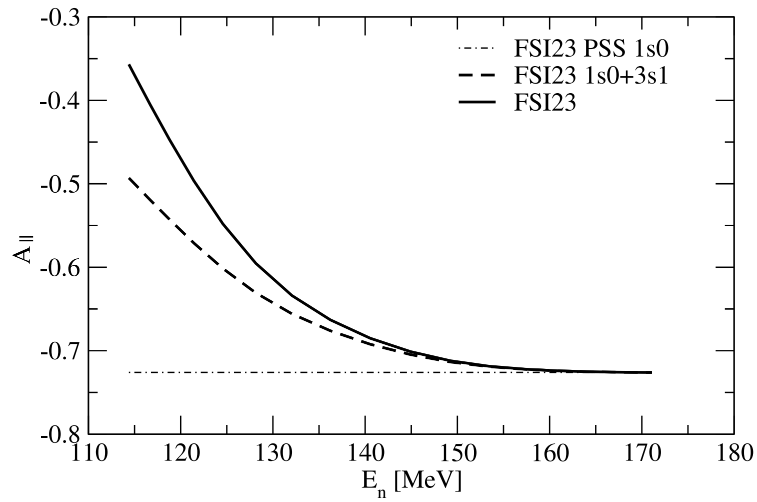
Asymmetries in $^3\vec{H}e(\vec{e}, e'p)pn$ process: beyond PWIA: FSI23

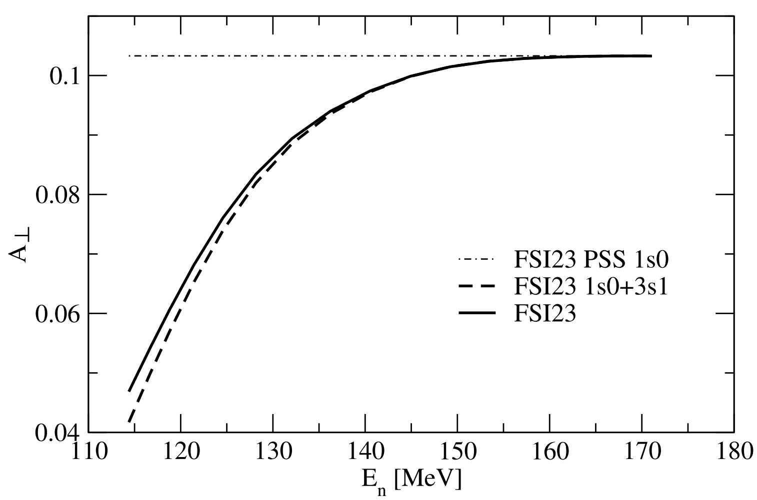


→ in FSI23, principal S-state is sufficient for $E_p \approx 170$ MeV.

→ in FSI23, $^1S_0$ component of t-matrix is insufficient.

Asymmetries in $^3\vec{H}e(\vec{e},e'n)pp$ process: beyond PWIA: FSI23

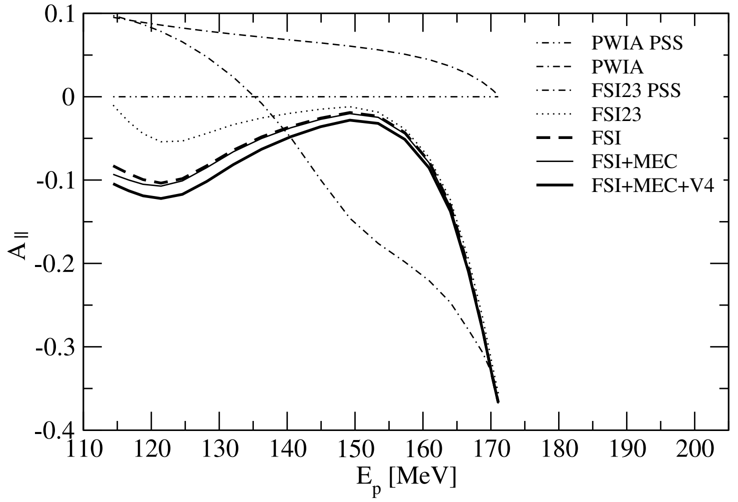


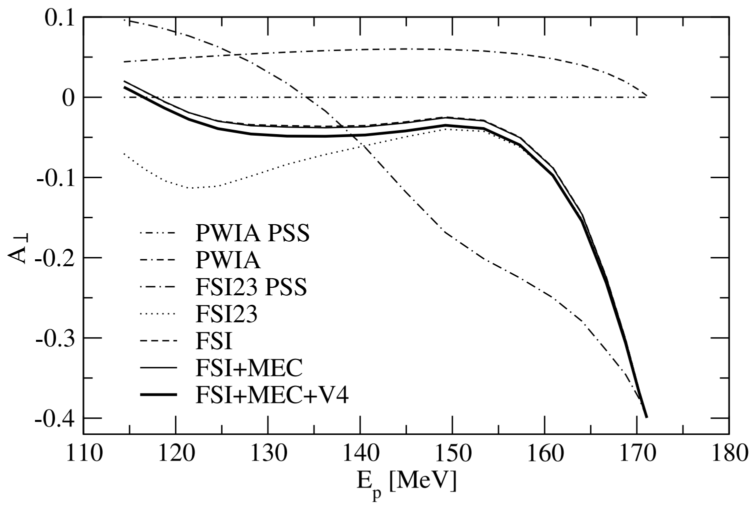


→ in FSI23, principal S-state is sufficient for $E_n > 140$ MeV.

→ in FSI23, $^1S_0$ component of t-matrix is sufficient.

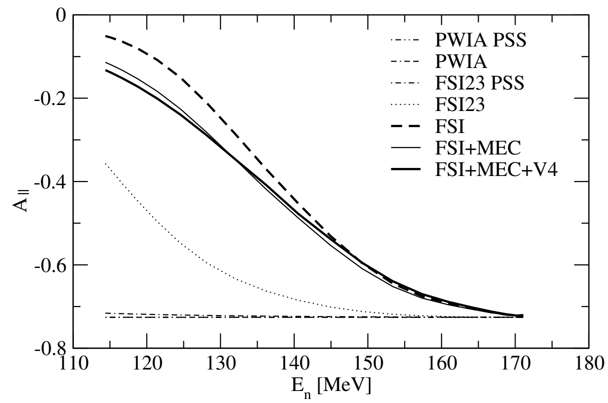
Asymmetries in $^3\vec{H}e(\vec{e}, e'p)pn$ process: beyond FSI23: Full predictions



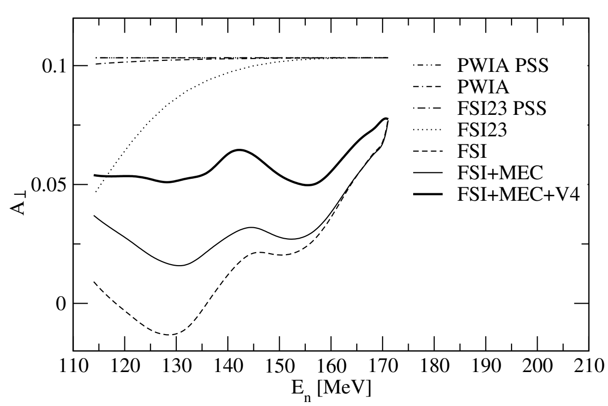


$\rightarrow$ FSI23 with full t-matrix, principal S-state is sufficient for $E_p \approx 170$ MeV.

Asymmetries in $^3\vec{H}e(\vec{e},e'n)pp$ process: beyond FSI23: Full predictions



→ PWIA, principal S-state is sufficient for $E_n > 160$ MeV
→ access to polarized neutron and G_n^M
→ importance of FSI23



→ all dynamical ingredients are important
→ difficult access to G_n^E

Summary

The electrodisintegration of ^{3}He is interesting because

- gives possibility to investigate all dynamical ingredients: nuclear forces, current.
- allows to investigate properties of ^{3}He, like spin independent and spin dependent momentum distributions
- unpolarized exclusive processes - cross section gives examples for different role of FSI, MEC and 3N forces
- unpolarized exclusive 3N breakup - nucleon momentum distribution
- $^3\vec{H}e(e,e'\vec{p})d$ and $^3\vec{H}e(e,e'\vec{d})p$ processes give access to spin dependent momentum distributions for low proton/deuteron momenta. Unfortunately, not easy to measure.
- $^3\vec{H}e(\vec{e},e'p)d$ reaction
  - can be measured more easily
  - simple approach is sufficient what allows to study details of ^{3}He wave function
  - scattering on polarized proton

- $^3\vec{H}e(\vec{e}, e' N_1)N_2 N_3$ reaction
  under FSI23 and principal S-state assumptions:
  - no scattering on a polarized proton
  - scattering on a polarized neutron

  these assumptions work
  - for proton knockout at high energies
  - for neutron knockout and $A_{\parallel}$ at high energies
    - $\rightarrow$ scattering on polarized neutron
    - $\rightarrow$ investigations of neutron magnetic formfactor is possible
  - for neutron knockout and $A_{\perp}$: FSI, exchange currents and 3N force have to be included

Future

- consistent NN interaction, 3N forces and nuclear current based on χPT
- relativistic current and nuclear states
- to all above studies new precise data are needed.