Measurement of the ^{2}H(p, n) breakup reaction at 170 MeV and the three-nucleon force effects

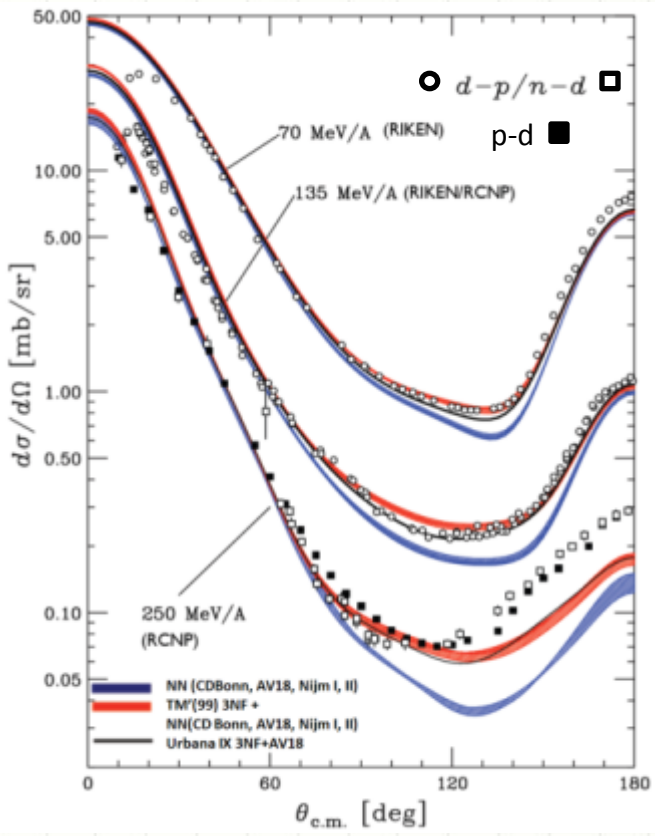
Y. Maeda, **T. Saito**, H. Miyasako (**Univ. of Miyazaki**)
T. Uesaka, S. Ota, S. Kawase, T. Kikuchi, H. Tokieda (CNS)
T. Kawabata (Kyoto Univ.) K. Yako (Univ. of Tokyo)
T. Wakasa, S. Sakaguchi (Kyushu Univ.) R. Chen (RIKEN)
H. Sakaguchi, T. Shima, T. Suzuki, A. Tamii, (RCNP)

EFB22, Krakow, Poland, 2013 Sep 9

Introduction

Three-nucleon force effects are important not only in a few-body nucleon systems but also in the studies of unstable nuclei or neutron star etc.
N+d Elastic scatterings at the intermediate energy region are simple & good probe for 3NF effects study.

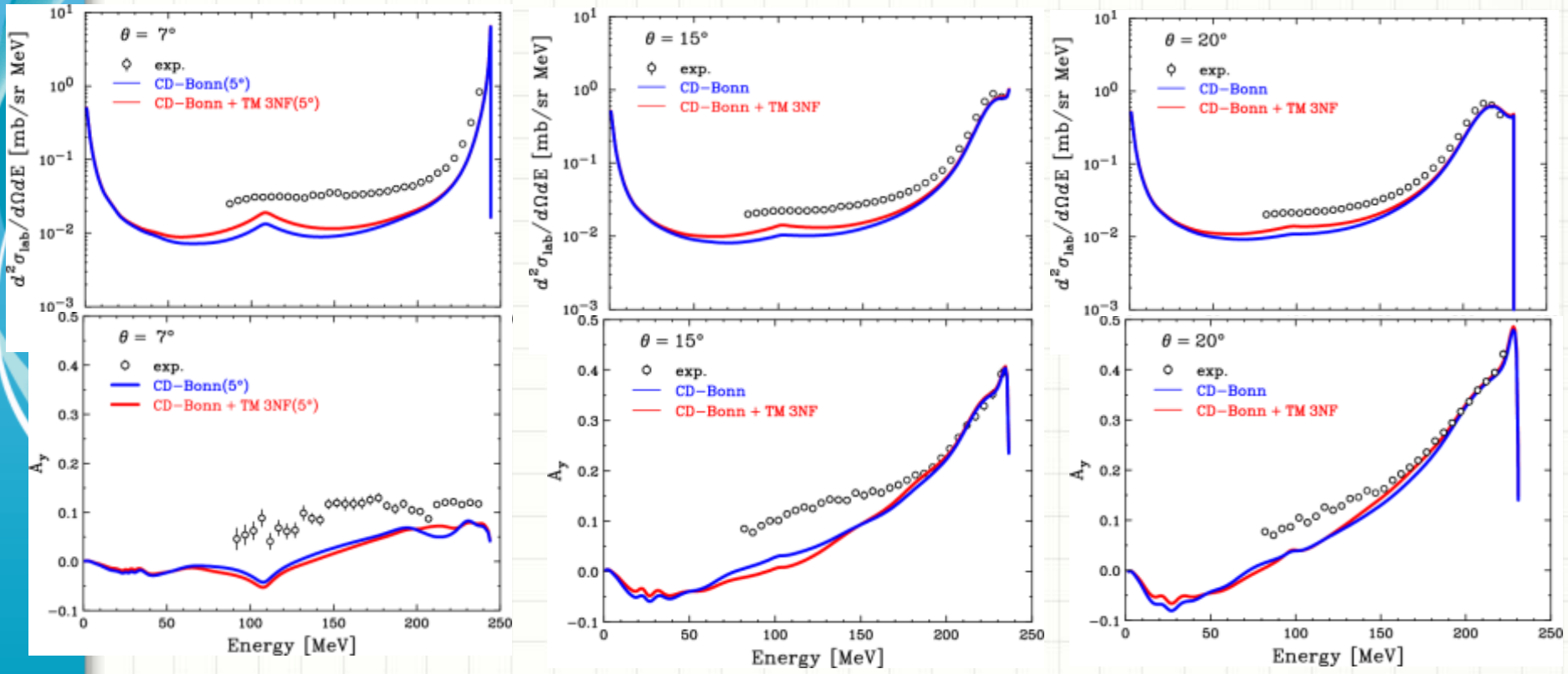
- Differential Cross Sections
  - are well reproduced by the Faddeev calculations with 3NF at intermediate energy region.
  - show large discrepancies between the data and the calculations at 250 MeV.
- Spin observables
  - A_y are well reproduced by introducing the 3NF.
  - Some observables (A_{ij}, spin transfer coefficients) indicate a defect of the spin-dependent part of 3NF.



K. Sekiguchi et al.

D(p,p)pn inclusive breakup reactions at 250 MeV

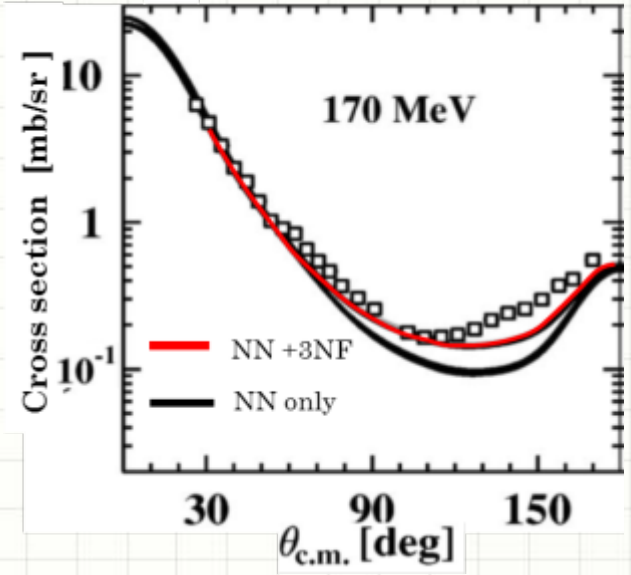
S. Kuroita, Master's thesis, Kyushu University, (2004)



- The comparison between the data and the Faddeev calculations show large disagreements.
- The effects of 3NF, relativistic, Coulomb can't explain it.

Motivation

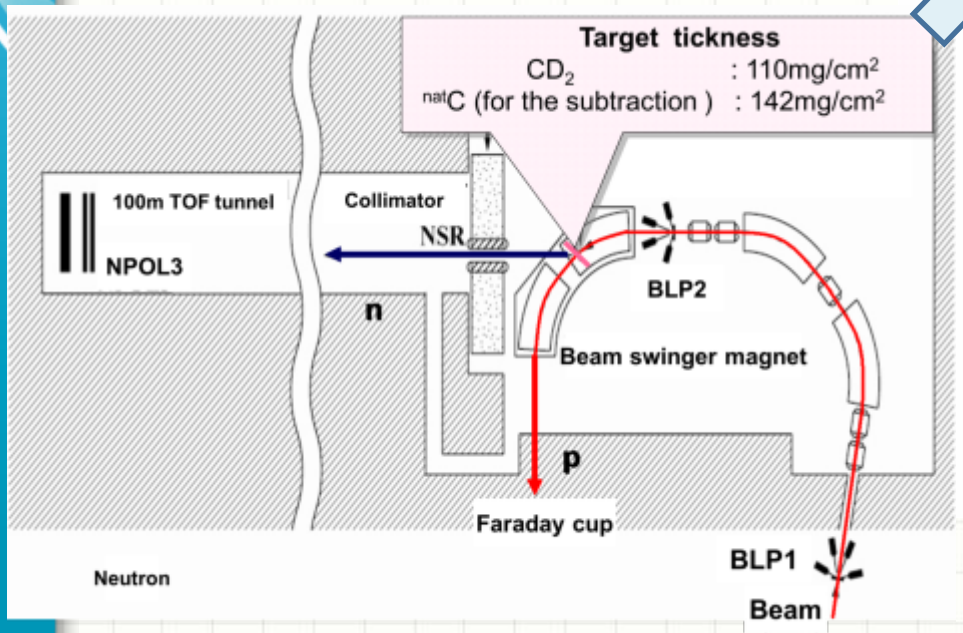
- We carried out the experiment of D(p, n) inclusive breakup reaction at E_p = 170MeV
  - To study the origin of such a large disagreement in the inclusive breakup reactions systematically.
  - At the energy below the π-threshold (210 MeV).
  - (p, n) measurements with TOF technique can cover the wide energy region by one shot.

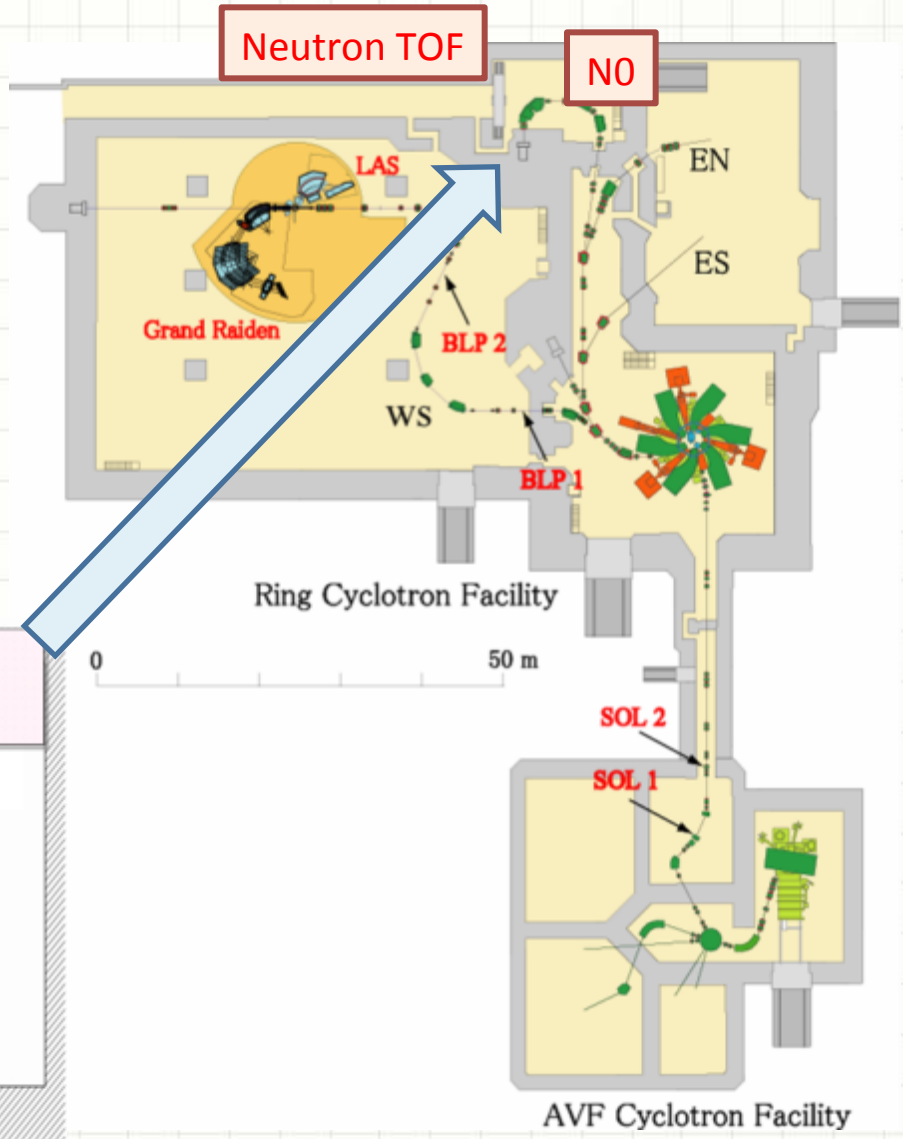


K. Ermisch et al, PRC **68** 054004, PRC **71** 064004

Experimental procedure

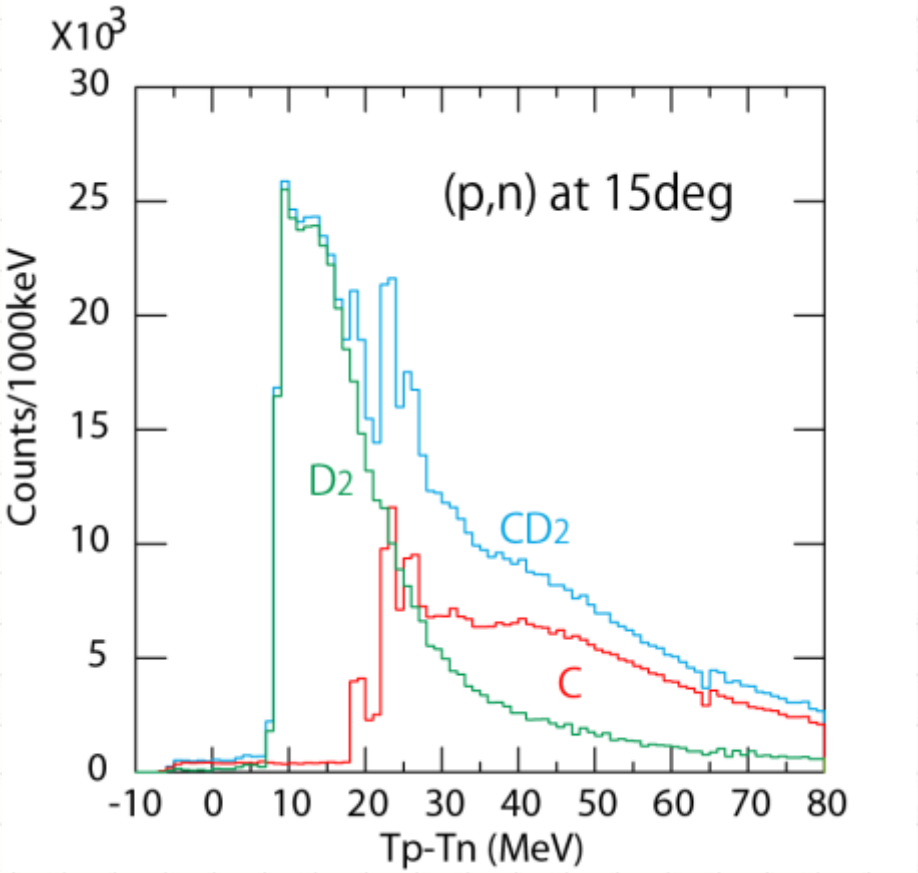
- RCNP, N0 experimental hall.
  - Polarized 170MeV p beam
  - CD_2, C, Li target
  - Scattering angles : θ_{lab} = 0, 7, 15 degree.





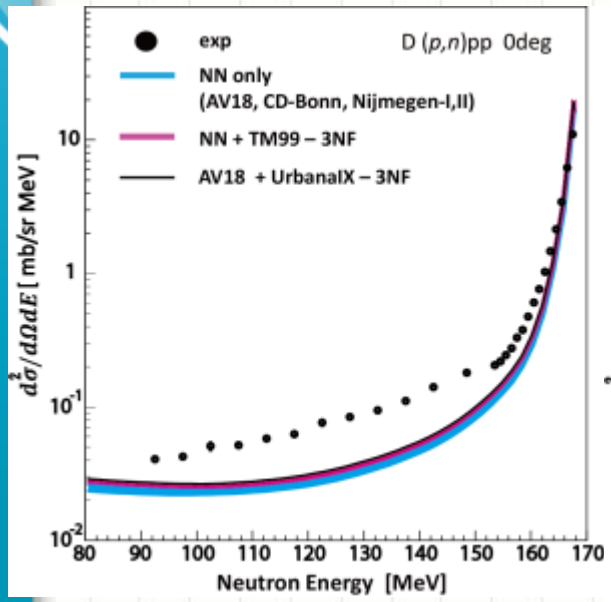
Spectrum

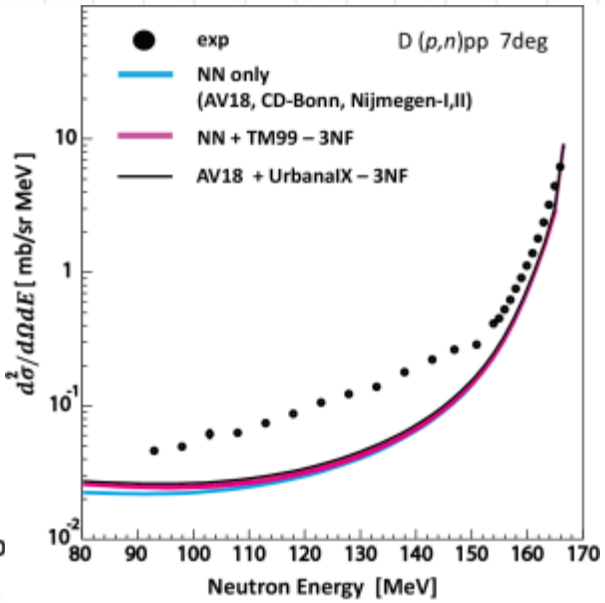
- Subtractions of the Carbon contributions from CD_2 spectrum
  - Normalized by Target thickness, Beam amount, DAQ live time.

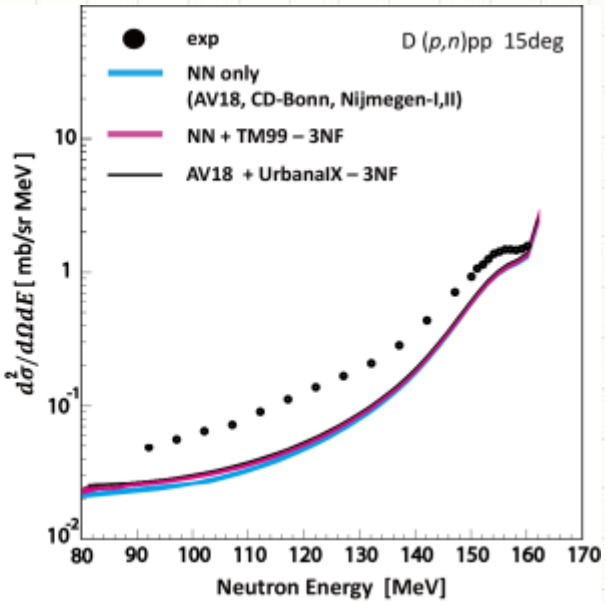


Results (1)

- Differential cross sections
  - Energy Bin ΔE = 1MeV (T_n > 155 MeV) & 5MeV (T_n < 155 MeV)
  - Statistical errors < 2 %, Systematic errors ~ 12 %
- Comparison with Faddeev calc. with 2π-exchange type 3NF
  - Calculations by Prof. H. Witala.
  - Large discrepancies at higher excited energy region.

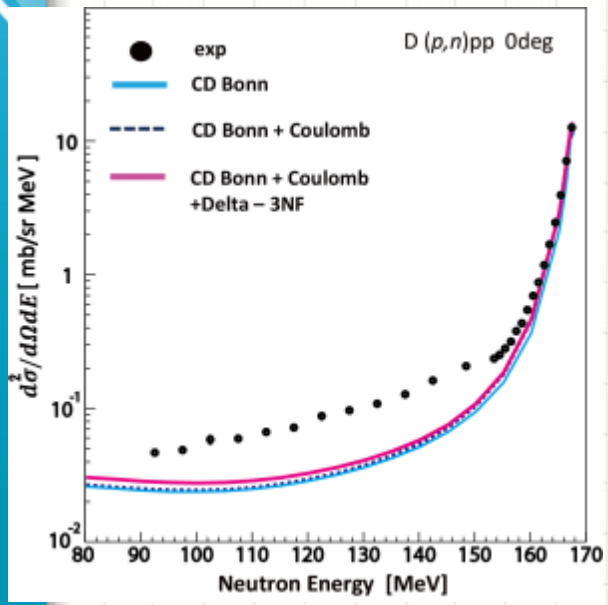


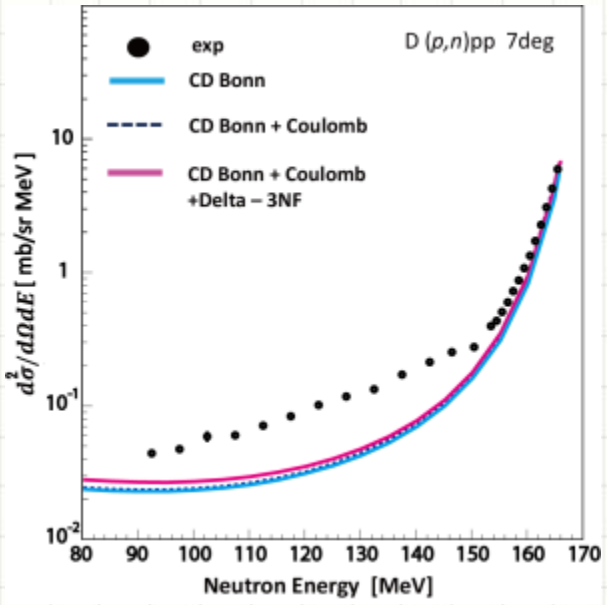


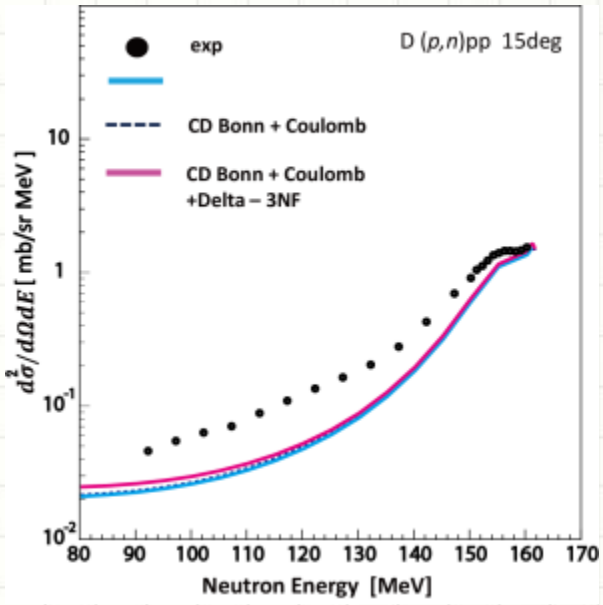


Differential cross sections (2)

- Comparison with Faddeev calc. with Δ-type 3NF
  - Calculations by Dr. A. Deltuva.
  - Large discrepancies at higher excited energy region.
  - Coulomb effects are small

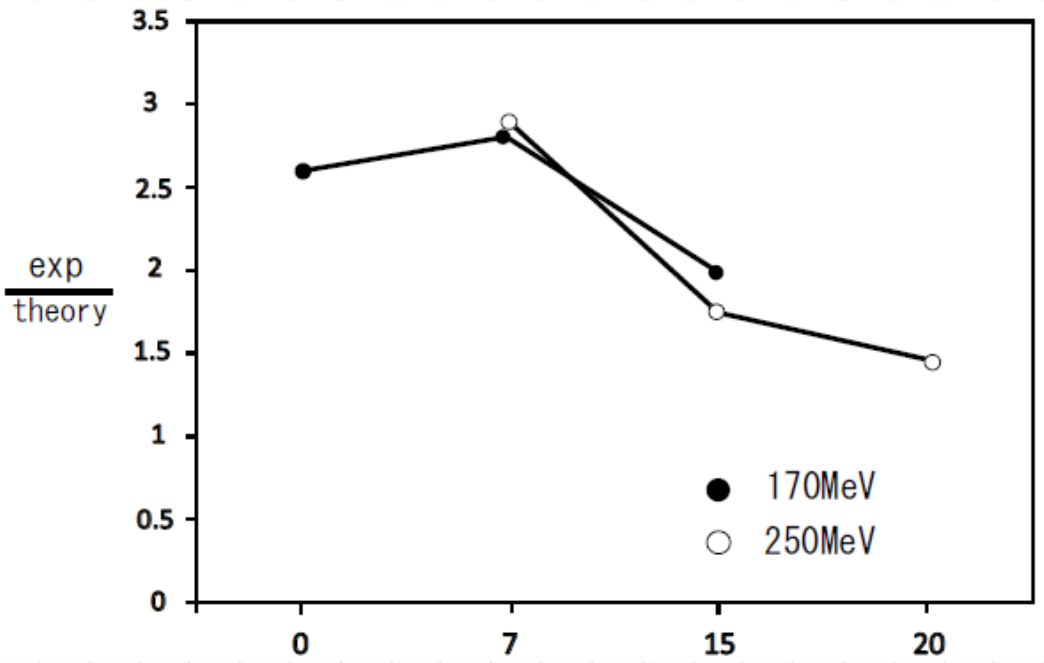


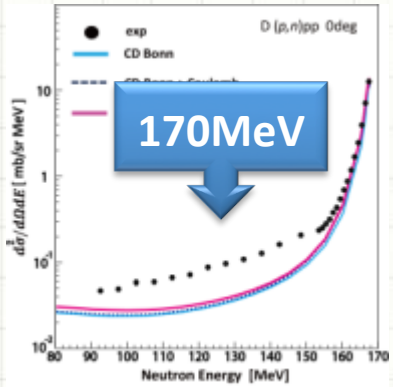


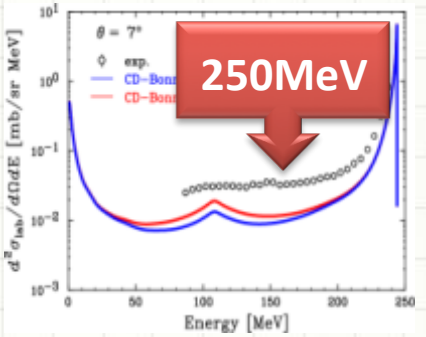


Energy dependency

- Ratio = Data / Calc.(NN+Delta-3NF+Coulomb)
- Discrepancies between the data and the calculations are similar with the case of D(p, p) pn at Ep = 250MeV

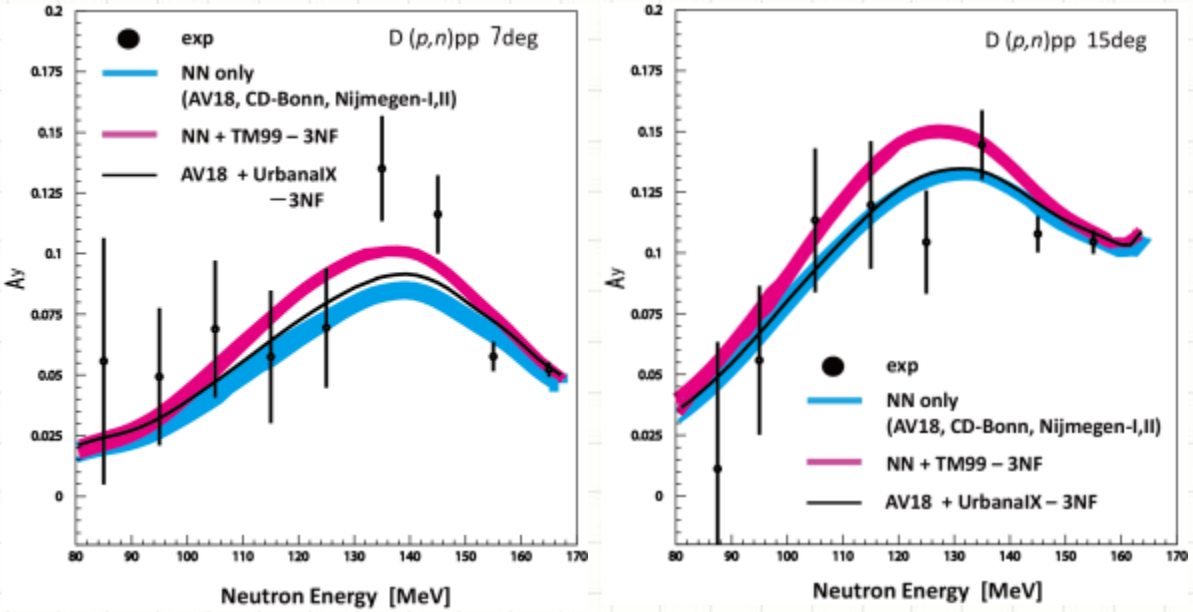






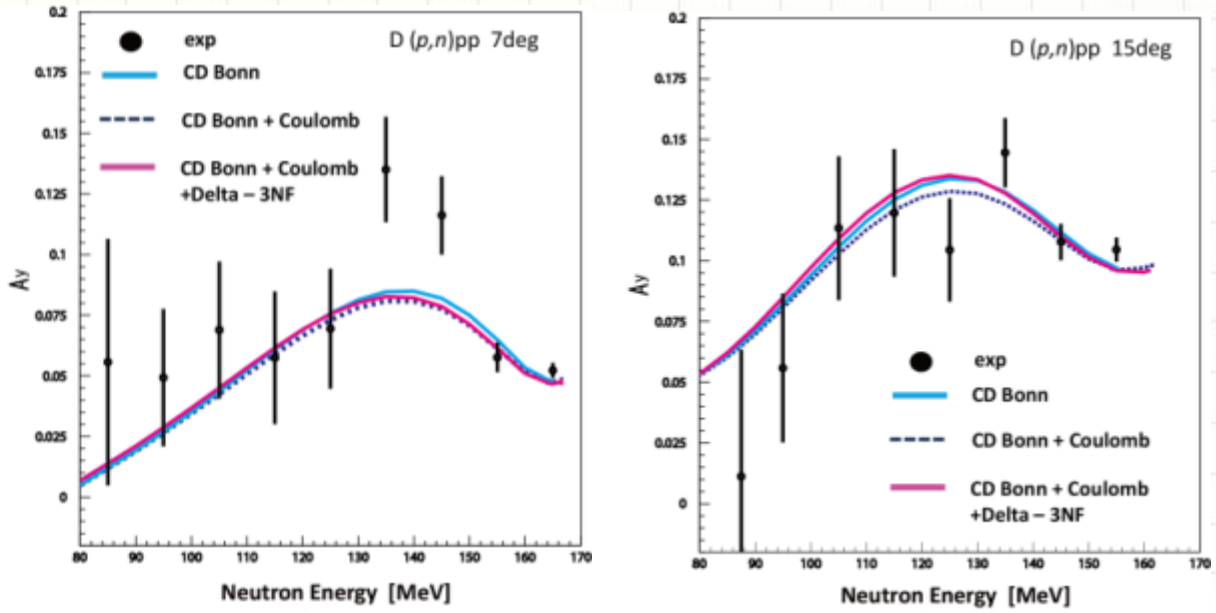
Analyzing powers (1)

- Results
  - Energy Bin ΔE = 10MeV
  - Statistical errors < 0.04
- Comparison with Faddeev calc. with 2π-exchange type 3NF
  - Calculations by Prof. H. Witala.
  - Good agreement within the data error bars.



Analyzing powers (2)

- Comparison with Faddeev calc. with Δ-type 3NF
  - Calculations by Dr. A. Deltuva.
  - Good agreement within the data error bars.



Summary

- Measurements of D(p, n)pp inclusive breakup reaction at 170 MeV
  - Differential cross sections and A_y
  - Scattering angles : 0, 7, 15 degree (Lab. frame)
- Comparisons between the data & the calc.
  - Differential cross sections
    - Faddeev calculations with 2π-exchange-3NF or Δ-3NF underestimate the data significantly.
    - These discrepancies become lager at the high excited energy region as same as the case at 250 MeV.
  - Ay
    - The data are well reproduced by the calc. within large experimental errors.
- More precise simulation of NPOL3 efficiency are now under going to finalize the results.

BACK-UP

Introduction

Nuclear force (2NF,3NF) input ⟺ Faddeev equation ⟺ numerical results ⟺ experimental results of 3NS

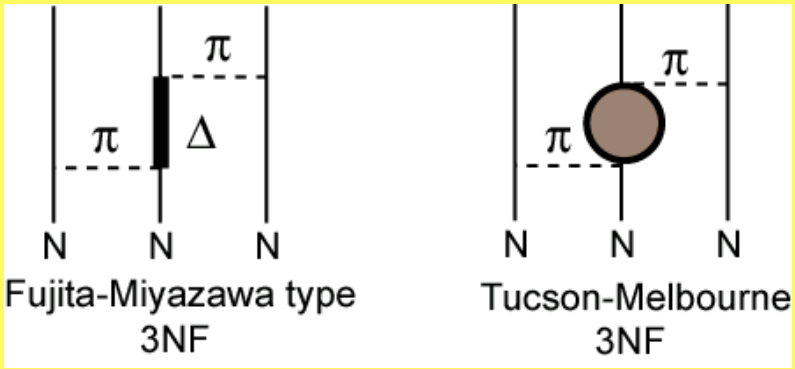
CDBonn, AV18, Nijmegen I/II/93

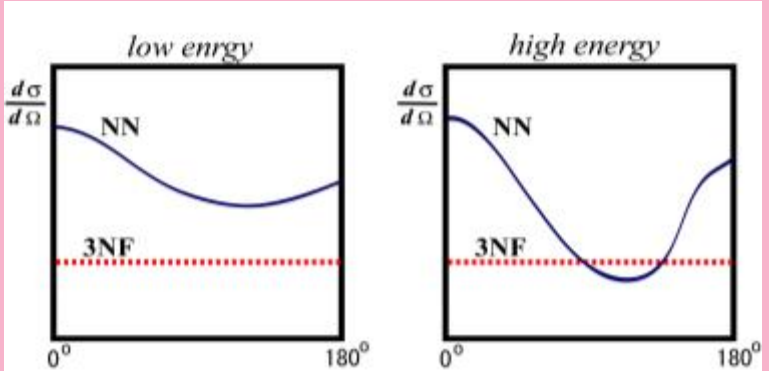
TM-3NF
Urbana IX-3NF

Nd scattering at intermediate energy region is good probe for 3NF effects.

Binding Energy of ^{3}H, ^{3}He

Cross Section
Spin Observables

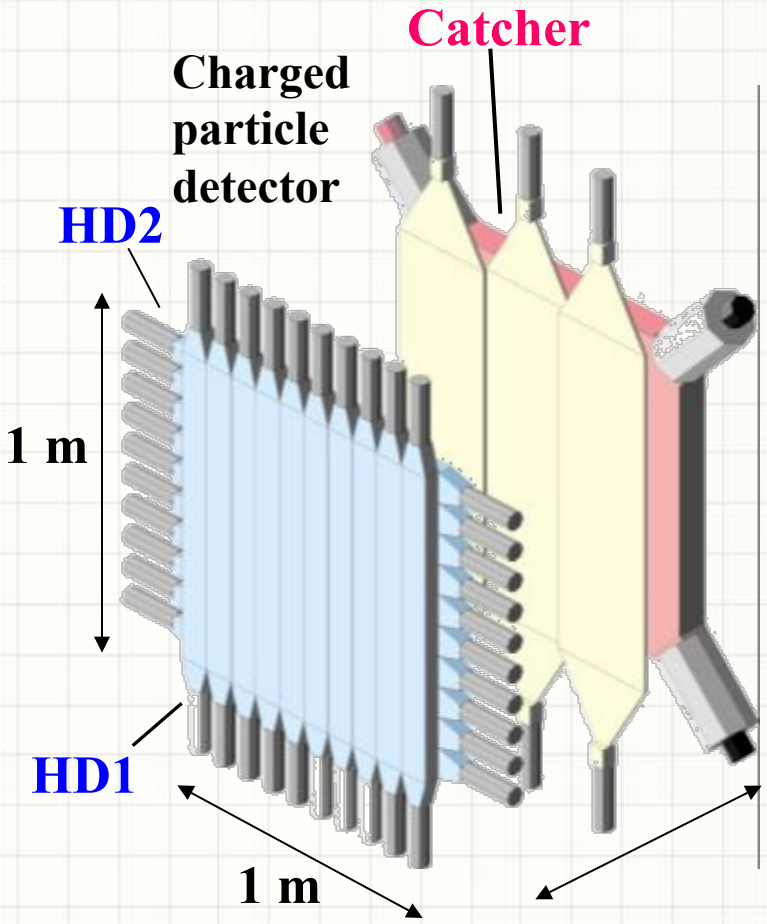




The 3NF effects play an important role also in the study of the light nuclei structure and the nuclear matter, etc.

NPOL3

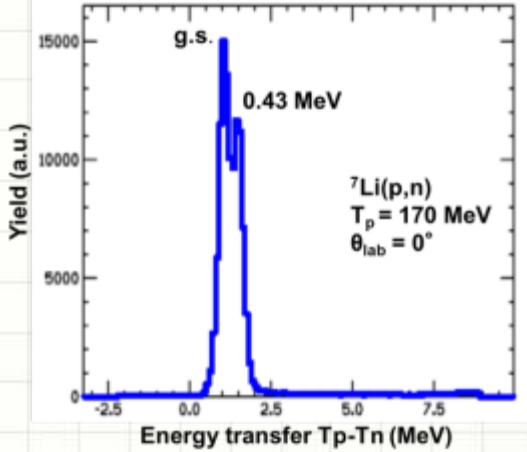
- Scattered neutrons were detected by NPOL3
  - HD1, HD2 : 10 plastic scintillators of $100\times10\times5^{t}$ cm^3.
  - Charged particle Veto counters : thin plastic scintillators
  - $\Delta\Omega$ = 1msr
- Neutron energy T_n is determined by TOF technique.
  - TOF length : 100 m
  - ΔE ~ 300 keV
  - Energy range of T_n : 90 -- 170 MeV



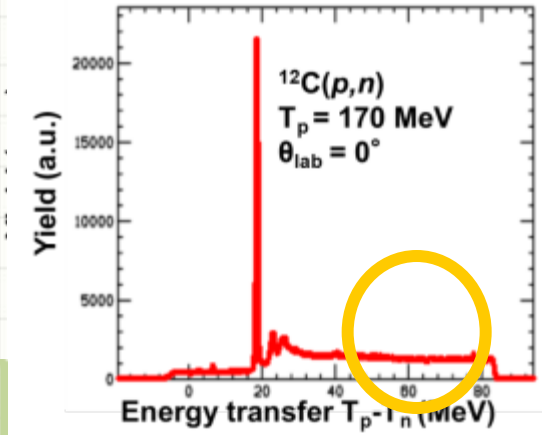
Efficiency of NPOL3

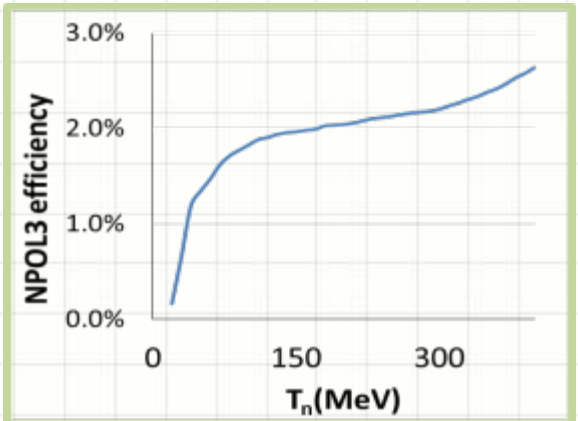
- Cross section measurement of $^{7}Li(p,n)^{7}Be$(g.s. +0.43MeV) at 0 degree.
  - $\sigma_{c.m.}$ = 27.0±0.8mb/sr at Ep = 170MeV
    (T. N. Taddeucci, et al., PRC41 (1990) 2458)
- ADC gate
  - For the selection of neutron events from γ events, we applied the threshold on the ADC signals.
  - Threshold : 18 MeV_{ee} --> ε = 1.27 %
- Neutron energy T_n dep.
  - PHITS Simulation
  - $\frac{\varepsilon(170\ \mathrm{MeV})}{\varepsilon(90\ \mathrm{MeV})} \sim 110\%$

^{7}Li : 59.4 mg/cm^2



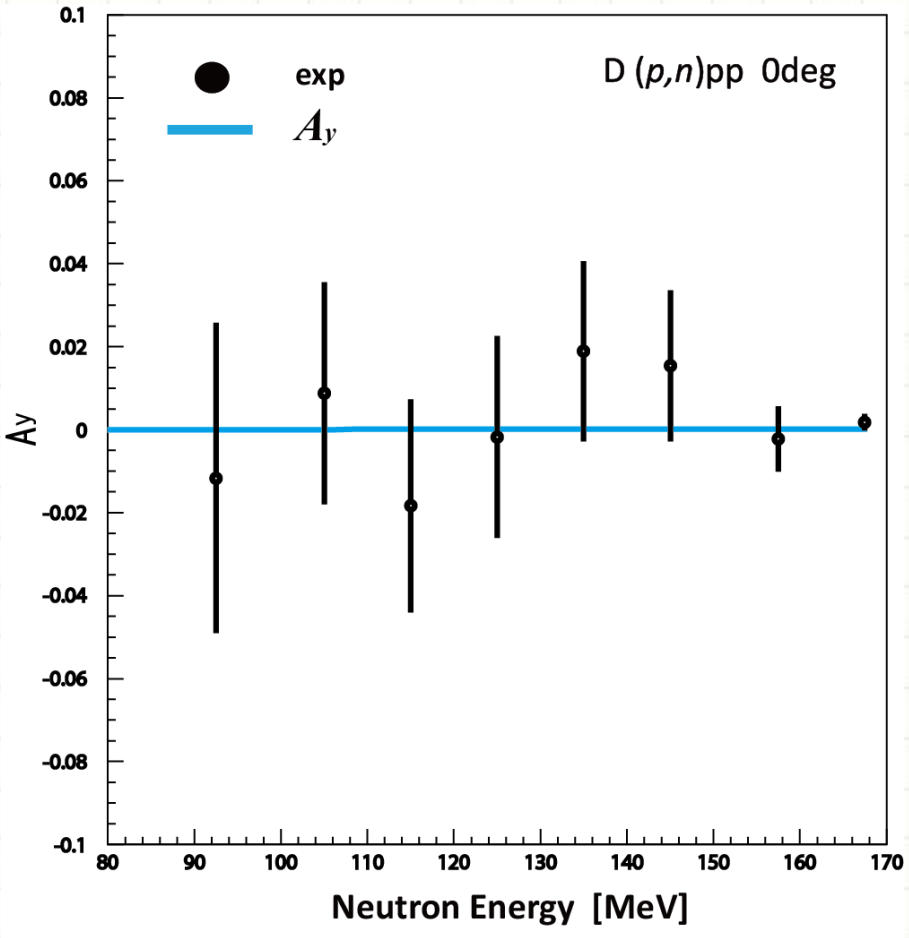
threshold = 18.0MeV_{ee}



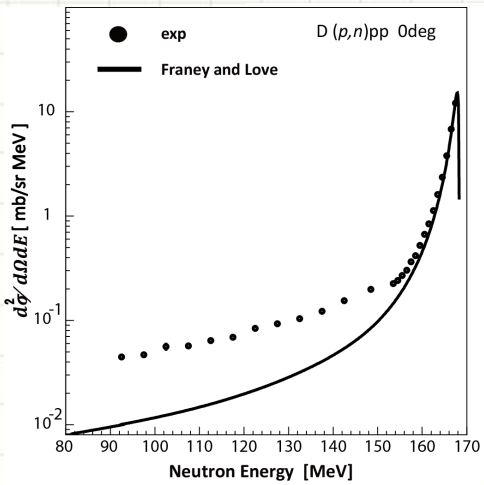


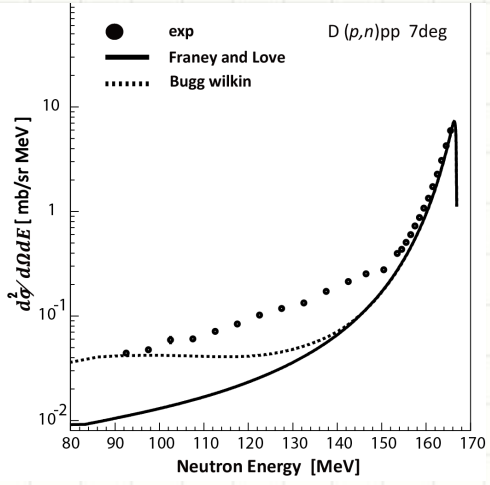
False asymmetry

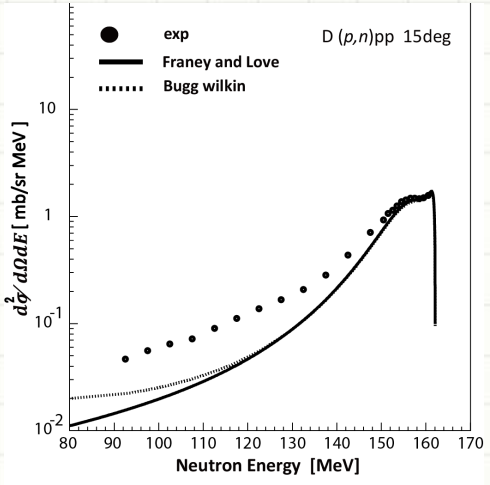
- We successfully deduced $A_Y = 0$ observables within the statistical errors.

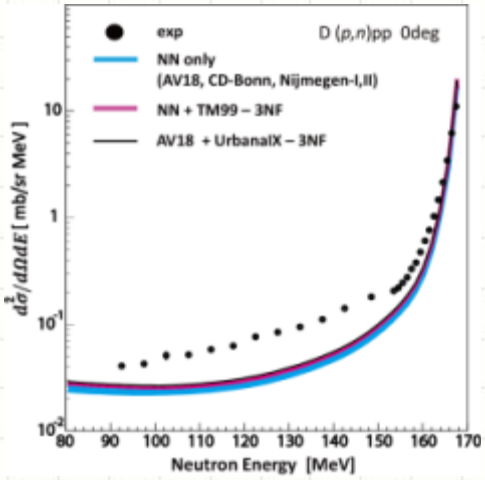


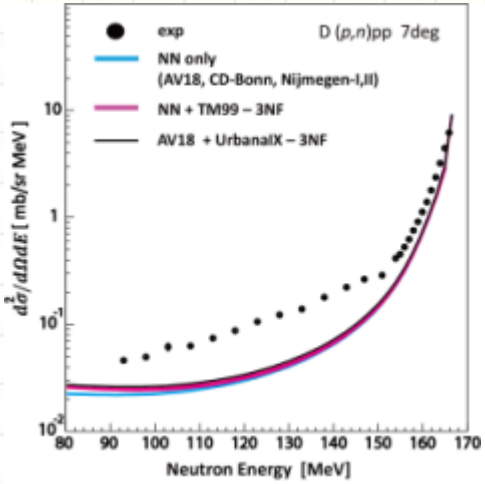
Comparison with PWIA calculations (log)

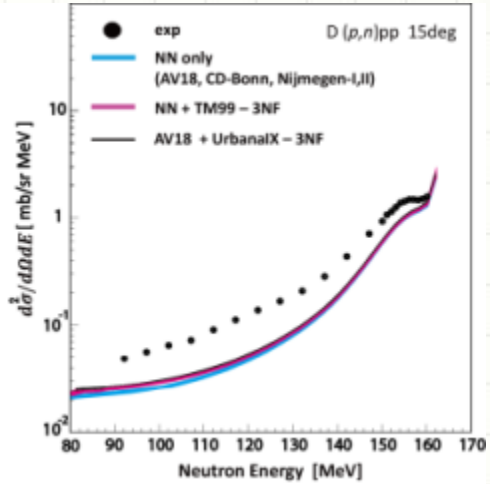










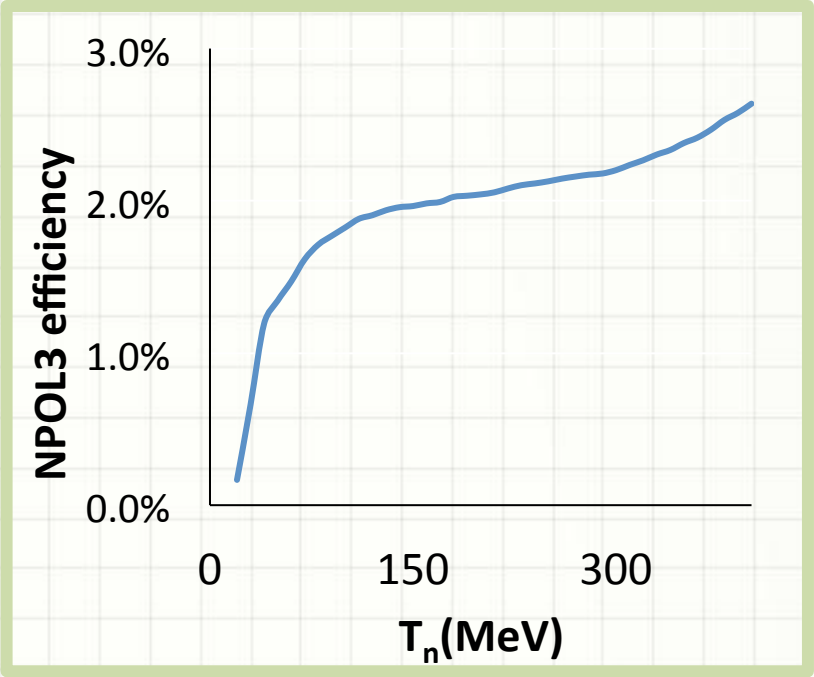


Efficiency of NPOL3

- ADC threshold dependency

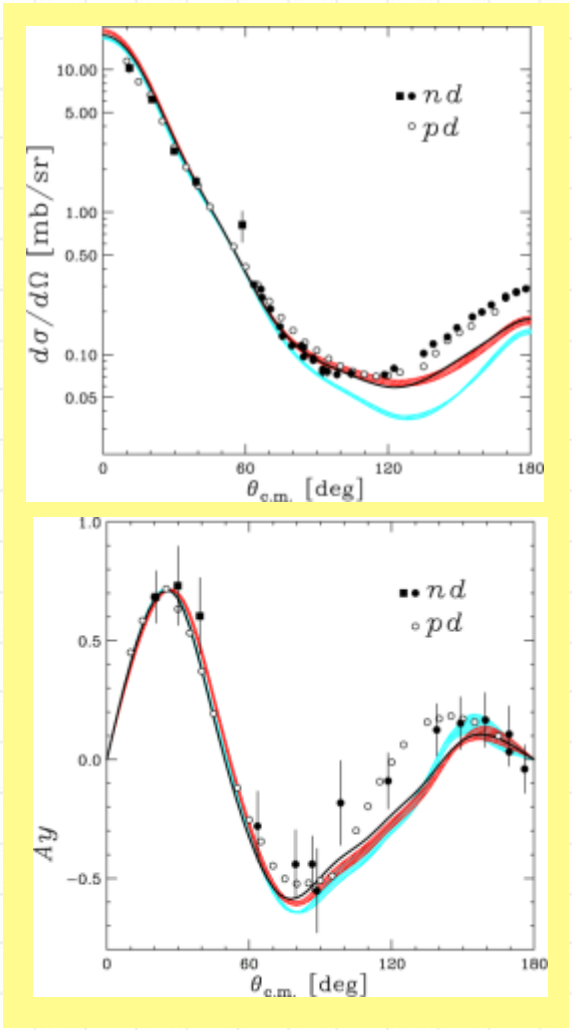
Threshold (MeV_{ee})	5.0	10.0	18.0
Efficiency (%)	2.53	2.07	1.27

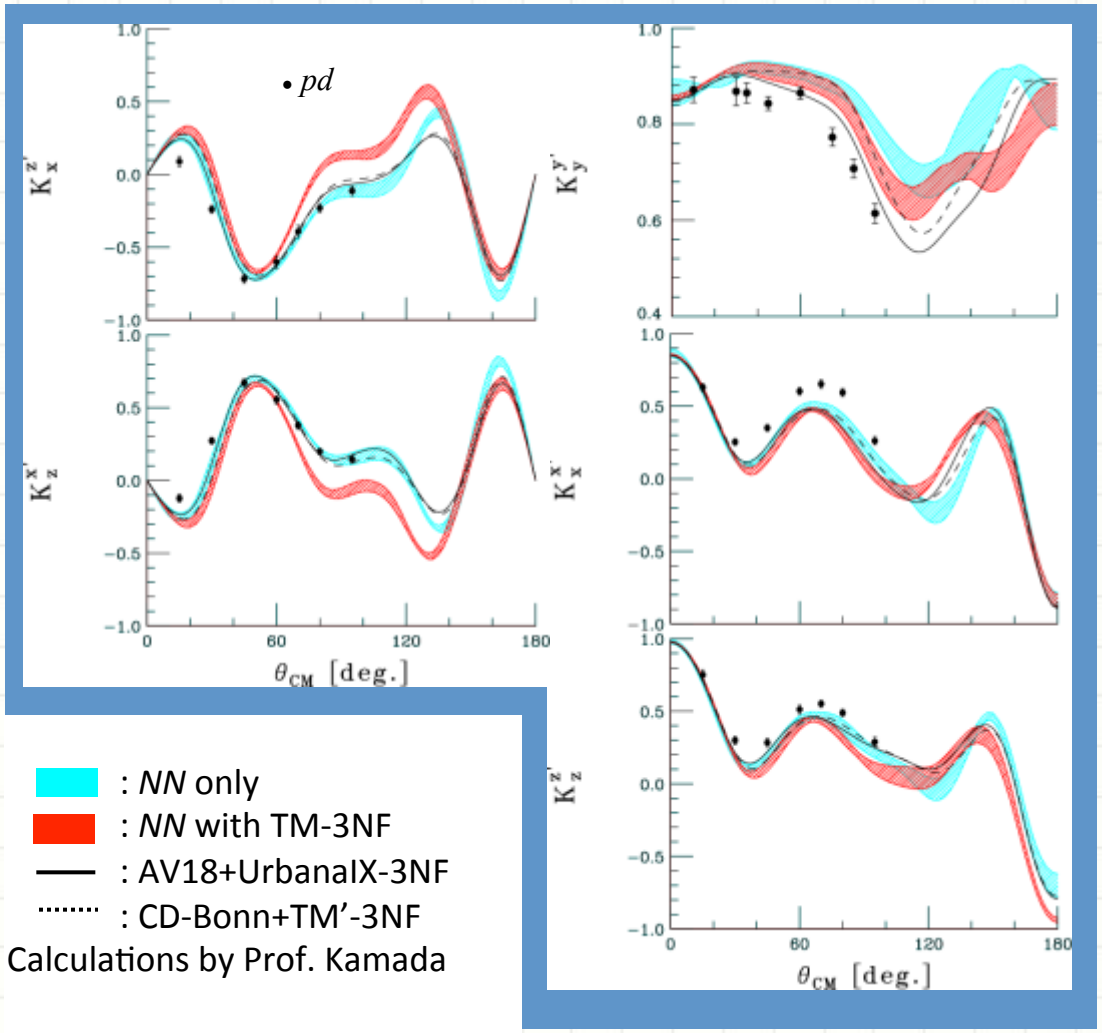
- Neutron energy dependency
  - Simplified simulation by **PHITS** (Particle and Heavy Ion Transport code System)
  - $\frac{\varepsilon(170\ \mathrm{MeV})}{\varepsilon(90\ \mathrm{MeV})} \sim 110\%$



N+d elastic scattering at 250MeV

- *p+d* (K. Hatanaka *et.al*, PRC**66**(2002)044002) & *n+d* (Y. Maeda PhD thesis) measurements at RCNP



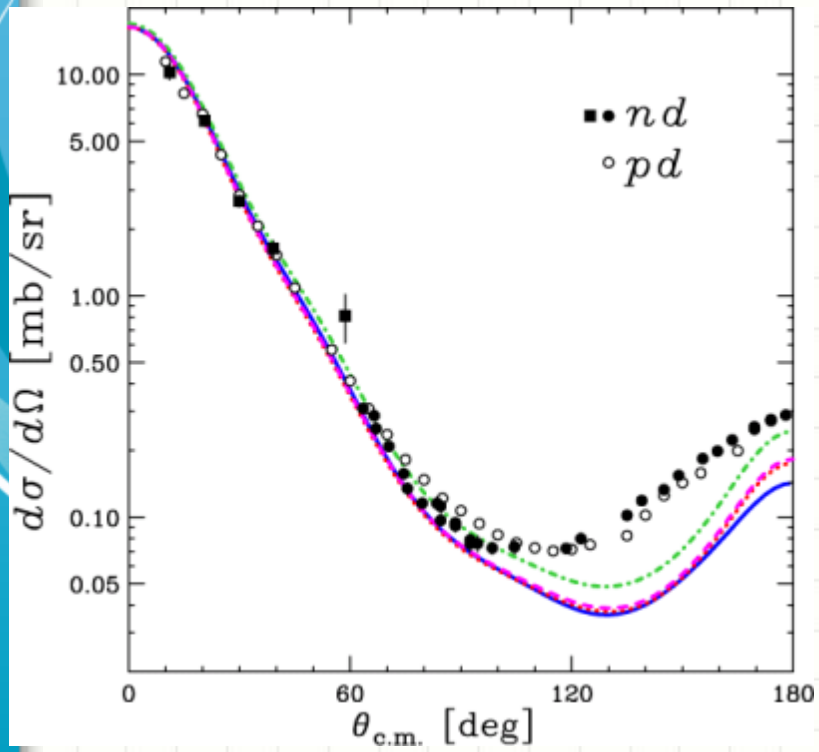


: *NN* only
: *NN* with TM-3NF
: AV18+UrbanaIX-3NF
: CD-Bonn+TM'-3NF

Calculations by Prof. Kamada

Relativistic effects

- Fully relativistic calculations by Witała *et al*.



Non-Rel.

Rel. NN potential

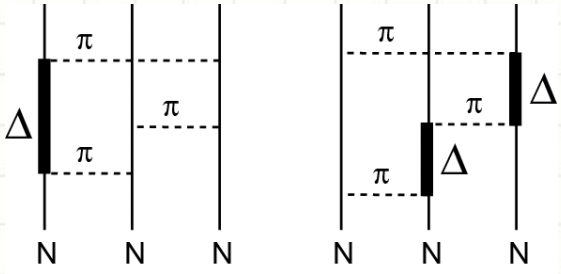
Lorentz boosted potential

Approx.1

Approx.2

Relativistic effect is limited to the very backward angles.

Large discrepancy indicates that we need other types of 3NF (?)

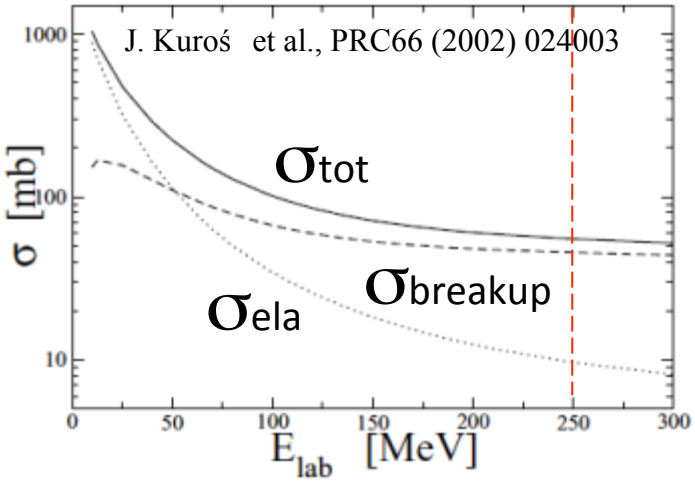


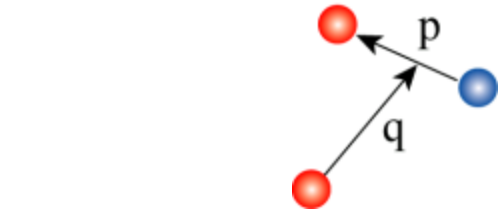
More studies of 3NF at 250 MeV are important to understand this discrepancy.

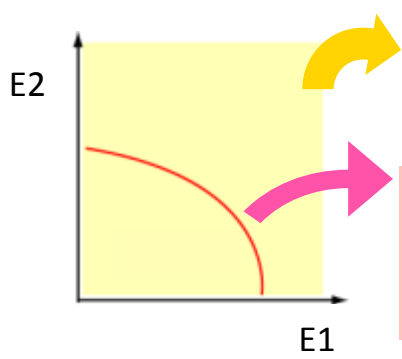
pd breakup reaction

- Why are *Nd* breakup reactions good at this energy?

Cross section becomes relatively large.



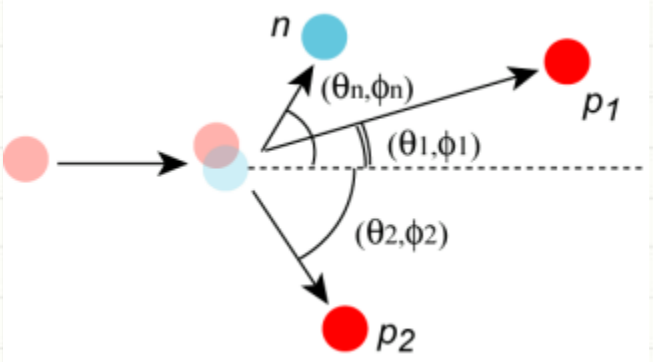




Elastic scattering
→ Integration of all *p*

Breakup reaction
→ Select a point on the S-curve

It is important to select good kinematical configuration to search the detail of 3NF effect.



2π-exchange 3NF models

$$V^{(3)} = \frac{1}{(2\pi)^6}\frac{g_{\pi NN}^2}{4m^2}\frac{F_{\pi NN}^2(q^2)}{(q^2+m_\pi^2)}\frac{F_{\pi NN}^2(q'^2)}{(q'^2+m_\pi^2)}\vec{\sigma}_1\cdot\vec{q}\,\vec{\sigma}_2\cdot\vec{q}'\left[o^{\alpha\beta}\tau_\alpha\tau_\beta\right]$$

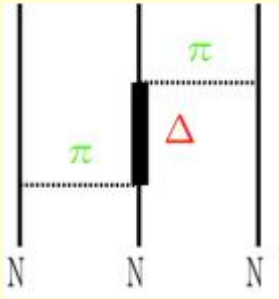
$$o^{\alpha\beta} = \delta^{\alpha\beta}\left[a + b\vec{q}\vec{q}' + c(q^2+q'^2)\right] - d(\tau_3^\gamma\varepsilon^{\alpha\beta\gamma}\vec{\sigma}_3\cdot\vec{q}\times\vec{q}')$$

$$F_{\pi NN}^2(q^2) = \frac{\Lambda^2 - m_\pi^2}{\Lambda^2 + q^2} \qquad \pi\mathrm{NN}\ \text{form factor}$$

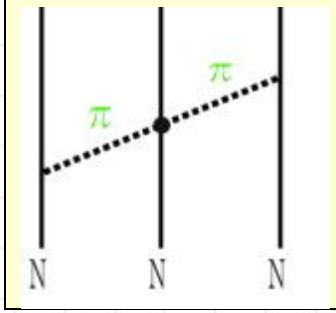
Λ : cut – off parameter

3NF model	a	b	c	d
FM	0.0	-1.15	0.0	-0.29
TM	1.13	-2.62	1.05	-0.60
Urbana IX	0.0	-1.20	0.0	-0.30
TM'	-0.87	-2.62	0.0	-0.60

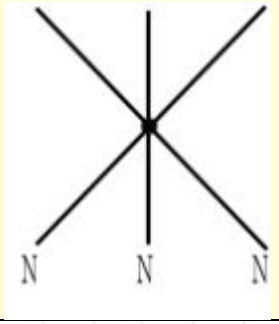
b, d **p-wave**

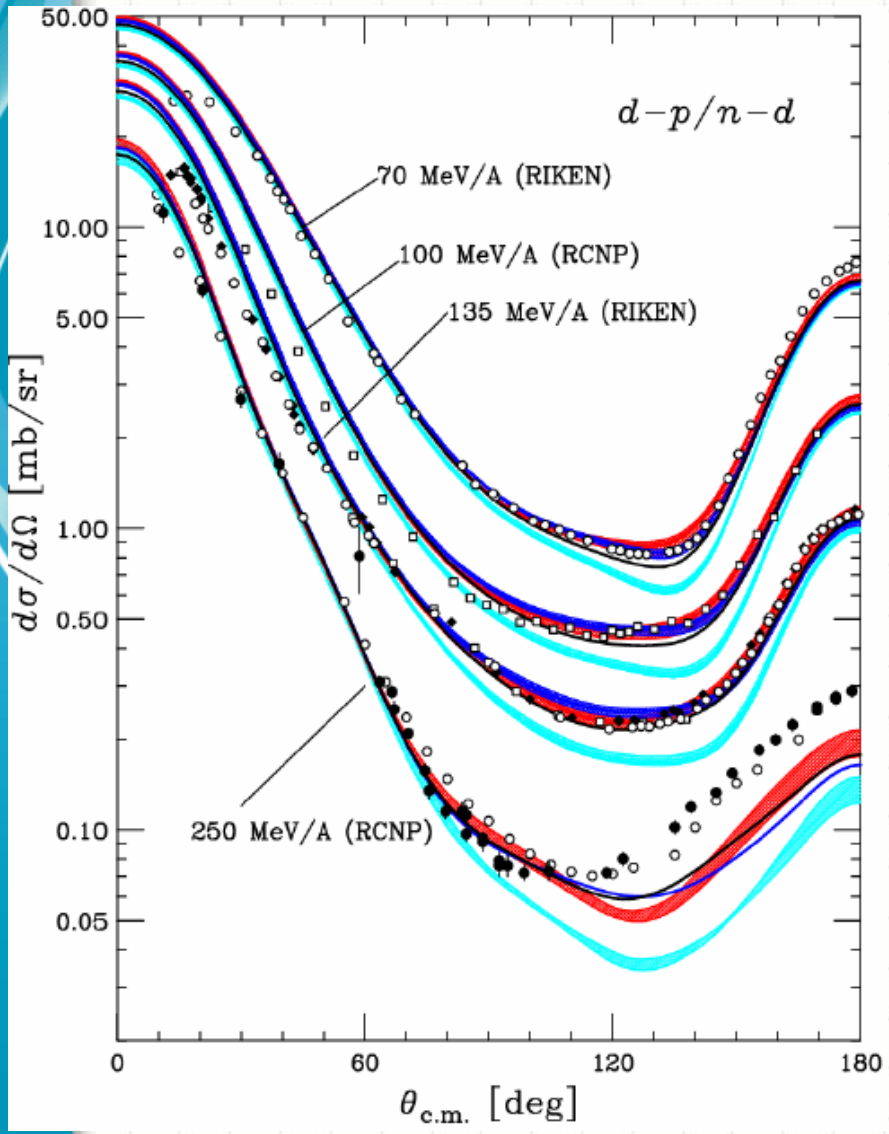


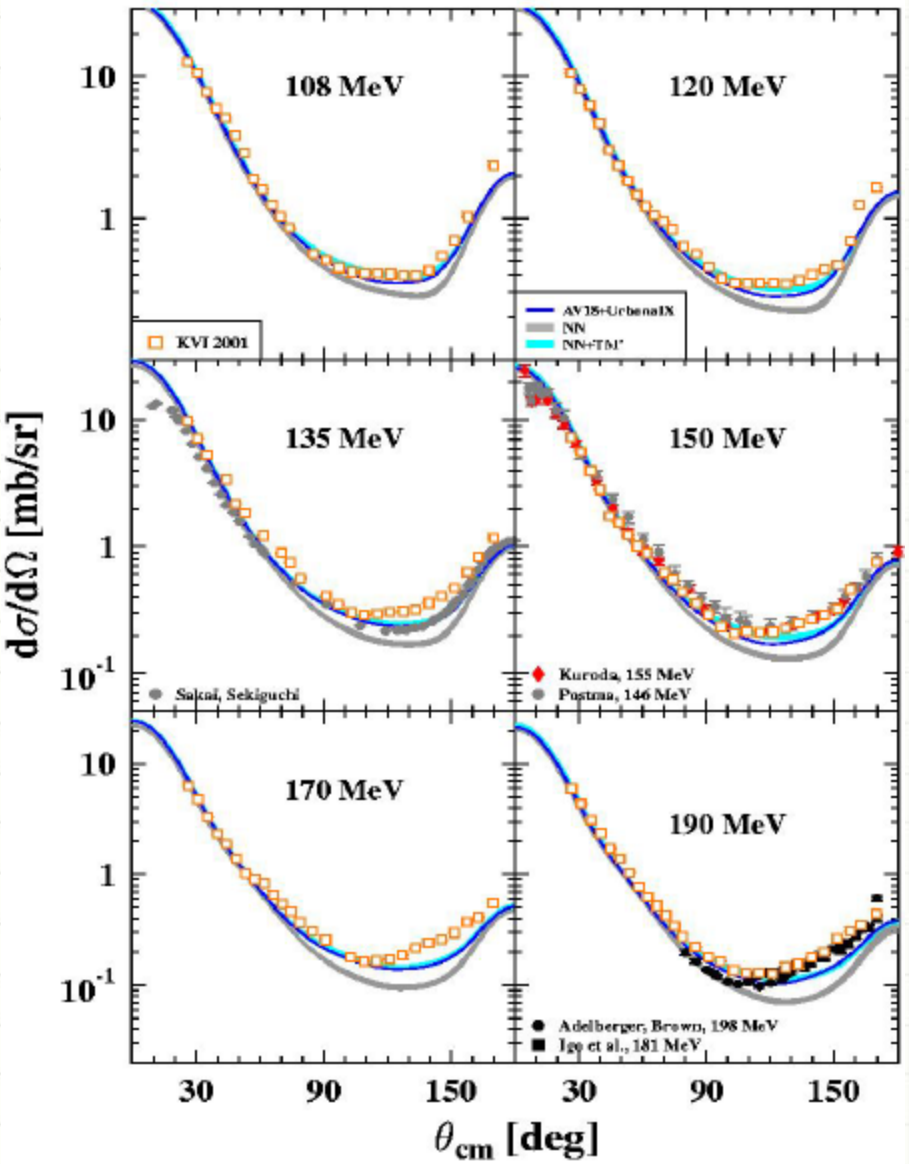
a **s-wave**



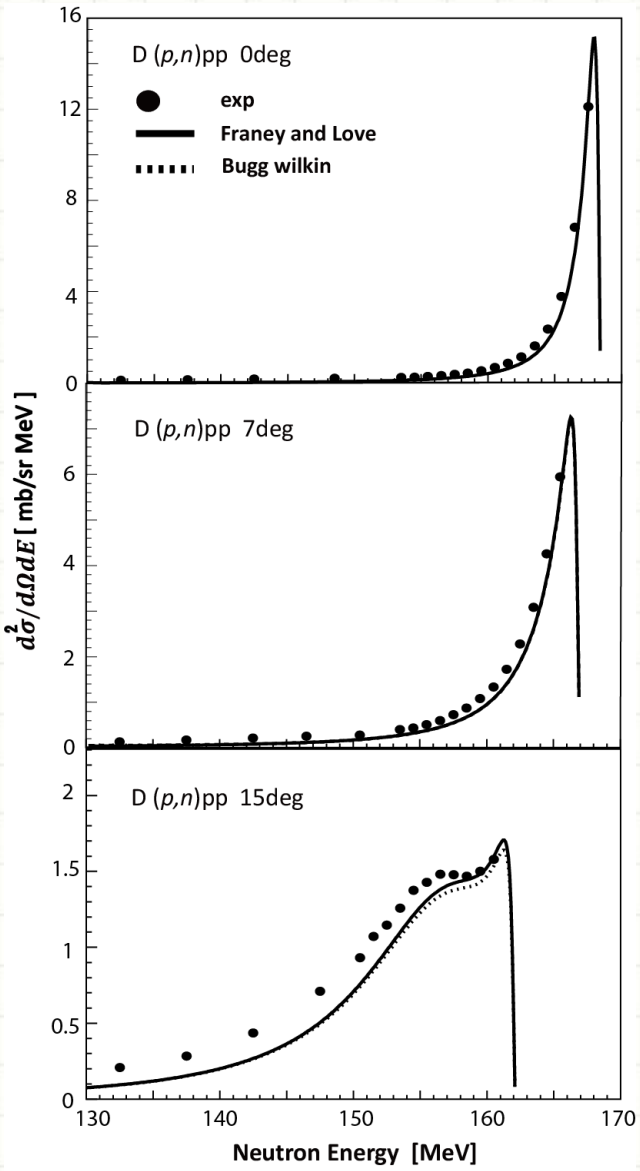
c

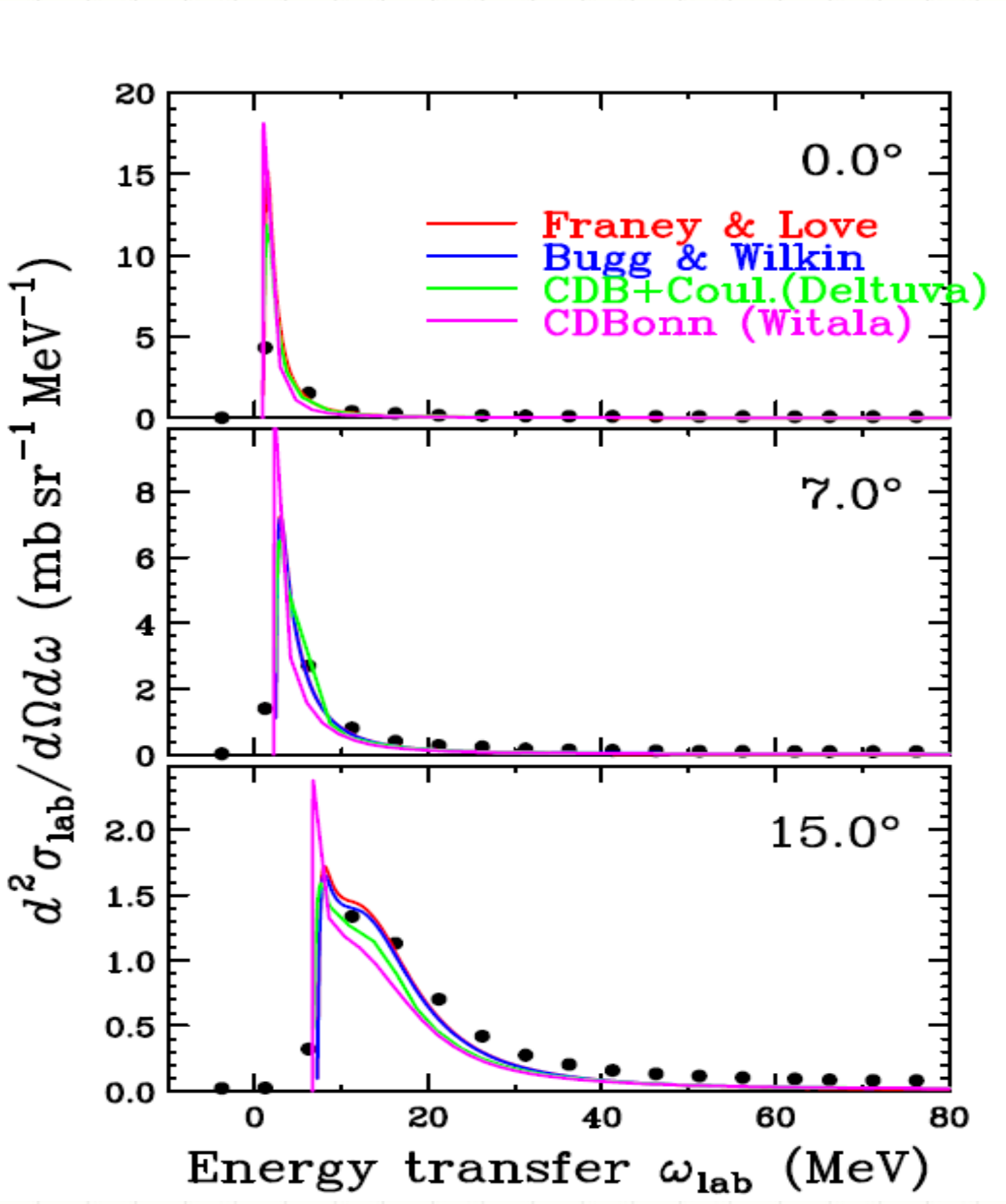



d−p/n−d
70 MeV/A (RIKEN)
100 MeV/A (RCNP)
135 MeV/A (RIKEN)
250 MeV/A (RCNP)
dσ/dΩ [mb/sr]
θc.m. [deg]
50.00
10.00
5.00
1.00
0.50
0.10
0.05
0
60
120
180


108 MeV
120 MeV
135 MeV
150 MeV
170 MeV
190 MeV
KVI 2001
AV18+UrbanaIX
NN
NN+TM'
Sakai, Sekiguchi
Kuroda, 155 MeV
Postma, 146 MeV
Adelberger, Brown, 198 MeV
Ige et al., 181 MeV
dσ/dΩ [mb/sr]
θcm [deg]
10
1
10-1
30
90
150

Comparison with PWIA calculations (linear)




0.0°
7.0°
15.0°
Franey & Love
Bugg & Wilkin
CDB+Coul.(Deltuva)
CDBonn (Witala)
$d^2\sigma_{lab}/d\Omega d\omega$ (mb sr^{-1} MeV^{-1})
Energy transfer ω_{lab} (MeV)