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TOHOKU
UNIVERSITY

Study of 3NF effects *via* few-nucleon scattering

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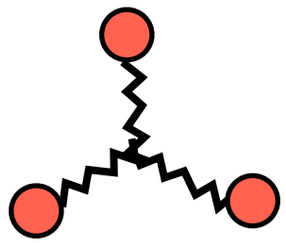
Tohoku University

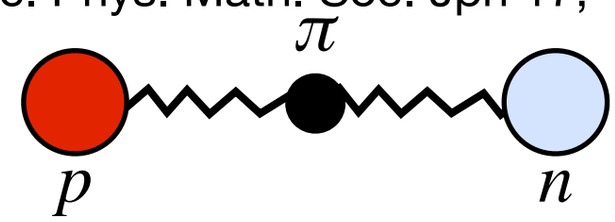


Introduction

NN Force

- meson exchange picture : H. Yukawa

Proc. Phys. Math. Soc. Jpn 17, 48 (1935)



meson exchange between two nucleons → nuclear force

many *N-N* scattering data
up to ～ 350MeV

1990's , **realistic NN potentials**
(CD Bonn, AV18, Nijimen I&II)

3000～4000 of *N-N* scattering data
are precisely reproduced($\chi^2 \sim 1$)

A≧3 system

- scattering observables (*d*+*p*)
- binding energies (^{3}H, ^{3}He)
- properties of nuclear matter (saturation density)

→ cannot be reproduced using realistic NN force alone

→ **Importance of three-nucleon force(3NF)**

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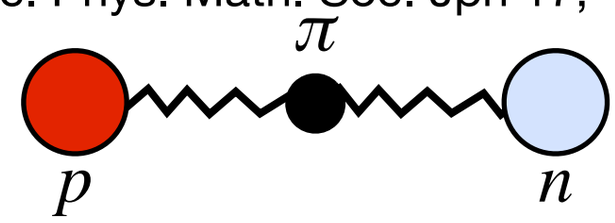

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→ **Importance of three-nucleon force(3NF)**

Few-nucleon scattering

precise data

- cross section : $\dfrac{d\sigma}{d\Omega}$
- spin observables (T_{ij}, C_{ij}, K_{ij})
  - angular distribution
  - energy dependence

theoretical calculation

- *NN*-potentials (1990's)
  (*e.g.* CDBonn, AV18, Nijmegen I&II)
- 3NF-models (*e.g.* TM'99, Urbana IX)

Faddeev (-Yakubovsky) equation :
rigorous description for
quantum 3(4)-body system

direct comparison between **experimental data** and **theoretical calculation**

—> quantitative discussion of 3NF

Scattering experiment (A≧3)

- momentum dependence
- spin dependence (using pol. beam or target)
- isospin dependence

- **deuteron - proton elastic scattering**

: the simplest system of A=3

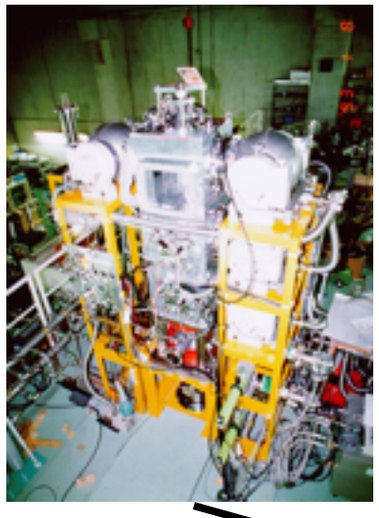
d+p scattering at RIKEN

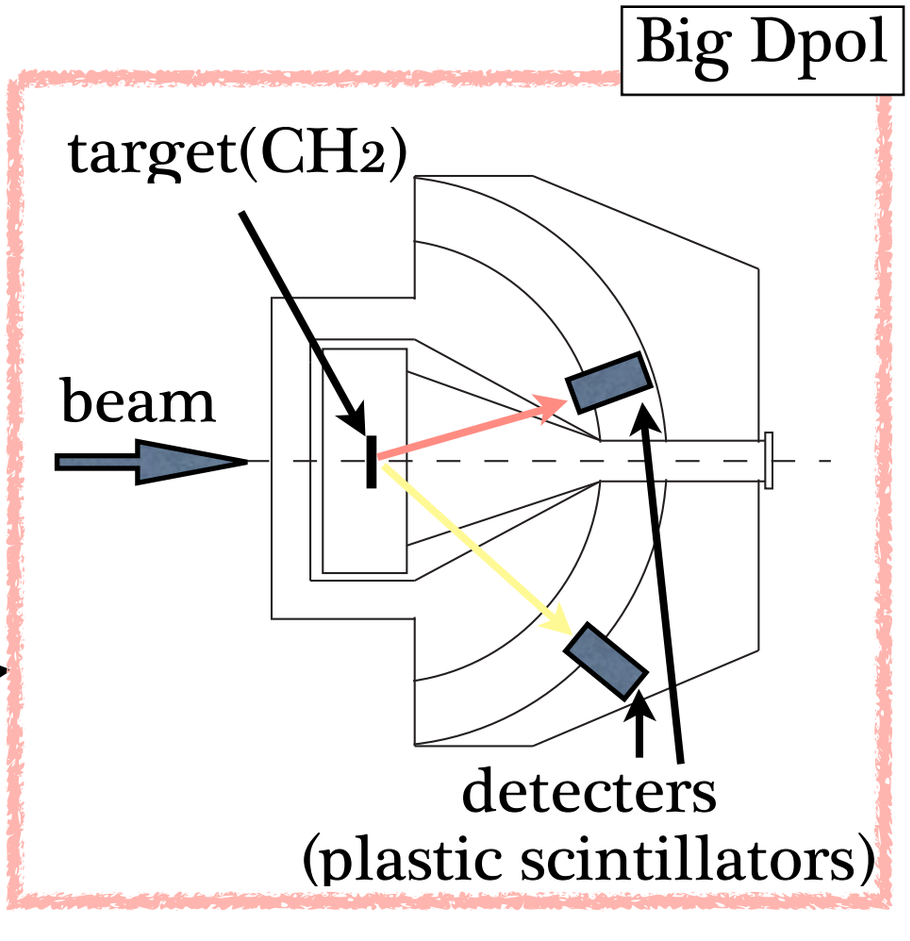
RIKEN RIBF

- Polarized *d* beam was provided by the polarized ion source
- Pol. *d* beam can be accelerated by the AVF+RRC+SRC up to ～400 MeV/A
- Spin axis of *d* beam was rotated by the Wien filter **prior to acceleration**
- For all cyclotron, single turn extraction was achieved (turn mixing < 1%)

PIS → Beam Polarization : 80% of theoretical maximum values

H. Okamura *et al.* AIP Conf. Proc. **293**, 84 (1994)





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PIS

→ Beam Polarization : 80% of theoretical maximum values

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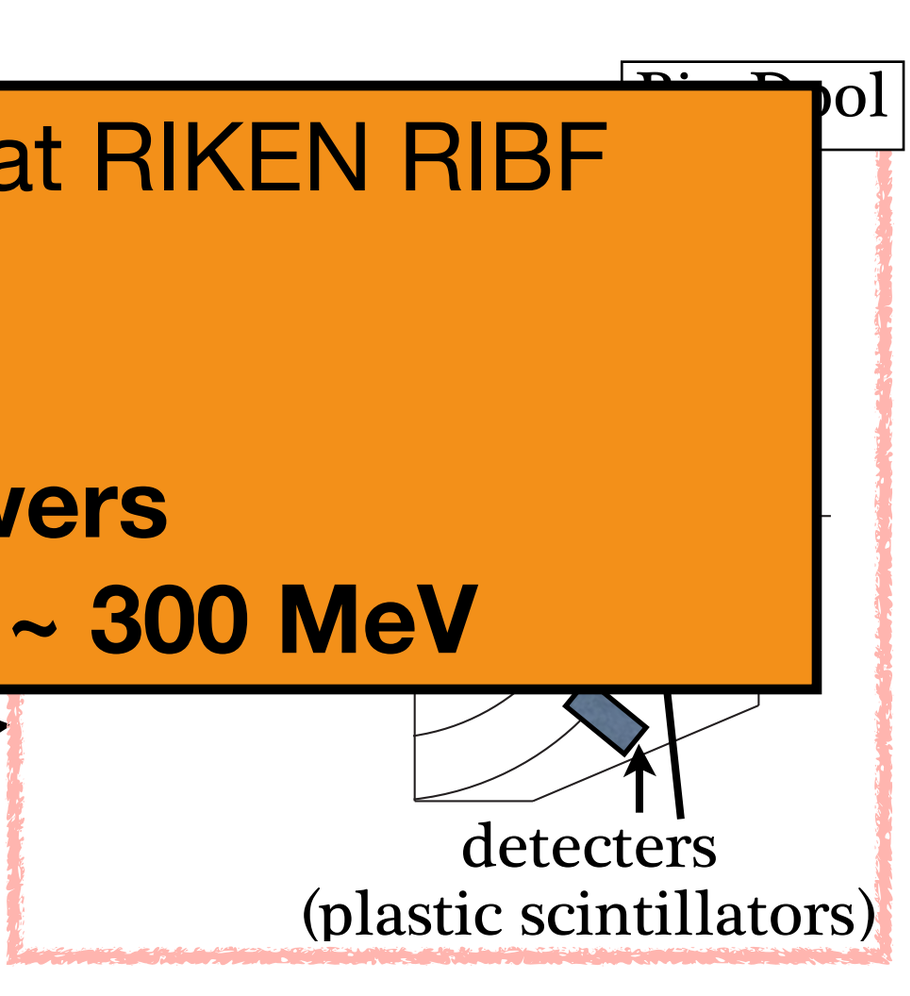
d+p elastic scattering experiments at RIKEN RIBF

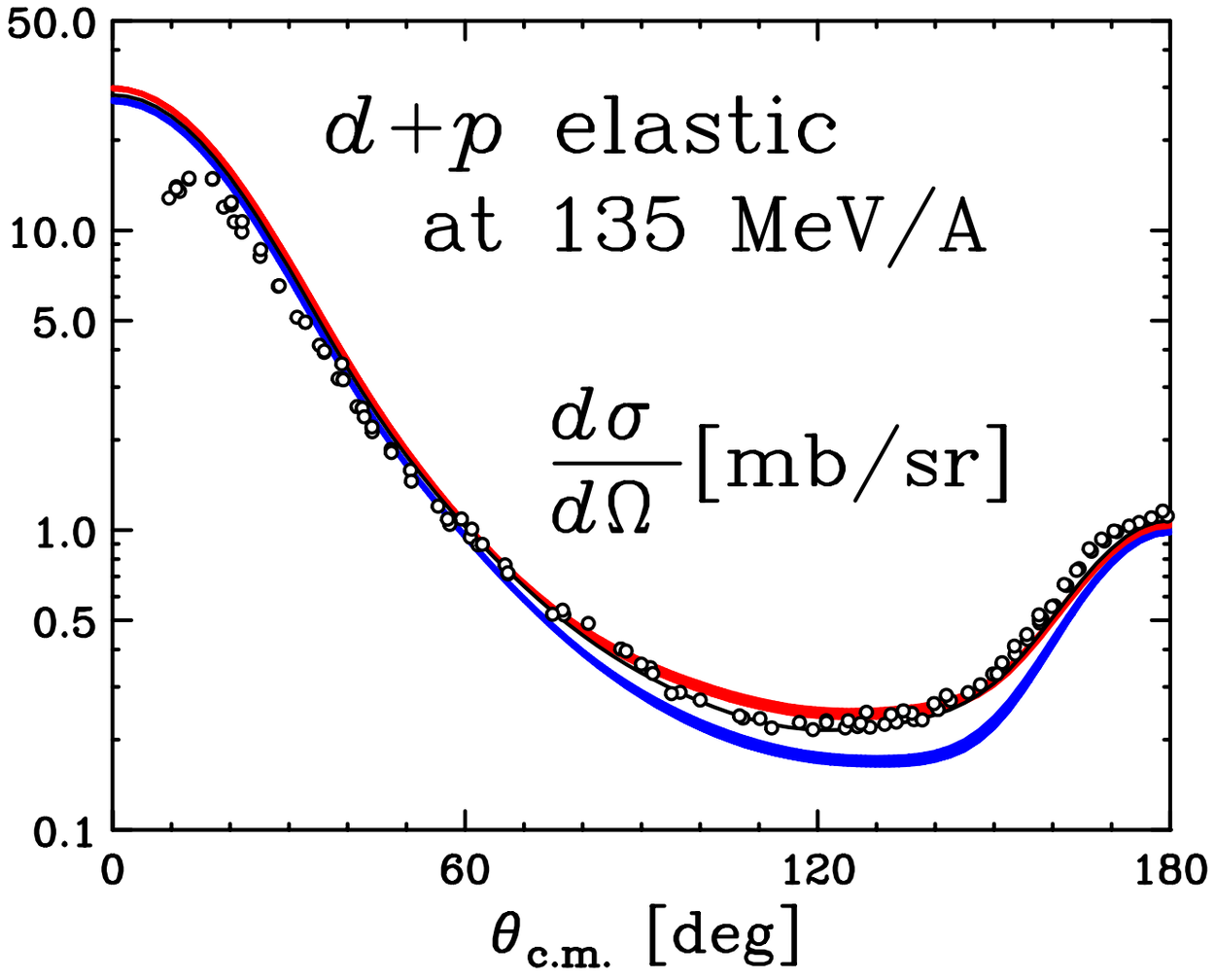
Observables :

- **differential cross section**
- **all deuteron analyzing powers**

at 70 ~ 300 MeV



3NF effect in *d*+*p* scattering



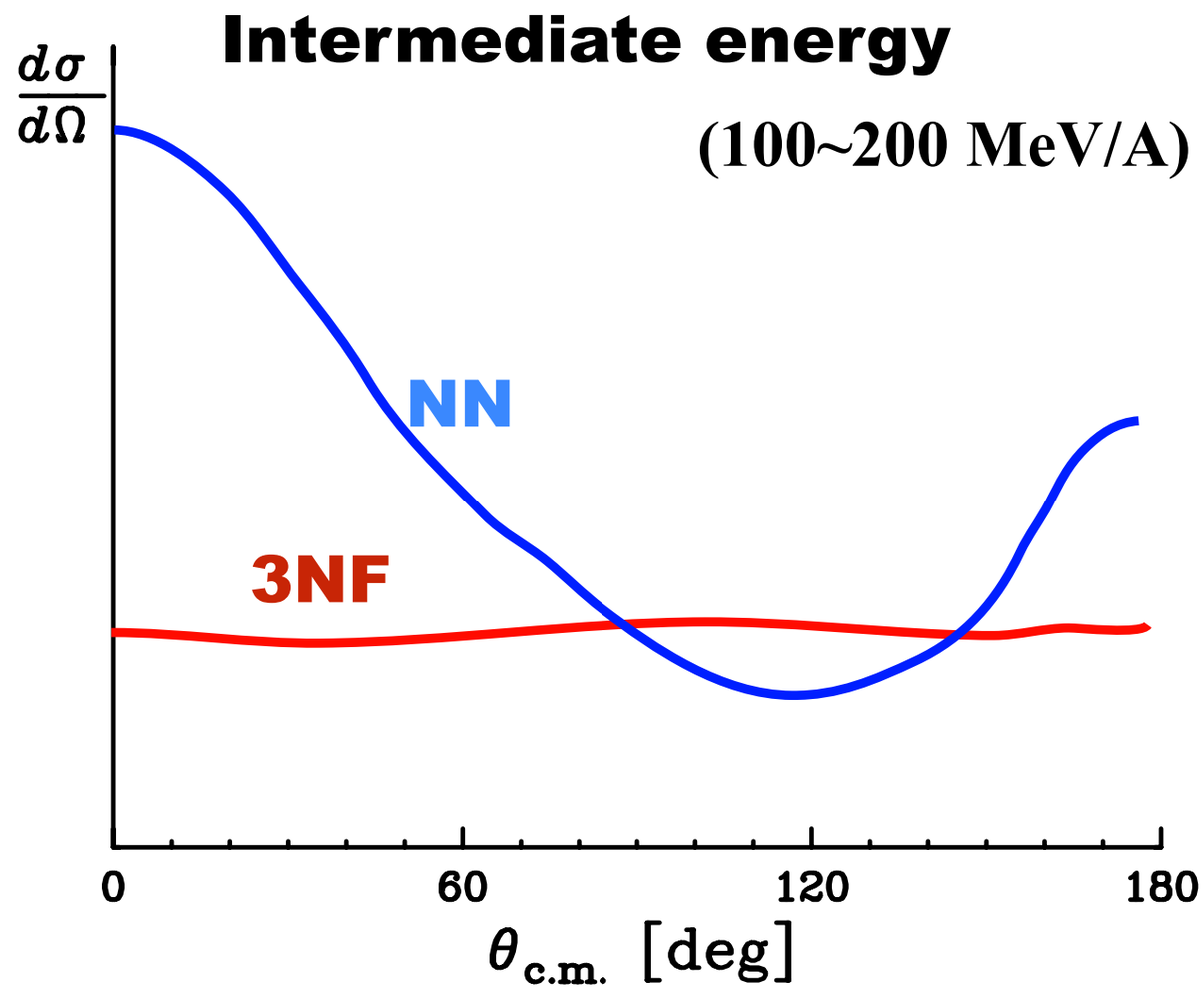
K. Sekiguchi *et al.*, Phys. Rev. C **65**, 034003 (2002)

2NF(CD Bonn, AV18, Nijimegen I,II)

3NF(TM'99)＋2NF

3NF(Urbana IX)＋2NF(AV18)

• theoretical prediction by H. Witala (1998)



The first evidence of 3NF in 3N scattering system (intermediate energy)

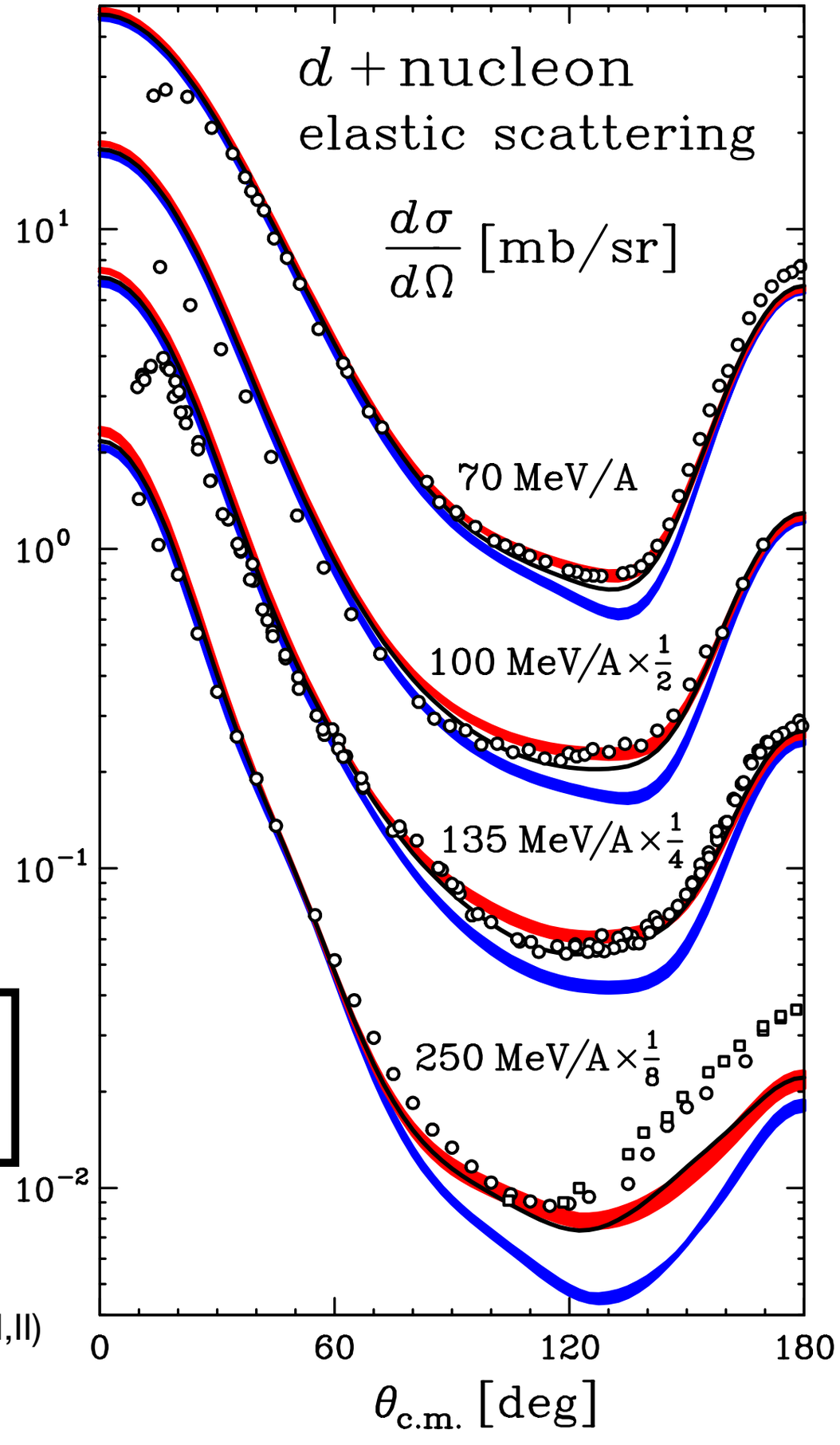
3NF effect in *d*+*p* scattering

- **How is the energy dependence ?**

・up to 135 MeV/A, the data are well explained by adding 3NF

・for 250 MeV/A, the calculations cannot describe our data at backward angles ($\theta_{c.m.}$>120°)

significant components are missing for high momentum region of 3NF's



2NF(CD Bonn, AV18, Nijimegen I,II)
3NF(TM'99)+2NF
3NF(Urbana IX)+2NF(AV18)

deuteron analyzing powers

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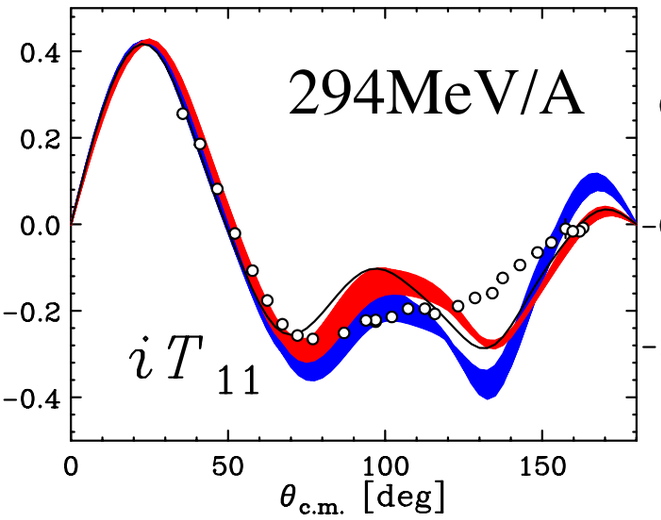
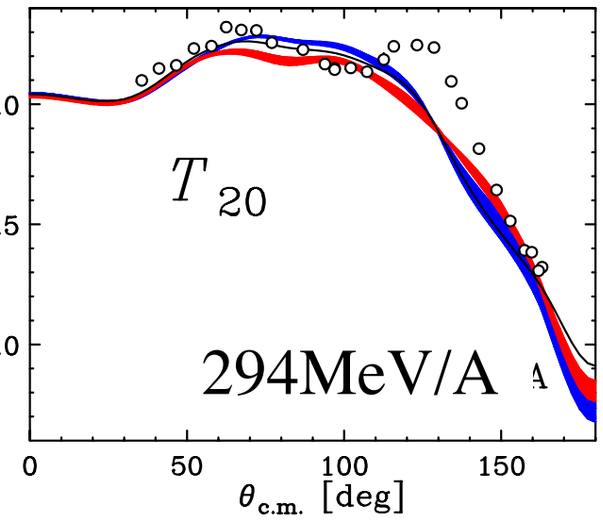
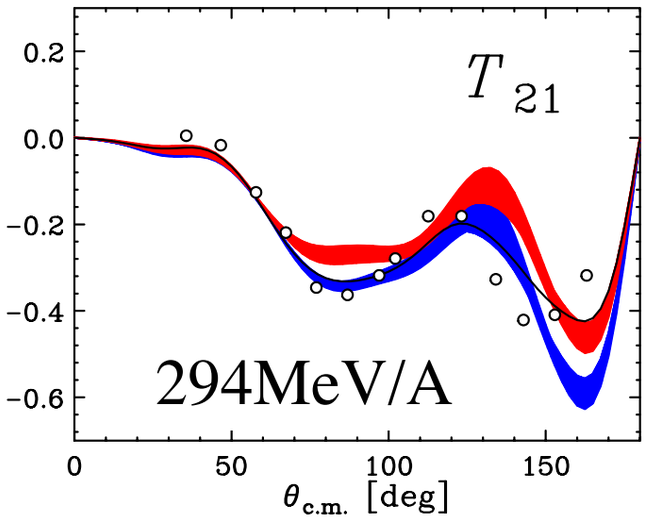
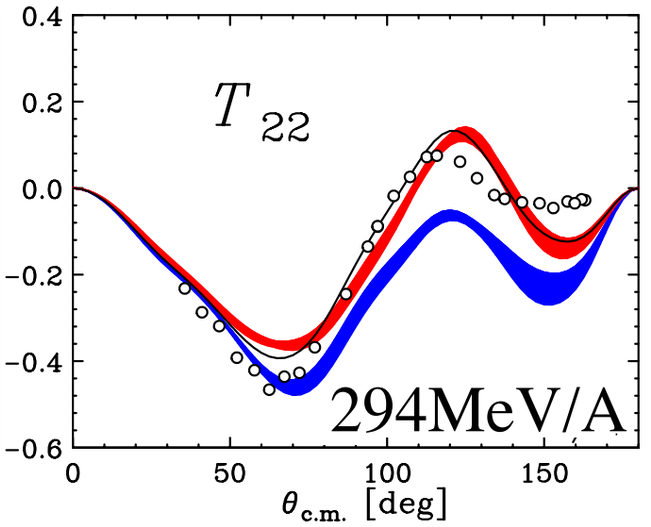
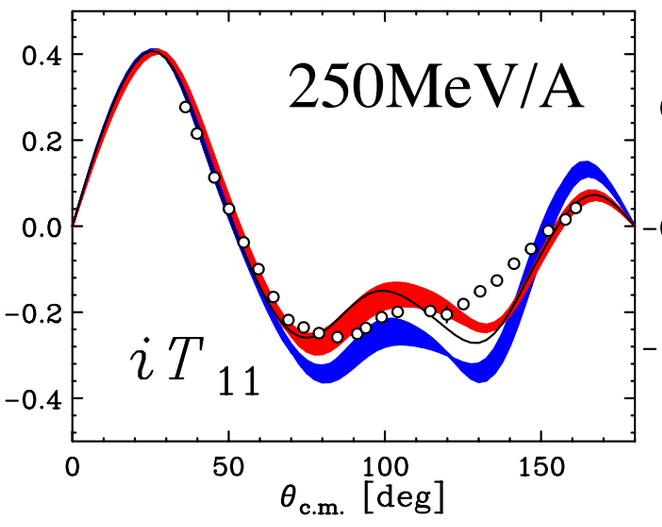
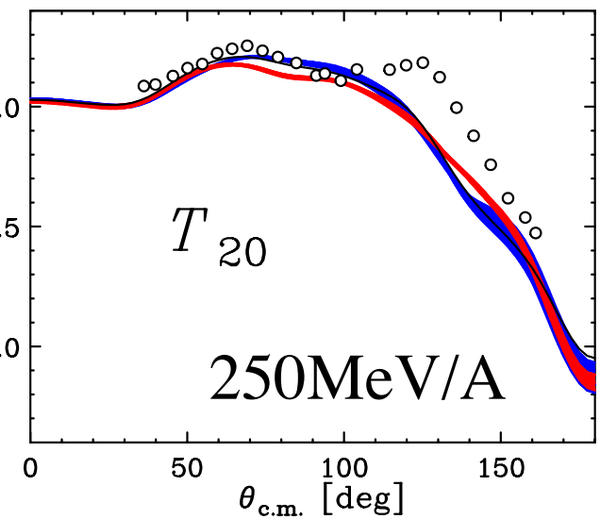


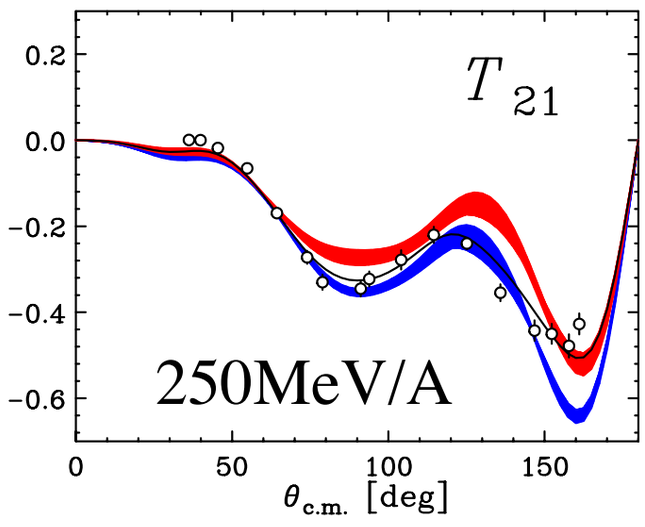


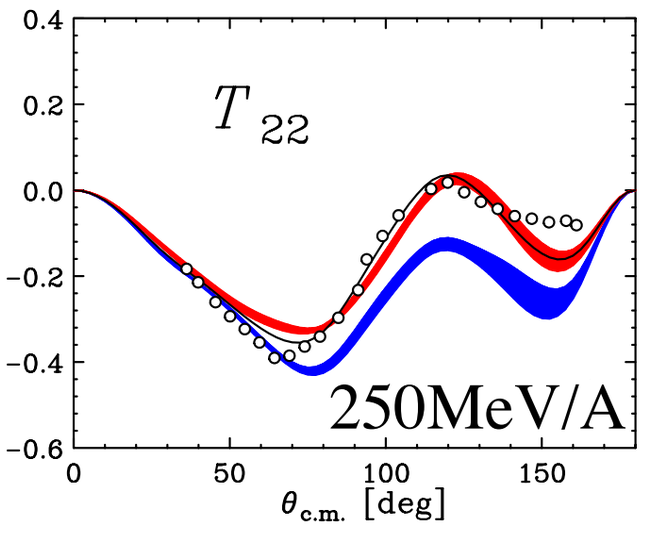


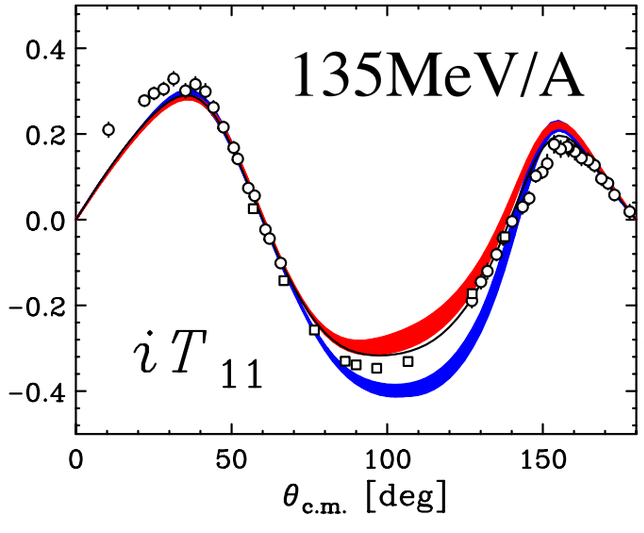


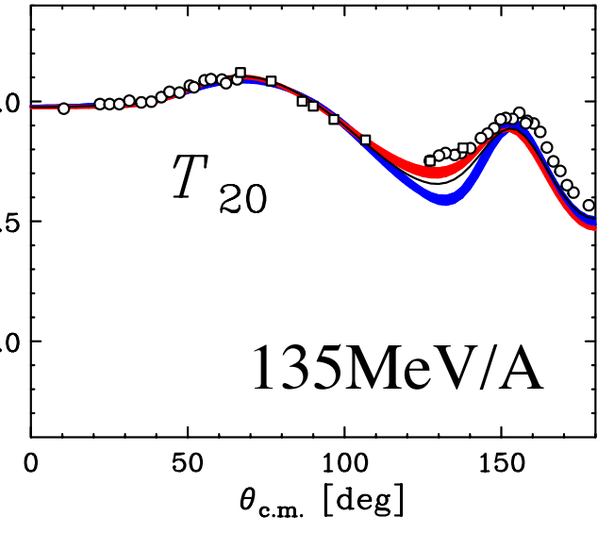


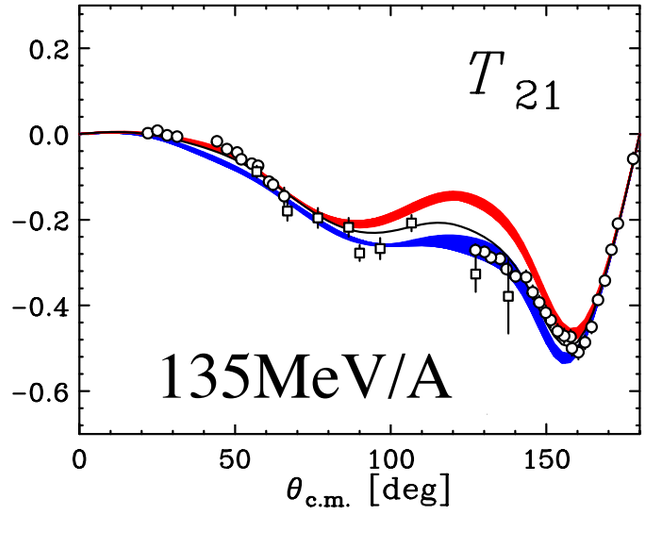


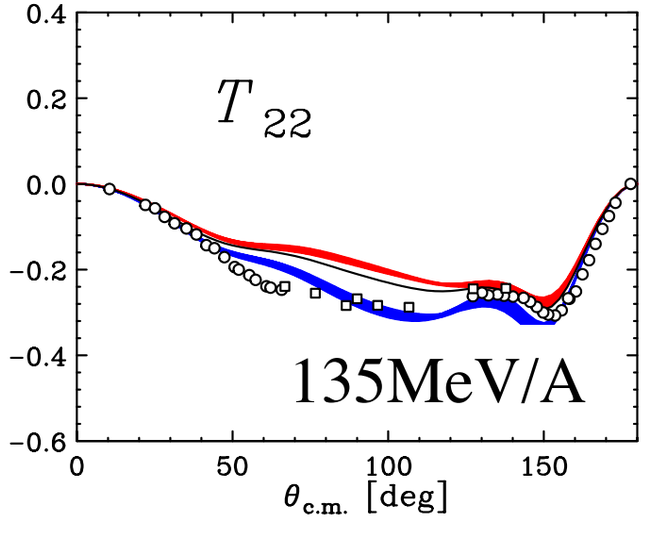












deuteron analyzing powers

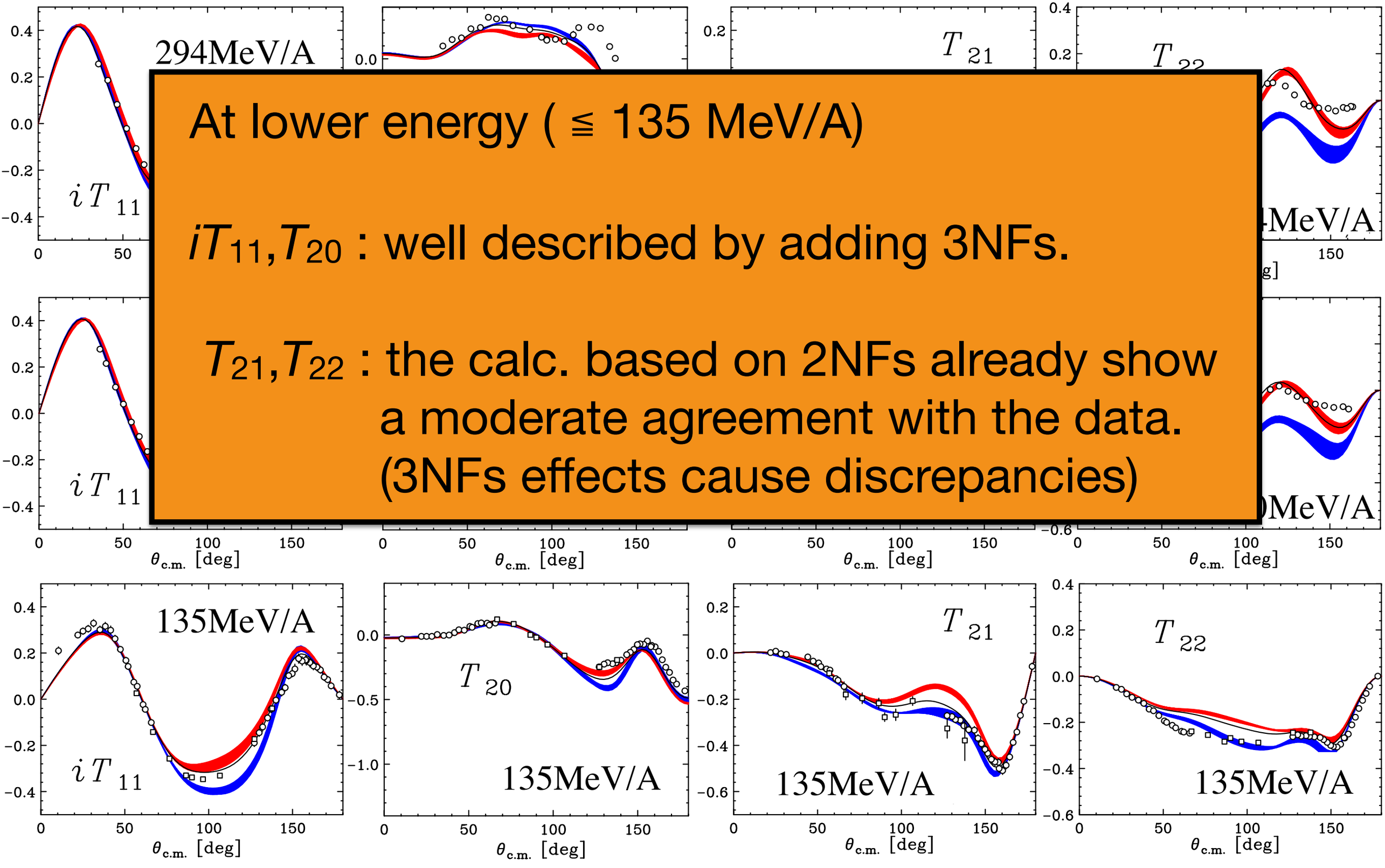
K. Sekiguchi *et al.*, Phys. Rev. C **65**, 034003 (2002)

K. Sekiguchi *et al.*, Phys. Rev. C **89**, 064007 (2014)

At lower energy (≦ 135 MeV/A)

iT_{11},T_{20} : well described by adding 3NFs.

T_{21},T_{22} : the calc. based on 2NFs already show a moderate agreement with the data. (3NFs effects cause discrepancies)



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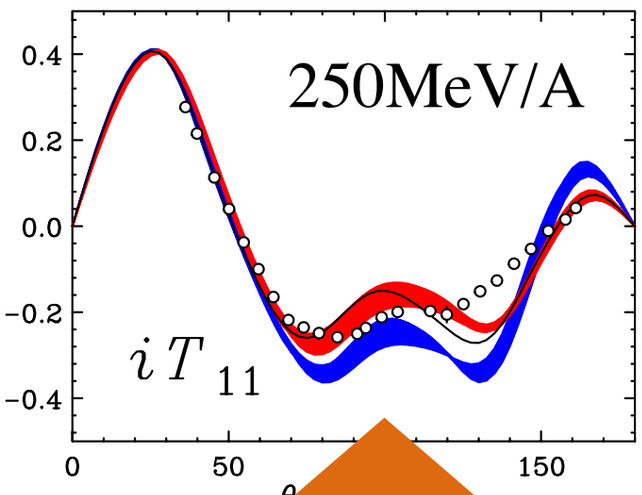
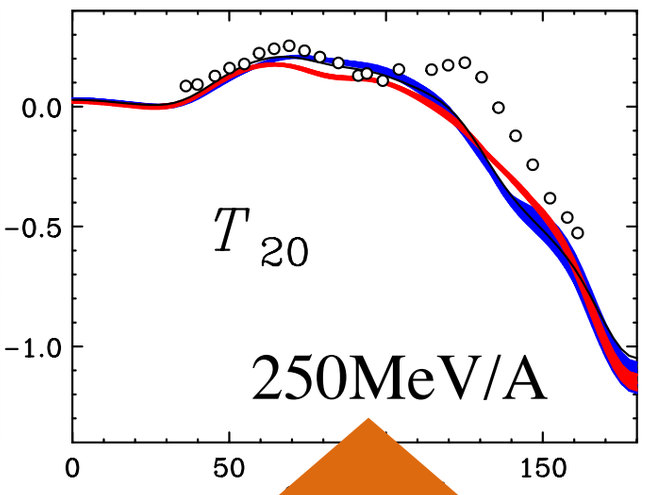
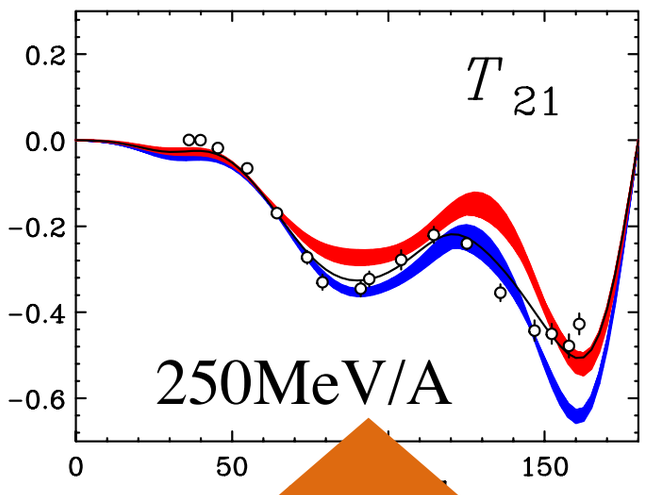
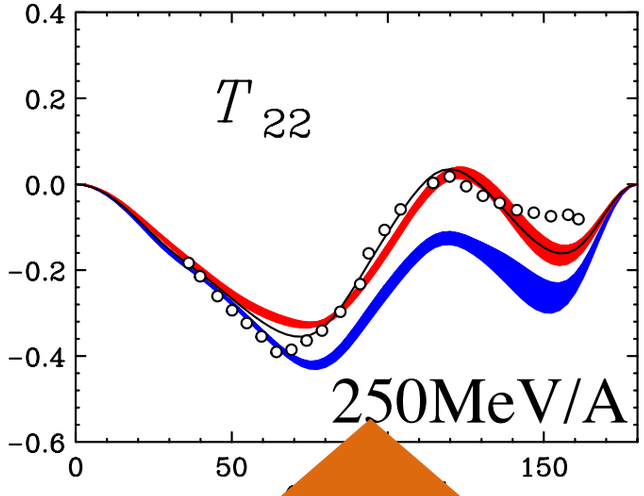
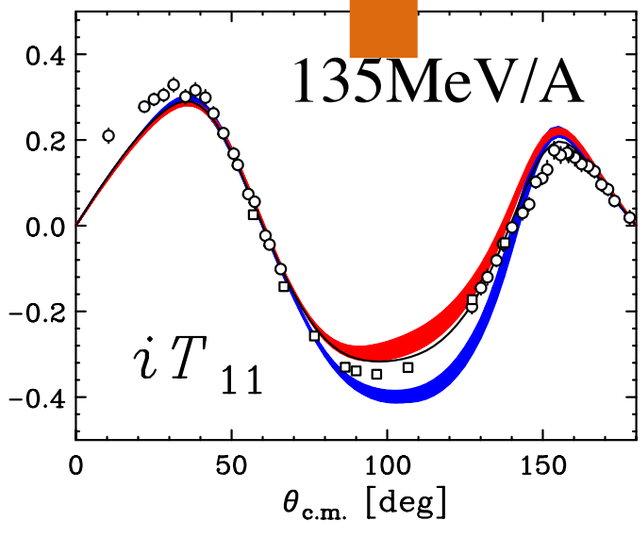
When incident energy ≧ 250 MeV/A,
the behaviors of angular distribution become different from those at 135 MeV/A

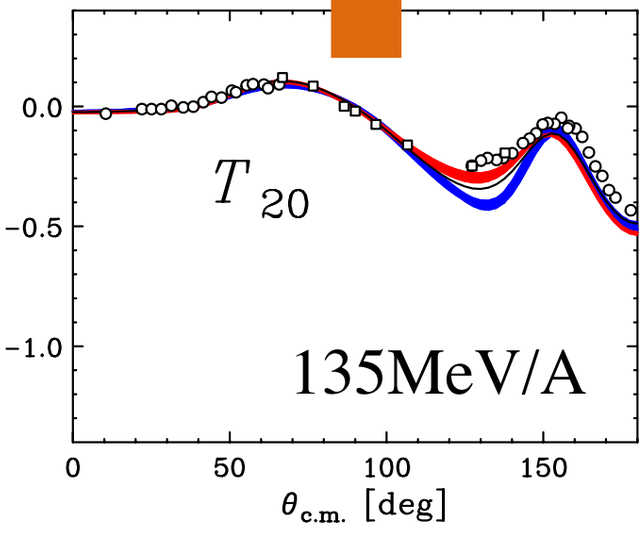


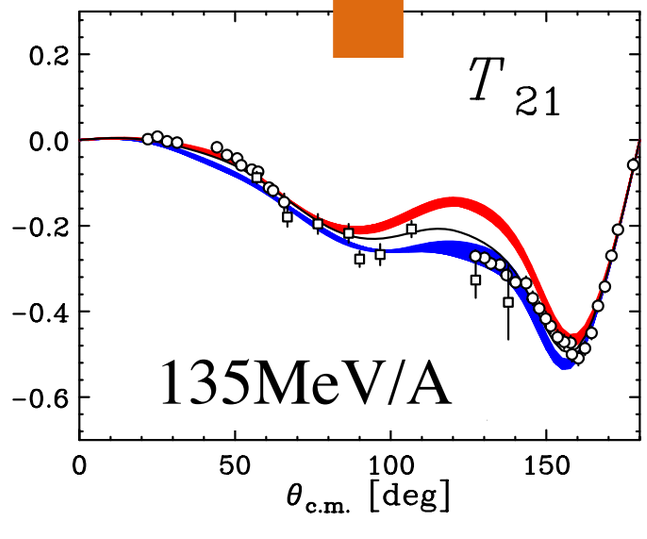


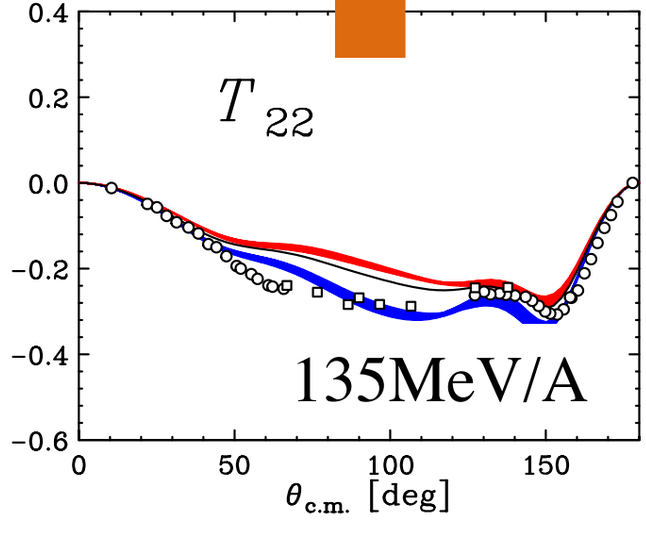












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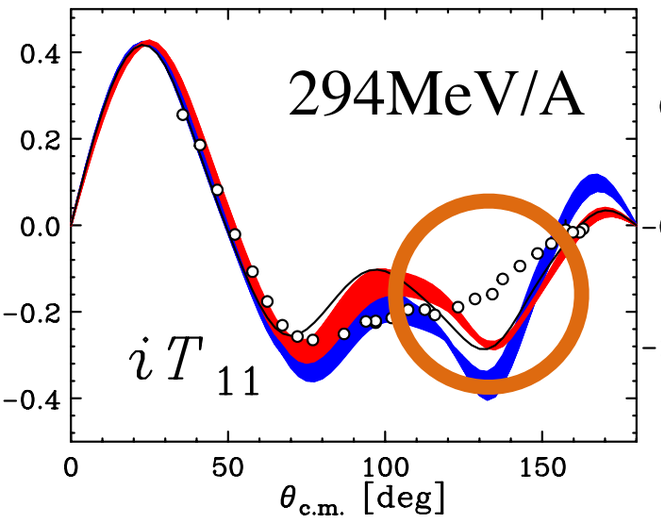

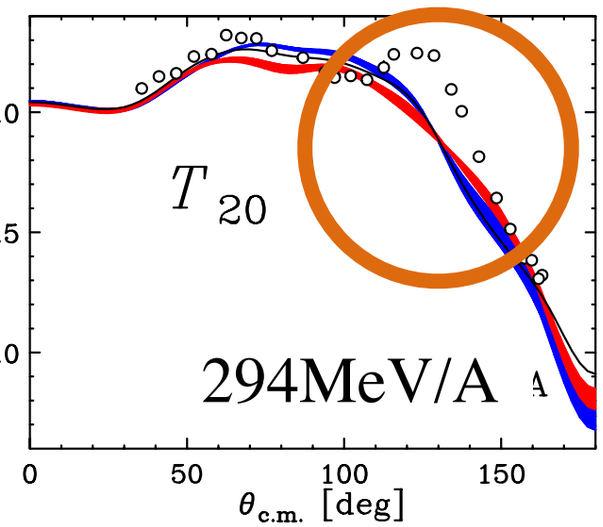

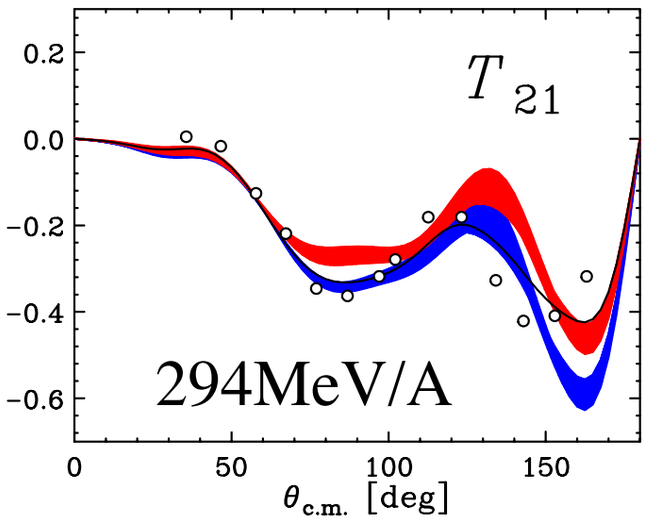

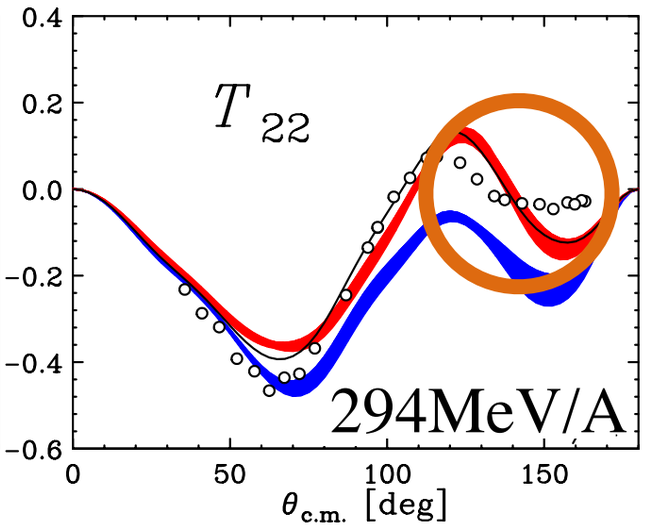

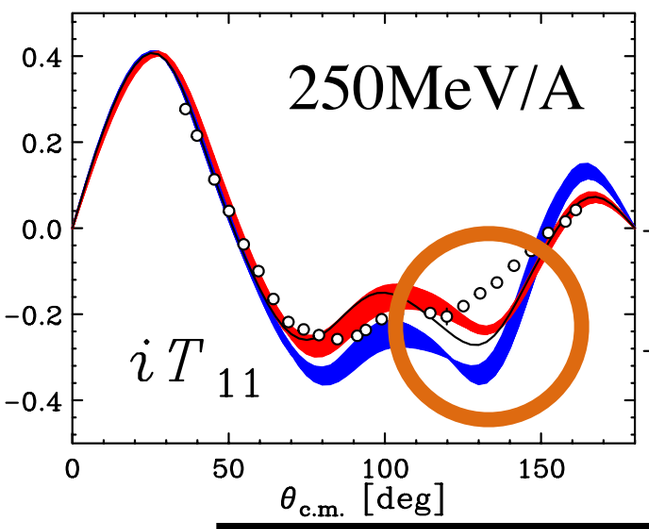

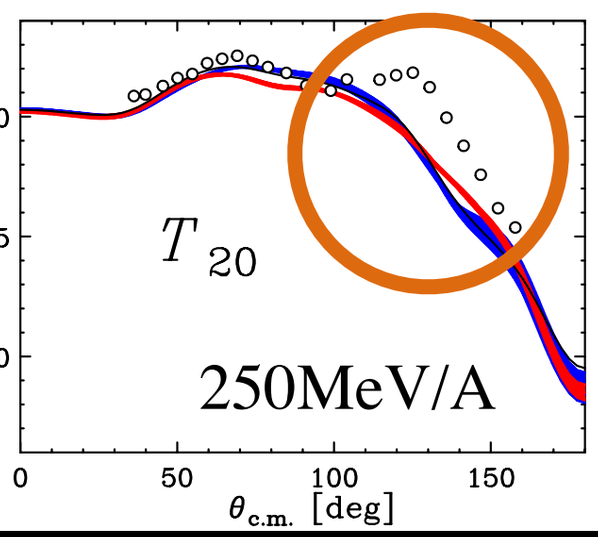

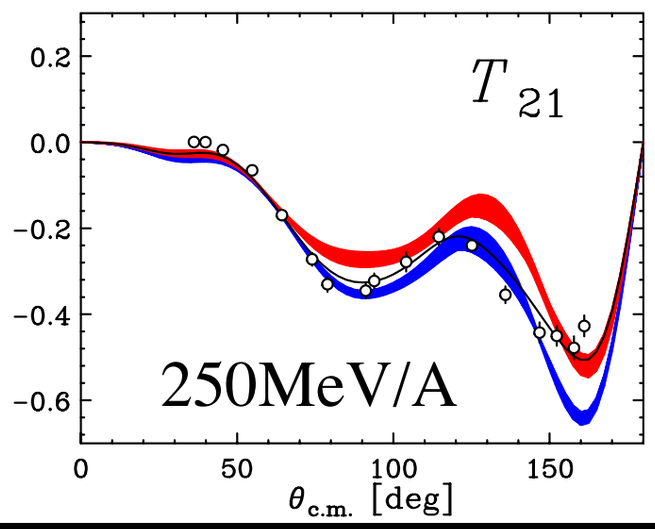

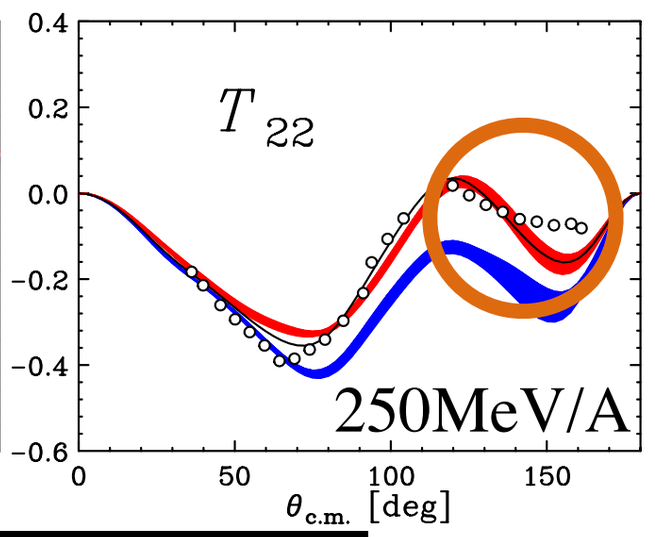

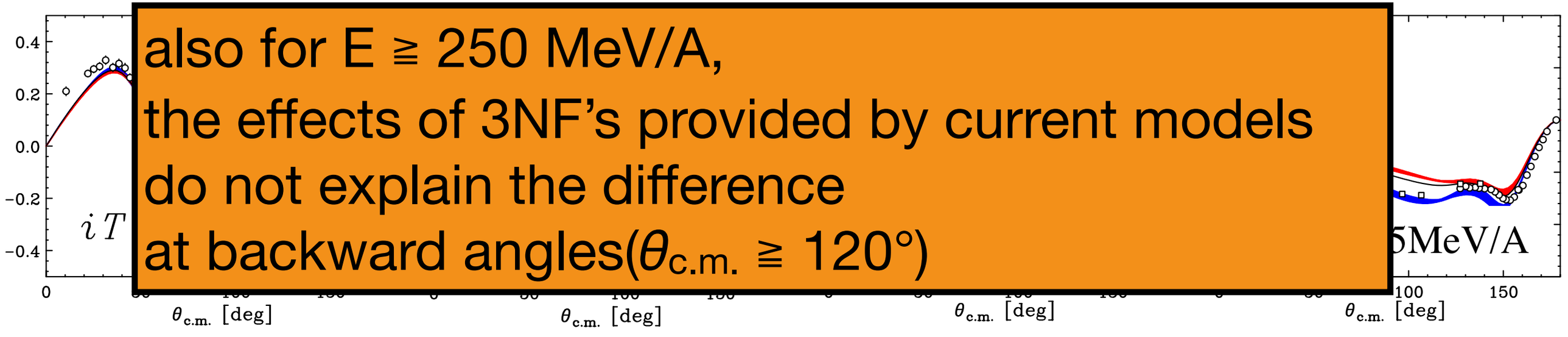

also for E ≧ 250 MeV/A,
the effects of 3NF's provided by current models
do not explain the difference
at backward angles($\theta_{\rm c.m.}$ ≧ 120°)

deuteron analyzing powers

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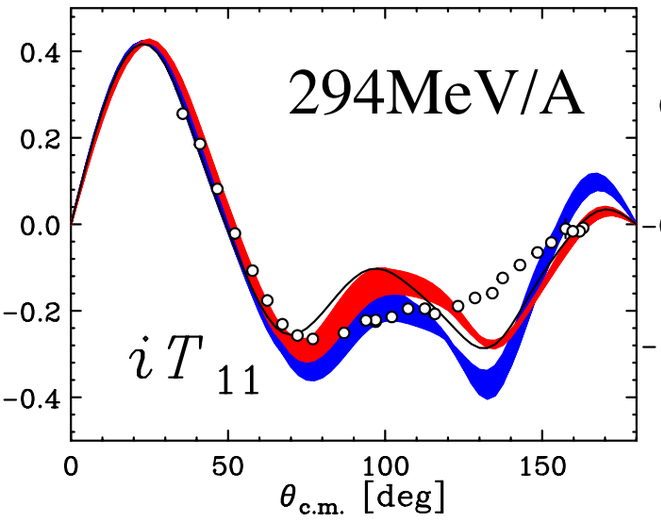
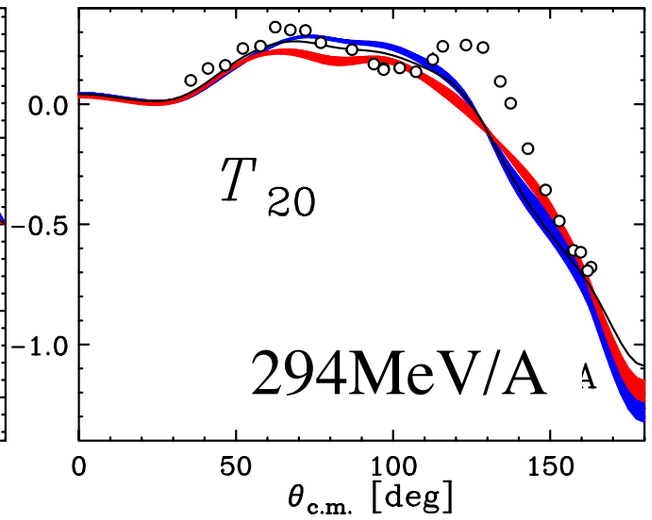
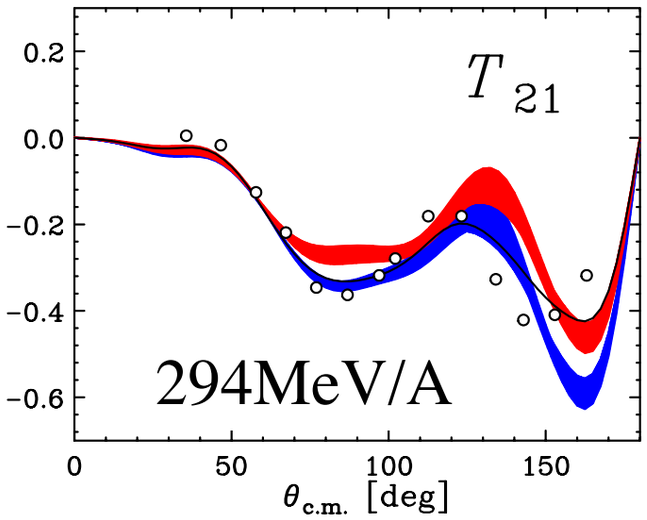
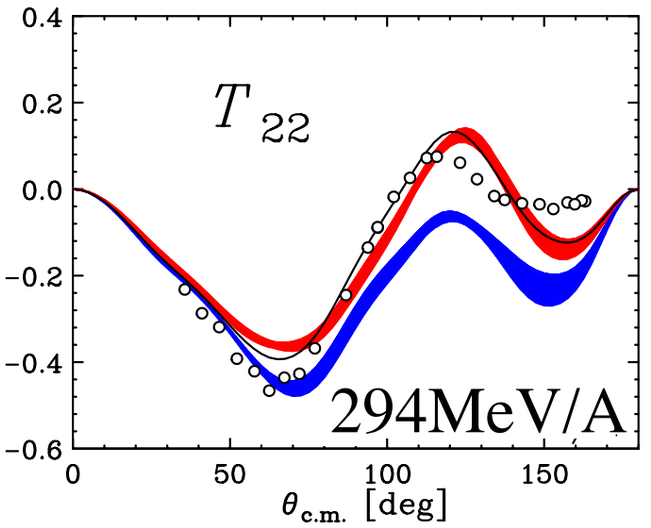
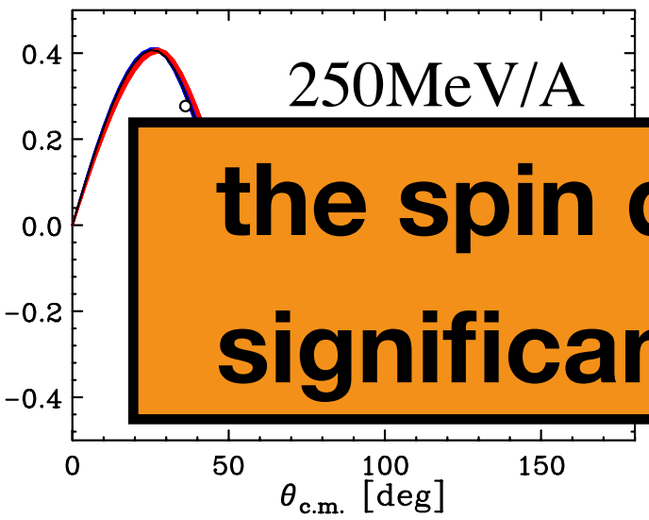
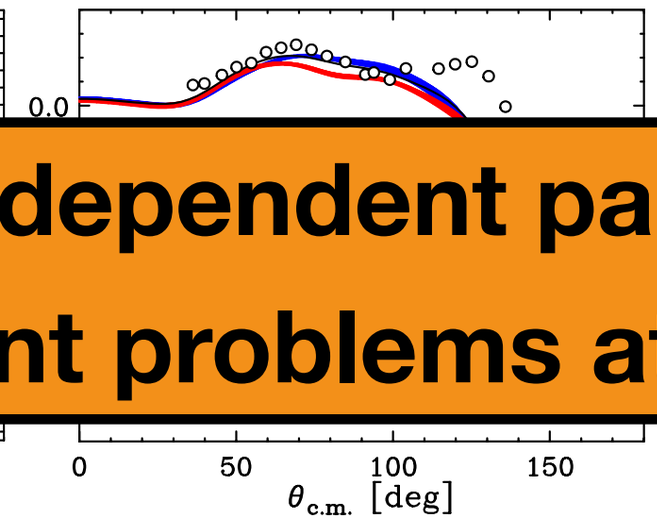


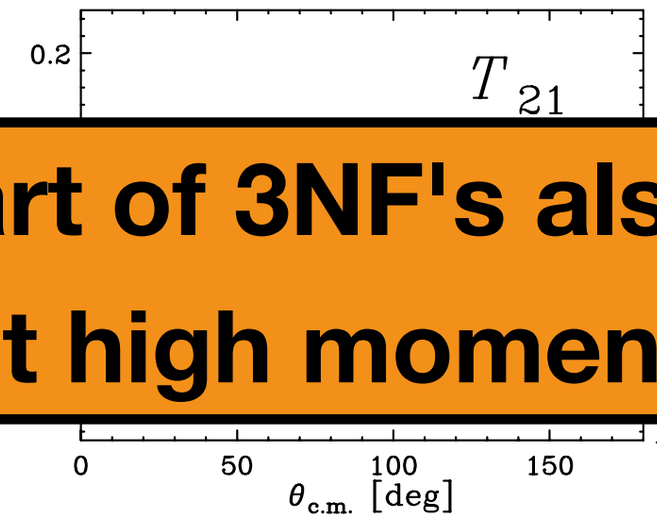


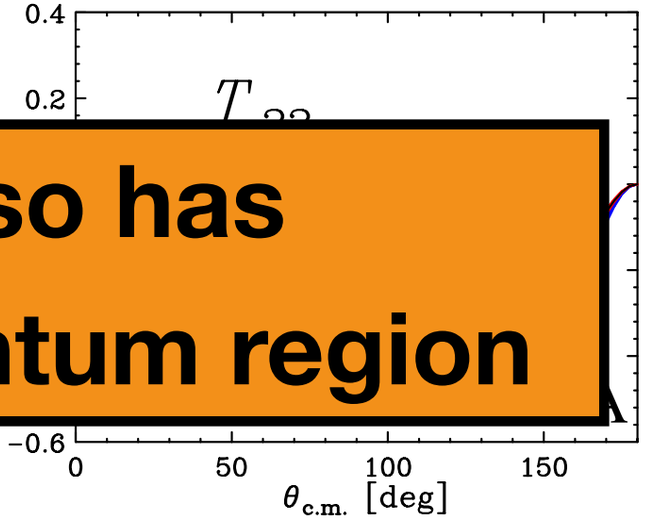




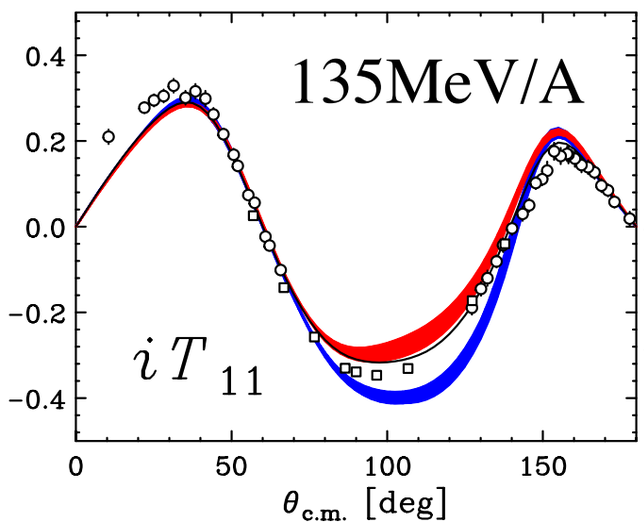


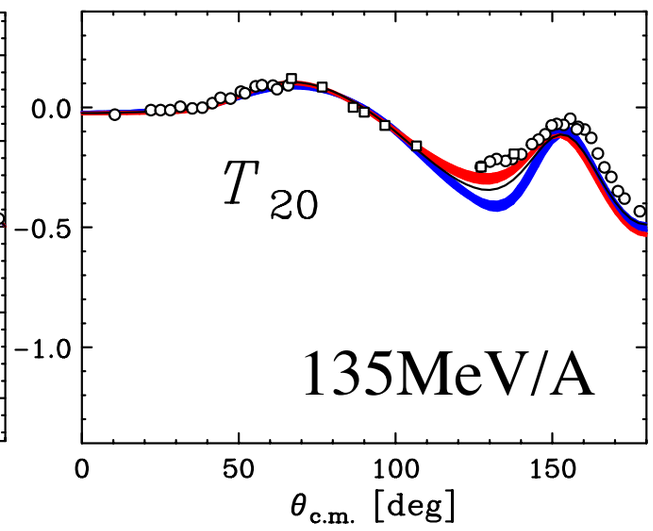


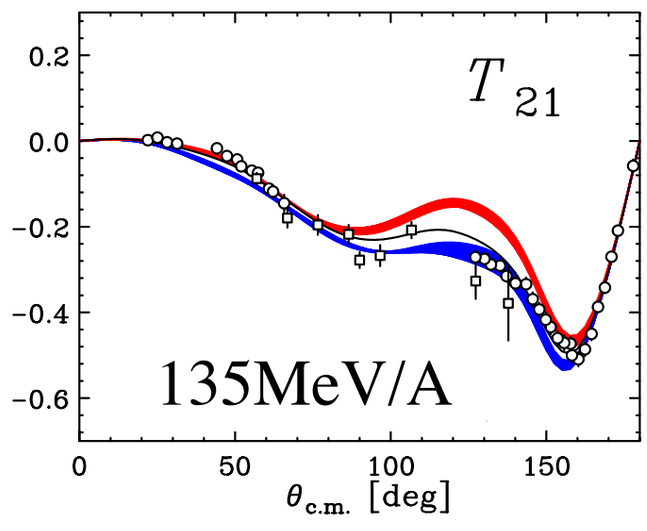


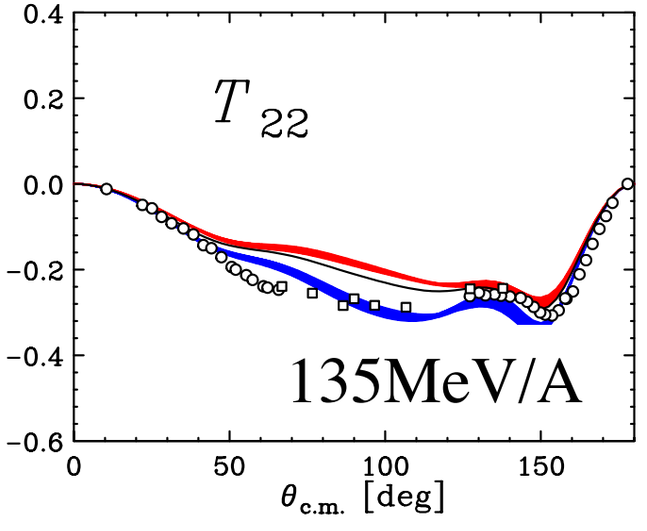


the spin dependent part of 3NF's also has significant problems at high momentum region









Summary

Importance of 3NF

- **few nucleon scattering experiment**

  - we can compare the data and the theory directly
  - we can study the dynamical aspects of 3NF's

A=3 scattering system : *d*+*p* elastic scattering (70 ~ 300 MeV/A)

- the first evidence of 3NF effect in 3N scattering system
- at backward angles($\theta_{c.m.} \geqq 120°$), the calculations cannot describe the data at higher energies (≧ 250 MeV/A)

future plan : all deuteron analyzing powers measurement around 190 MeV/A

Next step of 3NF study : A=3 to A=many system

- p+^{3}He scattering experiment at intermediate energies

Collaborators

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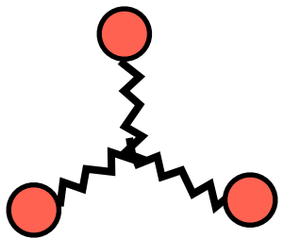
RCNP, Osaka Univ.	H. Okamura, K. Miki

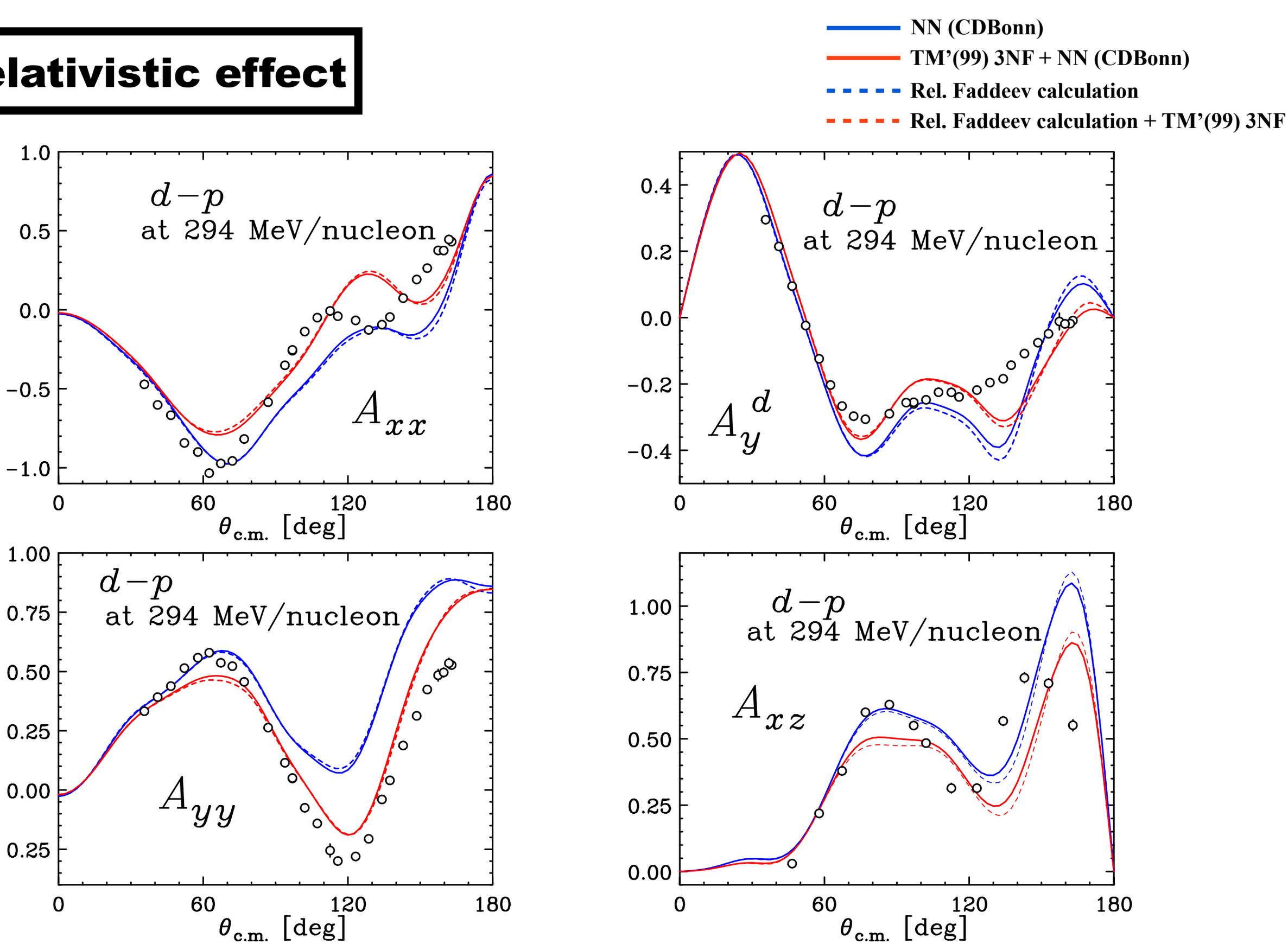
Thank you.



Experimental condition

- Parameters
  - Beam : Polarized deuteron at (70～294 MeV/A)
  - Beam intensity : ~ 2 nA
    - Beam polarization : ~80% of the theoretical maximum values
  - Target : CH_2 (282 mg/cm^2)
- Detection systems
  - Detectors : plastic scintillators with PMT
    - *d* & *p* are detected in kinematically coincidence conditions
  - azimuthal dependence : ϕ = 0°,90°,180°,270°
- Observables
  - differential cross section
  - All deuteron analyzing powers

Relativistic effect



Mr. Witala private communication

- Relativistic effect do not explain discrepancy between data and calculations

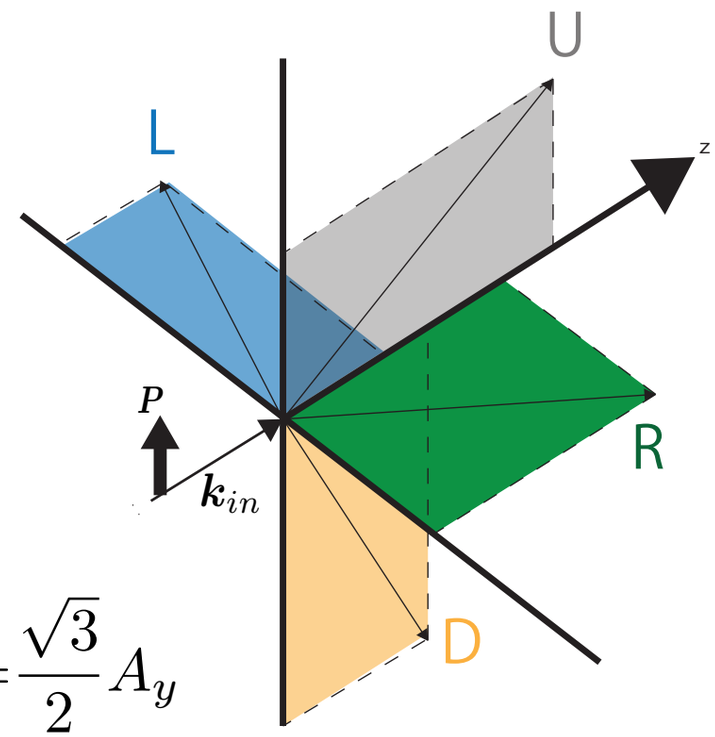
• Differential cross section of $\vec{d}+p$ elastic scattering

$$I(\theta,\phi) = I_0(\theta)[1 + \frac{3}{2}p_y A_y(\theta) + \frac{2}{3}p_{xz}A_{xz}(\theta) + \frac{1}{3}(p_{xx}A_{xx}(\theta) + p_{yy}A_{yy}(\theta) + p_{zz}A_{zz}(\theta))]$$

$$A_{xx}(\theta) + A_{yy}(\theta) + A_{zz}(\theta) = 0$$

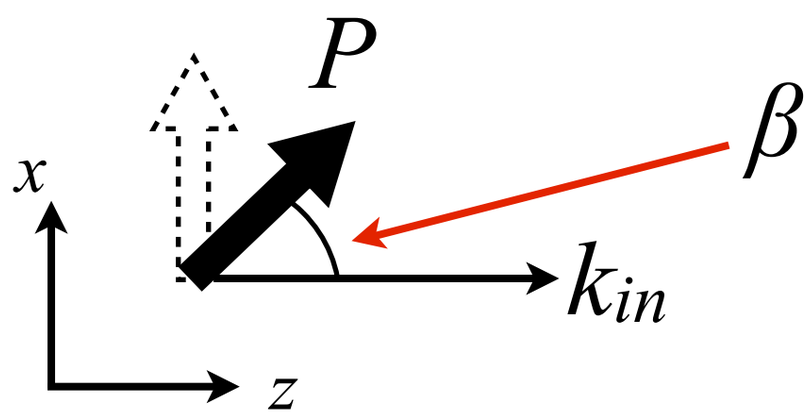
$$L = L_0[1 + \frac{3}{2}p_Z A_y + \frac{1}{2}p_{ZZ}A_{yy}] \qquad U = U_0[1 + \frac{1}{2}p_{ZZ}A_{xx}]$$

$$R = R_0[1 - \frac{3}{2}p_Z A_y + \frac{1}{2}p_{ZZ}A_{yy}] \qquad D = D_0[1 + \frac{1}{2}p_{ZZ}A_{xx}]$$



• Measurement of A_{xz}

$$\beta = 43.7 \pm 0.4[\mathrm{deg}]$$



$$iT_{11} = \frac{\sqrt{3}}{2}A_y$$

$$T_{20} = \frac{1}{\sqrt{2}}A_{zz}$$

$$T_{21} = -\frac{1}{\sqrt{3}}A_{xz}$$

$$T_{22} = \frac{1}{2\sqrt{3}}(A_{xx} - A_{yy})$$

PIS

spin mode	P_z	P_{zz}
0	0	0
1	1/3	−1
2	−2/3	0
3	1/3	1

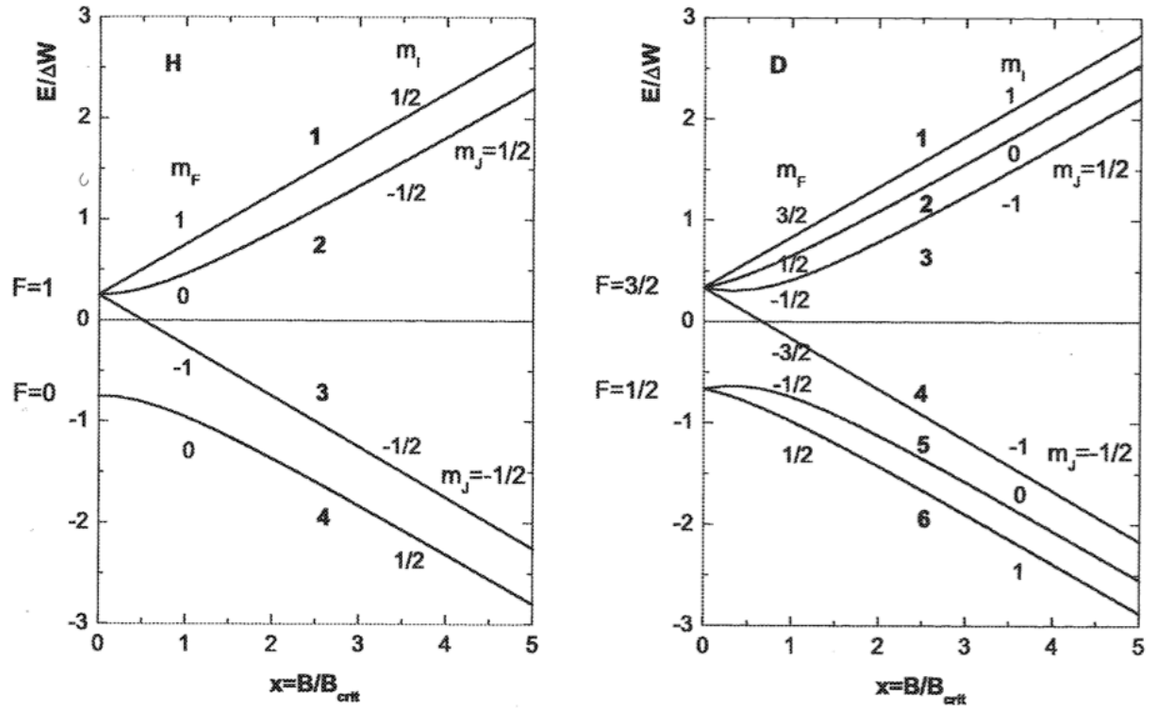


Fig. 8.3 Zeeman splitting (Breit-Rabi diagrams) of the HFS of a system with $J = 1/2$; $I = 1/2$ (e.g. H) and a system with $J = 1/2$; $I = 1$ (e.g. D) as function of the magnetic-field parameter $x = B/B_{crit}$. The states are usually numbered consecutively starting with the highest-energy state

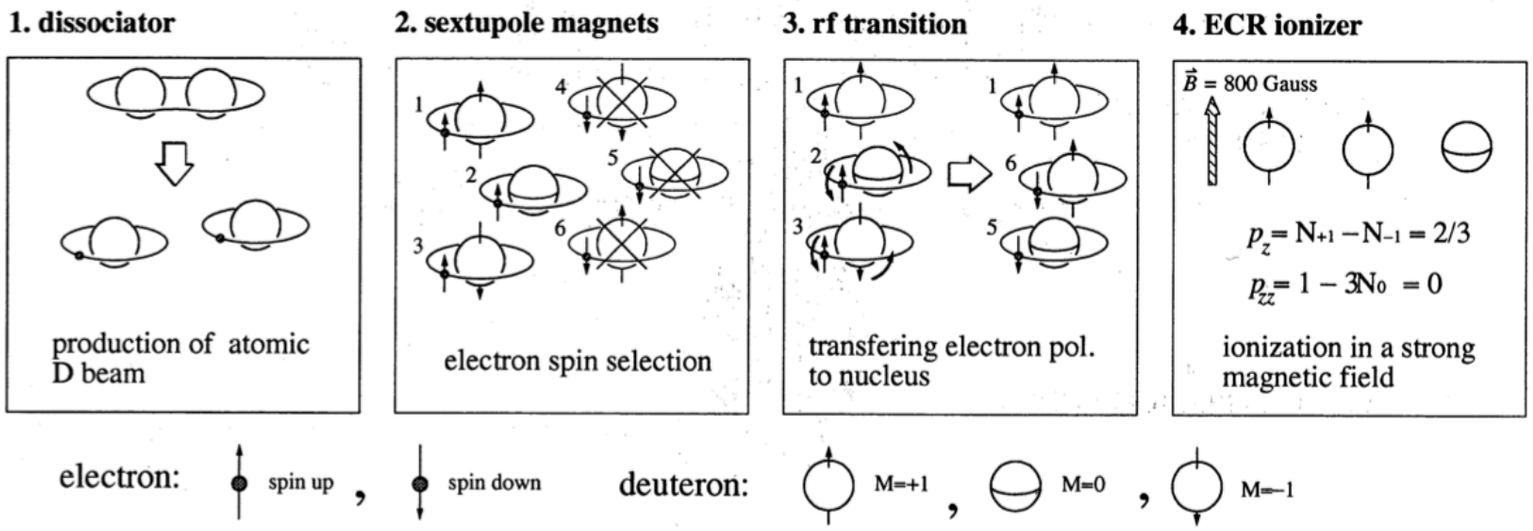


Figure 2.1: Block diagram of the production of polarized deuteron beam. The number 1∼6 stands for the hfs substates number (see Appendix C). Here pure vector polarized deuteron beam ($p_Z = 2/3$, $p_{ZZ} = 0$) is obtained.

total nuclear electron

$$\boldsymbol{F} = \boldsymbol{I} + \boldsymbol{J}$$

BigDpol

- Detectors:Plastic Scintillators with PMT
  - deuteron :35mm^{H}×20mm^{W}×20mm^{D}, R = 670 ~ 1.6 msr
  - proton :35mm^{H}×20mm^{W}×20mm^{D}, R = 770 ~ 1.2 msr
  - for pp scattering :
    - 35mm^{H}×55mm^{W}×10mm^{D}, R=670 ~ 4.3 msr
    - 35mm^{H}×50mm^{W}×10mm^{D}, R=670 ~ 3.9 msr