CNS Summer School, Sept. 20, 2003

Looking for Three-Body Forces by the Nucleon-Deuteron Elastic Scattering at Intermediate Energy

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RIKEN

’How about the problem of the three bodies?’ whispered Kriltsov, smiling with great effort.

’The solution is difficult? ’

Resurrection, 1899, Chapter XX

by Leo Tolstoy

Three-Body Problems in Classic Mechanics

- ☐ Gravitational motion (Newton eq.)

$$\mathbf{H} = \frac{1}{2}\left(\frac{\vec{p}_1^{\,2}}{m_1} + \frac{\vec{p}_2^{\,2}}{m_2} + \frac{\vec{p}_3^{\,2}}{m_3}\right) - \frac{m_1 m_2}{r_{12}} - \frac{m_2 m_3}{r_{23}} - \frac{m_3 m_1}{r_{31}}$$

- ☐ H. Poincaré(1892)

non-existence of analytic solution

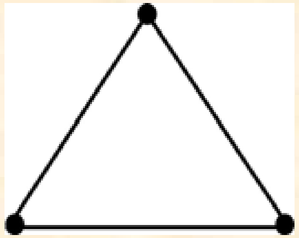
sometime chaotic behavior → CHAOS

Three-Body Problems in Classic Mechanics

- **2 special solutions are known**

straight line

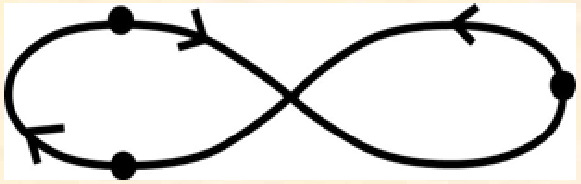
equilateral triangle



- **3rd one found 3 years ago!**

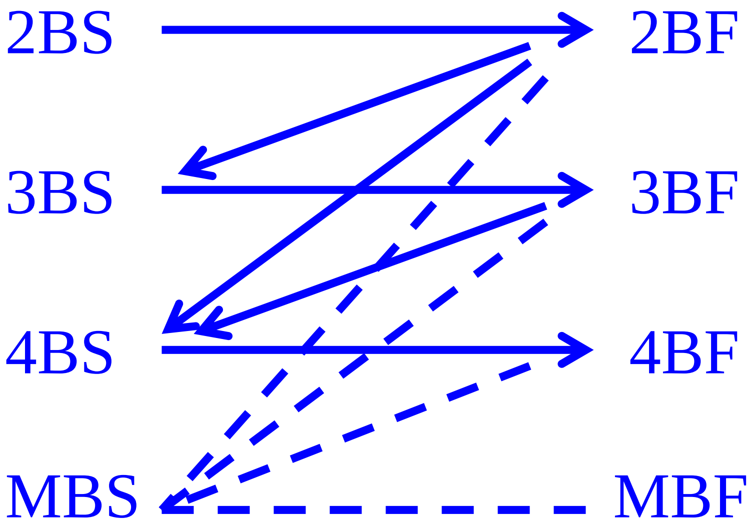
Chenciner-Montgomery, Ann. Math. **152**(2000)881

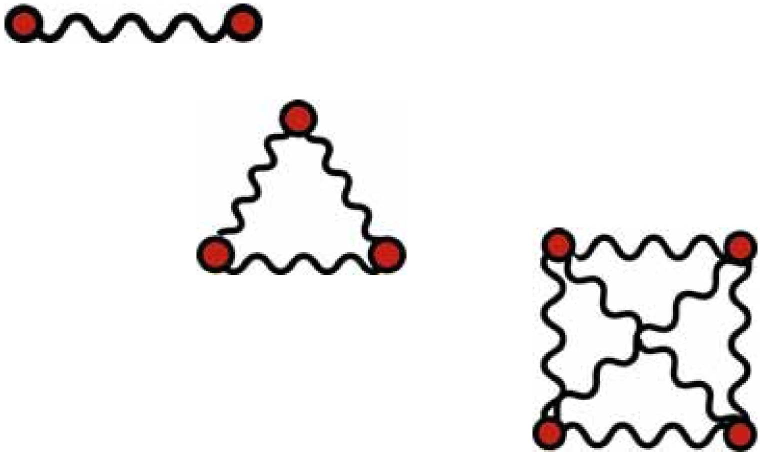
eight (8) shape with equal mass



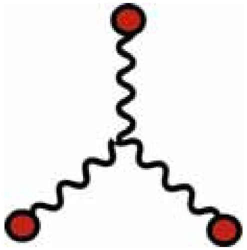
Three-body problem is general and important in science related with various fields.

Are there three-body forces?


2BS
2BF
3BS
3BF
4BS
4BF
MBS
MBF



- Equations of motion must be solved exactly.
- To learn 3BF, 2BF must be known precisely.



$$V(\vec{r}_1, \vec{r}_2, \vec{r}_3)$$
$$V(\vec{p}_1, \vec{p}_2, \vec{p}_3)$$

Are there three-nucleon forces(3NF)?

◆3NF is much smaller than 2NF.

→3NF effects are easily masked by 2NF effects.

◆Equations of motion must be solved exactly.

→Faddeev eq.

→2NF must be reliable.

However, numerical calc. are extremely difficult.

Three-Body Problems in Quantum Mechanics

- L.D. Faddeev, Sov. Phys. JETP 12(1961)1014

Faddeev Equation

$$H = H_0 + V_{12}^{NN} + V_{23}^{NN} + V_{31}^{NN} + V_{123}$$

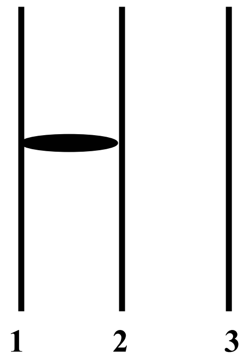
$$\Psi = \psi_{12}^{(\pm)} + \psi_{23}^{(\pm)} + \psi_{31}^{(\pm)}$$

$$\begin{pmatrix} \psi_{12}^{(\pm)} \\ \psi_{23}^{(\pm)} \\ \psi_{31}^{(\pm)} \end{pmatrix} = \begin{pmatrix} 0 \\ \psi_{\alpha} \\ 0 \end{pmatrix} + G_0 \begin{pmatrix} 0 & t_{12} & t_{12} \\ t_{23} & 0 & t_{23} \\ t_{31} & t_{31} & 0 \end{pmatrix} \begin{pmatrix} \psi_{12}^{(\pm)} \\ \psi_{23}^{(\pm)} \\ \psi_{31}^{(\pm)} \end{pmatrix}$$

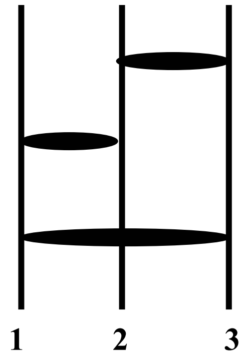
→ can be solved exactly!

CISS02 Lecture Note by Y. Koike:
http://www.cns.s.u-tokyo.ac.jp//summerchool/ciss02/lecturenotes

PWIA



Faddeev



Characteristics

nuclear force (2NF, 3NF) input

↓↑

Faddeev equation

↓↑

numerical results

↓↑

experimental results of 3NS

- **Independent of reaction models**
- **direct comparison possible between data and inputs**

Two nucleon force（2NF)

- **One π Exchange (OPE) model by Hideki Yukawa**

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

$m_\pi c^2 = 140$ MeV **$(J^\pi, T)=(0^-, 1)$**

$$V_{(1,2)}^{\mathrm{OPE}} = \frac{1}{3}\frac{f_\pi^{\ 2}}{\eta c} m_\pi c^2 (\vec{\tau}_1 \vec{\tau}_2)\left\{ \vec{\sigma}_1 \vec{\sigma}_2 + \left(1 + \frac{3}{x} + \frac{3}{x^2}\right) S_{12} \right\} \frac{\exp^{-x}}{x}$$

$$S_{12} = \frac{3(\vec{\sigma}_1 \vec{r})(\vec{\sigma}_2 \vec{r})}{r^2} - (\vec{\sigma}_1 \vec{\sigma}_2)$$

$$x \equiv \frac{m_\pi c}{\eta} r$$

- **Realistic modern 2 nucleon forces available now.**

reproduces more than 3,500 exp. NN data with $x^2 \cong 1$.

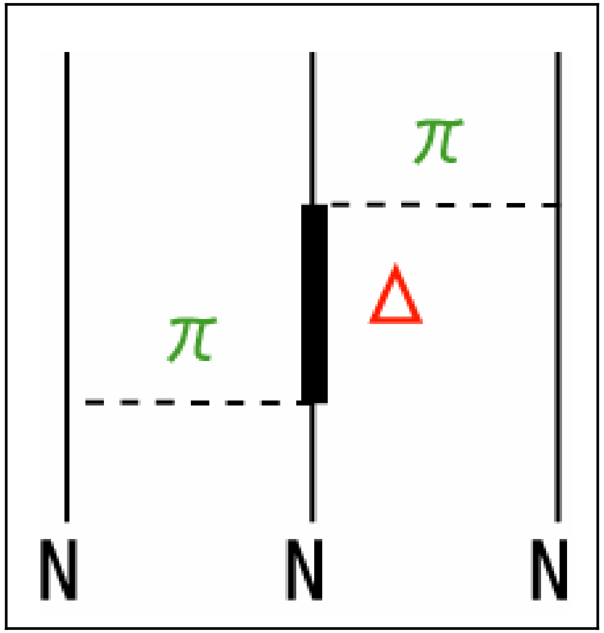
- ☐ **CD Bonn pot.** : strong non-locality
- ☐ **AV18 pot.** : OPE + phenom.
- ☐ **Nijmegen I/II/93 pot.** : one boson exch.

Main differences are of-shell properties

Three nucleon force（3NF)

◆ **Fujita • Miyazawa type 3NF**

(Prog. Theor. Phys. 17(1957)360.)



2π exchange type 3NF

N: proton / neutron

$$m_N c^2 = 940\ \text{MeV}$$

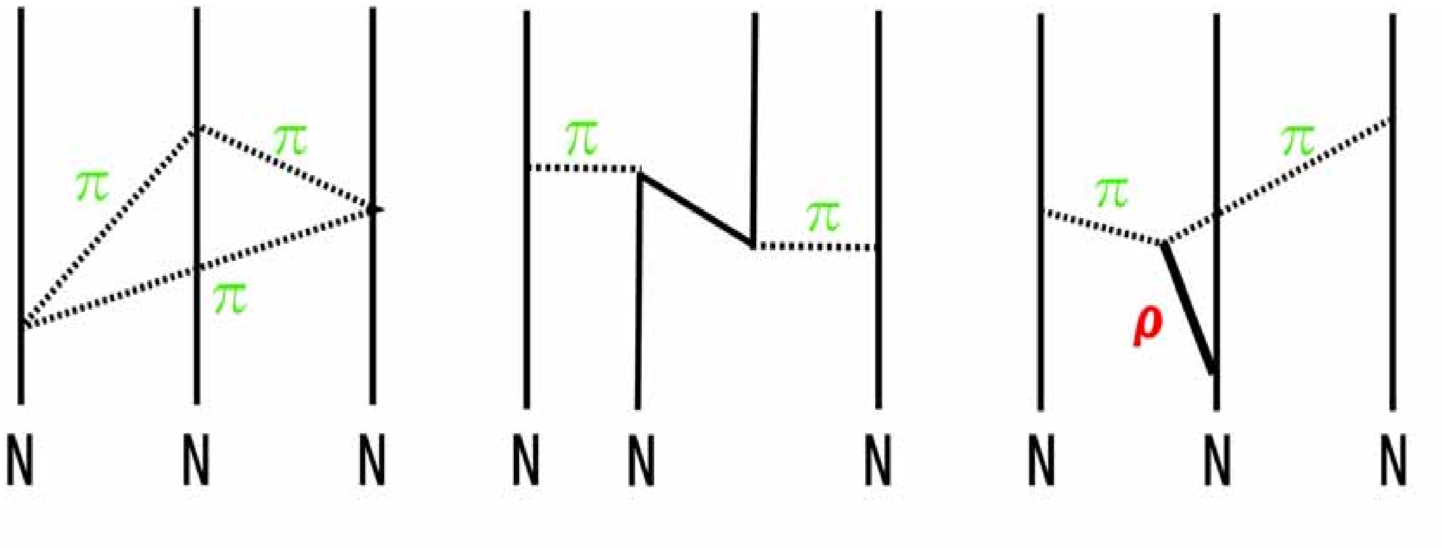
$$\left(J^\pi, T\right) = \left(\frac{1}{2}^+, \frac{1}{2}\right)$$

Δ ：excited state of nucleon

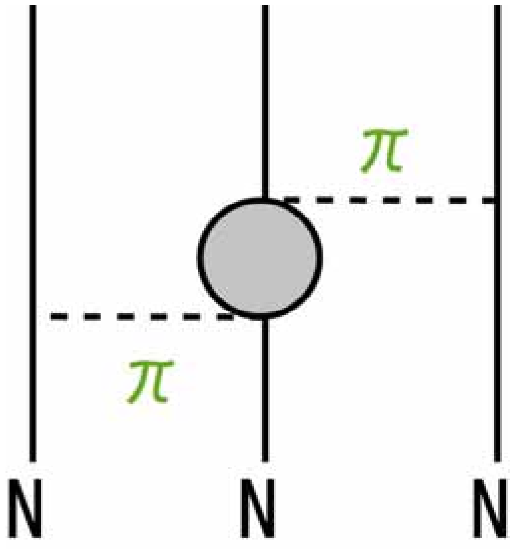
$$m_\Delta c^2 = 1232\ \text{MeV}$$

$$\left(J^\pi, T\right) = \left(\frac{3}{2}^+, \frac{3}{2}\right)$$

◆other type of 3NF



◆3NF based on 2π exchange model



- ☐ TM-3NF

  S.A.Coon *et al.*, Nucl. Phys. A317(1979)242.

  current algebra

- ☐ UR-3NF

  J.Carlson *et al.*, Nucl. Phys. A401(1983)59.

  FM+phenomenological SR term

- ☐ BR-3NF

  H.T. Coelho *et al.*, Phys. Rev. C28(1983)1812.

  chiral Lagrangian + current algebra

- ☐ Texas-3NF

  U.van. Kolck *et al.*, Phys. Rev. C49(1994)2932.

  chiral perturbation theory

Three-Nucleon Force

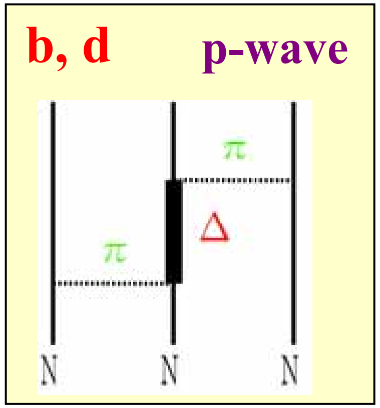
$$V^{(3)} = \frac{1}{(2\pi)^6}\frac{g^2_{\pi NN}}{4m^2}\frac{F^2_{\pi NN}(q^2)}{(q^2+m_\pi^2)}\frac{F^2_{\pi NN}(q'^2)}{(q'^2+m_\pi^2)}\vec{\sigma}_1\cdot\vec{q}\,\vec{\sigma}_2\cdot\vec{q}'\left[O^{\alpha\beta}\tau_\alpha\tau_\beta\right]$$

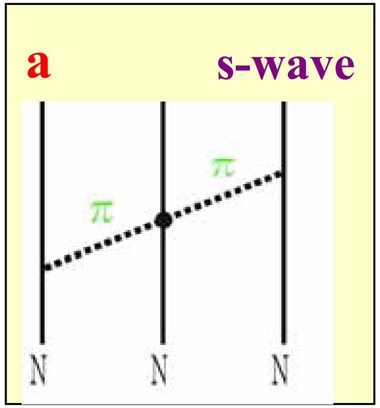
$$O^{\alpha\beta} = \delta^{\alpha\beta}\left[a + b\vec{q}\vec{q}' + c(q^2+q'^2)\right] - d(\tau_3^\gamma\varepsilon^{\alpha\beta\gamma}\vec{\sigma}_3\cdot\vec{q}\times\vec{q}')$$

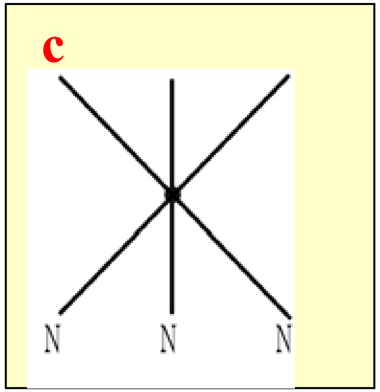
$$F^2_{\pi NN}(q^2) = \frac{\Lambda^2 - m_\pi^2}{\Lambda^2 + q^2}$$ πNN form factor

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
Brazil	1.05	-2.29	1.05	-0.77
Texas	1.87	-3.82	0.0	-1.12
Ruhr	0.51	-1.82	0.0	-0.48
TM’	-0.87	-2.62	0.0	-0.60







Faddeev type calculations

1 Bochum-Cracow-KIT group calculation

→ **H. Witała, H. Kamada, W. Glöckle, E. Epelbaum**

- Input data

NN	**3NF**
CD Bonn AV18 Nijmegen	Tucson-Melbourne Urbana IX

2 Hannover group calculation

→ **P.U. Sauer, D.Deltuva**

Parall. Session Th-3(finisshed)

- **Input data**

NN	**3NF**
CD Bonn	Δ – isobar

N and Δ on an equal footing!
dispersive two-body effects exist.

■**Both calc., *nd* scattering assumed.**

→No Coulomb force effects included.

First Evidence of 3NF Effects

- **B.E. of ^{3}H: 8.48 MeV**

Faddeev calculations

Bochum-Cracow-KIT group calc.

NN pot.	NN only	**NN+3NF(TM)**	Λ (m
CD Bonn	8.00	8.483	4.86
AV18	7.65	8.479	5.22
Nijm93	7.66	8.480	5.10
Ruhr	7.64	8.459	5.31

Hannover group C.C. calc.

CDBonn	8.00	8.29 (CDBonn + Δ)	–

●NN force only calc. is underboud by 0.5-1.0 MeV.

●3NF fills this gap.(but with Λ)

→ put constraint on overall strength of 3NF.

■to study dynamical properties of 3NF

→ scattering

→ No adjustable parameter in Faddeev calc.

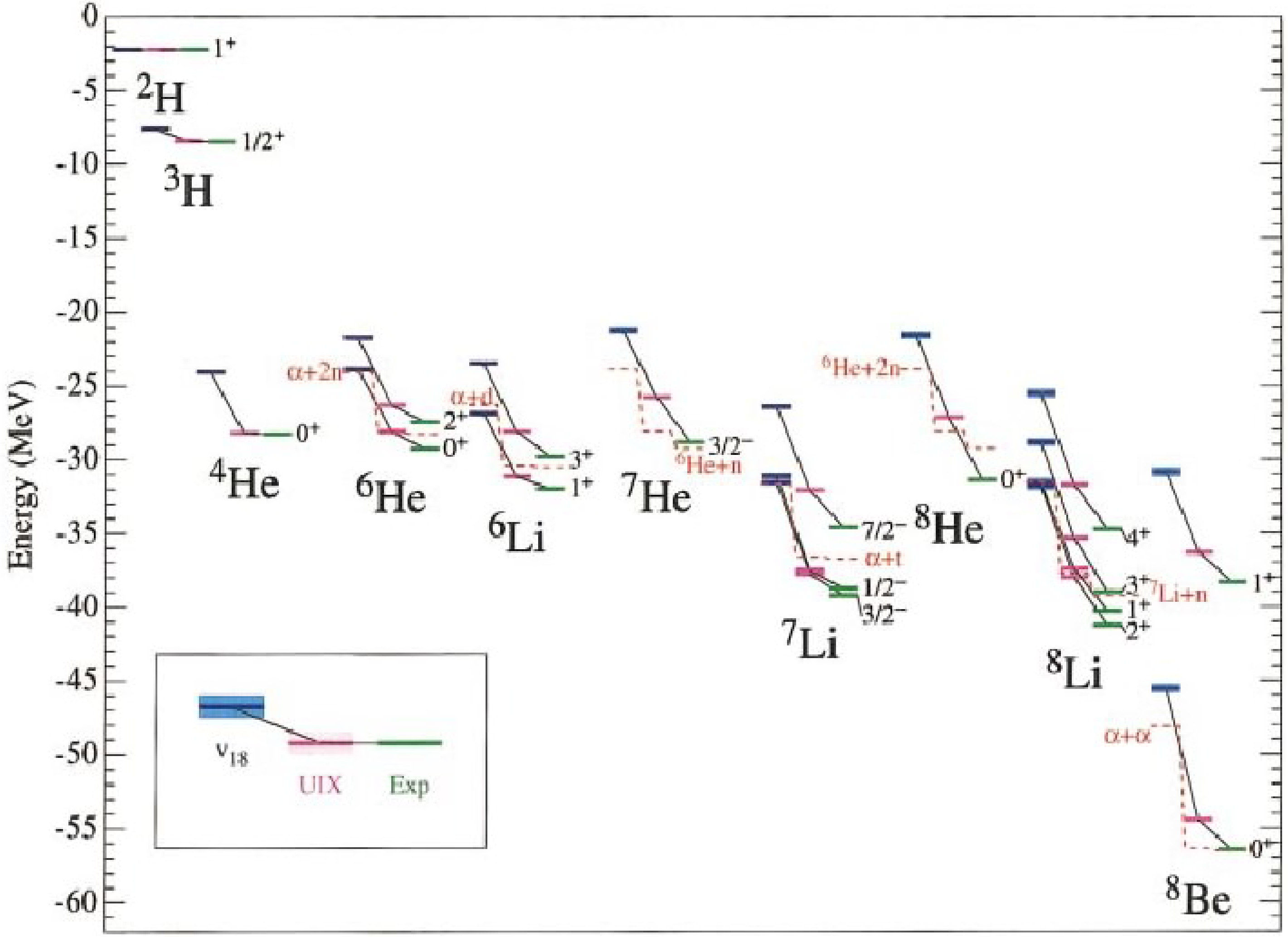
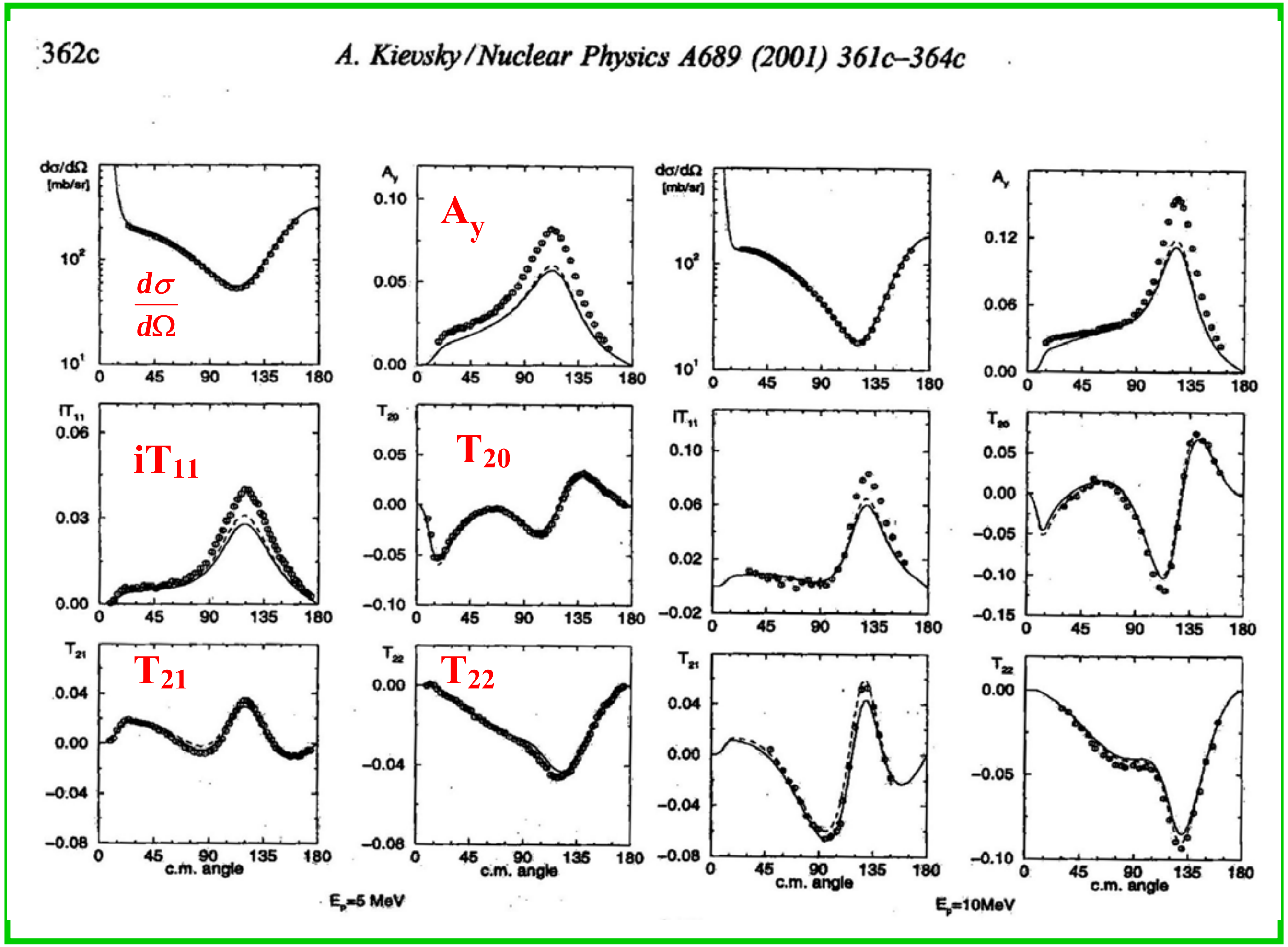


FIG. 1. (Color) Energies of ground or low-lying excited states of light nuclei computed with the AV18 and AV18/UIX interactions, compared to experiment. The light shading shows the Monte Carlo statistical errors. The dashed lines indicate the thresholds against breakup for each model or experiment.

To Where should we look for 3NF effects?

N*d* elastic scattering is very attractive since it is simple and offers a rich set of spin observables.

- **Low energy *pd* scattering**



362c A. Kievsky/Nuclear Physics A689 (2001) 361c–364c

What are

A_y, iT_{11},

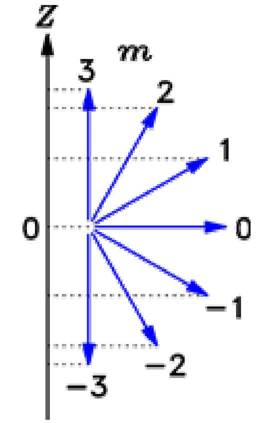
T_{20}, T_{21}, T_{22} ?

polarization ･･･ degree of spin polarization

Vector polarization(rank 1 tensor)

$$P_Z \equiv \frac{1}{s}\sum_{m=-s}^{+s} mP(m) \qquad P(m): \text{population of } m、 \quad \sum_{m=-s}^{+s} P(m) = 1$$

electron, proton($spin\,\frac{1}{2}$) : $P_Z = P(+\frac{1}{2}) - P(-\frac{1}{2})$



$s=3$

Deuteron spin 1

Tensor polarization (rank 2 tensor)

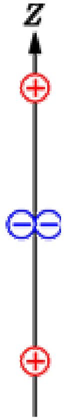
$$P_{ZZ} \equiv \frac{1}{s(2s-1)}\left[3\sum_{m=-s}^{+s} m^2 P(m) - s(s+1)\right]$$

$$P_{ZZ} \equiv P(+1) - 2P(0) + P(-1)$$
$$= 1 - 3P(0) \qquad \Lambda \text{ value } [-2, +1]$$

$P(+1)=0,\ P(0)=1,\ P(-1)=0 \quad \Rightarrow P_Z = P(+1) - P(-1) = 0$

different from no polarization $P(+1) = P(0) = P(-1) = 1/3$

$\Rightarrow P_{ZZ} = -2$



elctric quadrupole

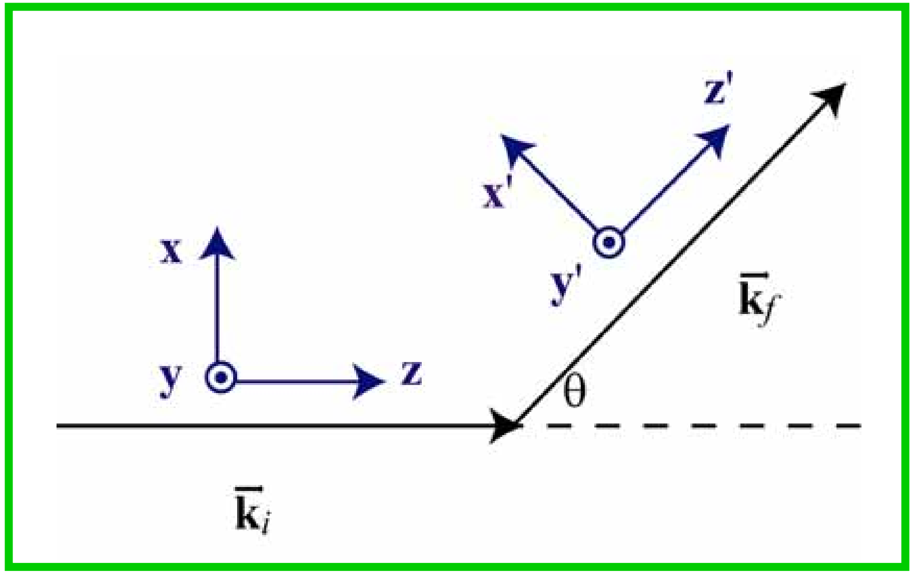
Polarization

Vector : $P_z = \dfrac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$

$= P(+) - P(-)$

Tensor : $P_{zz} = \dfrac{N_+ - 2N_0 + N_-}{N_+ + N_0 + N_-}$

$= P(+1) - 2P(0) + P(-1)$



Polarization in reaction

observables in this talk

1. Vector polarization $P^{y'}$
2. Vector analyzing power A_y (iT_{11})
3. Tensor analyzing powerss A_{xx}, A_{yy}, A_{xz} (T_{20}, T_{21}, T_{22})

Polarization in reaction

$$\vec{p} \quad : \quad \sigma = \sigma_0 (1 + p_y A_y)$$

$$\vec{d} \quad : \quad \sigma = \sigma_0 \left[1 + \frac{3}{2} p_y A_y^d + \frac{2}{3} p_{xz} A_{xz} + \frac{1}{3} (p_{xx} A_{xx} + p_{yy} A_{yy} + p_{zz} A_{zz}) \right]$$

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

$$T_{20} = \frac{-1}{\sqrt{2}} (A_{xx} + A_{yy})$$

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

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

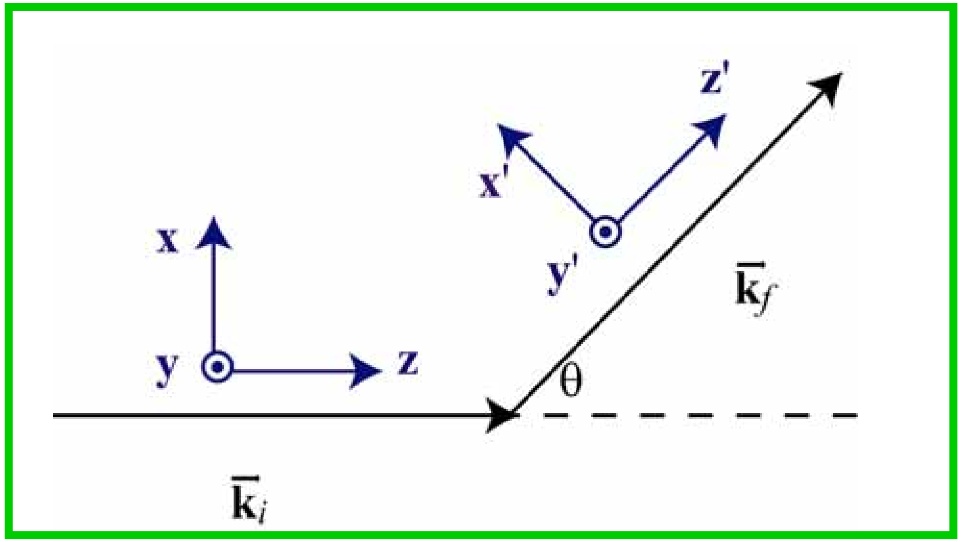
$$-1 \leq A_y \leq 1$$

$$-\frac{3}{2} \leq A_y \leq \frac{3}{2}$$

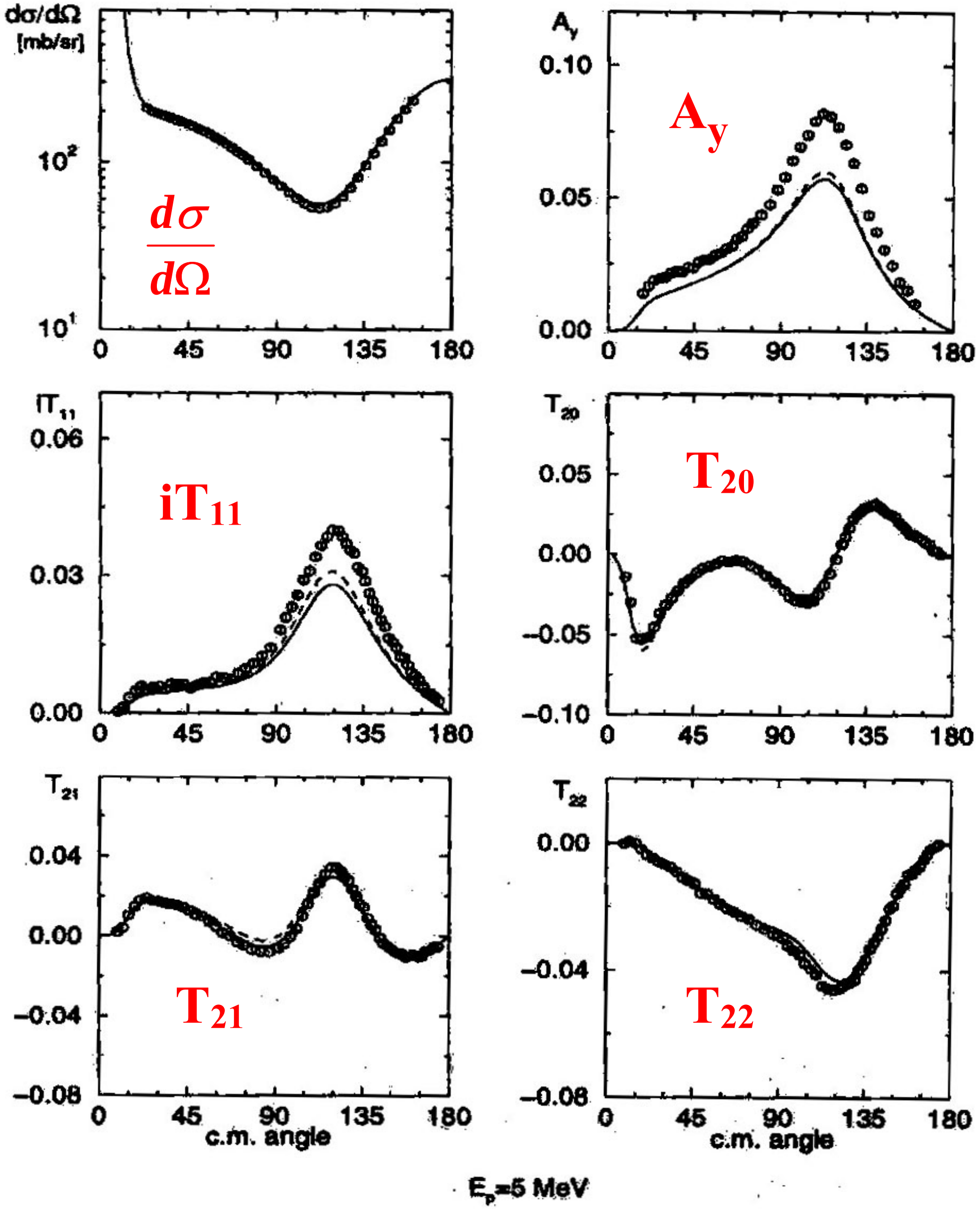
$$-2 \leq A_{xx(yy)} \leq 1$$

$$A_{xx} + A_{yy} + A_{zz} = 0$$

Sensitive to spin-orbit interactions



● Low energy *pd* scattering



Faddeev calc.

No parameter !

No need of 3NF !

A_y **(iT_{11})discrepancy**

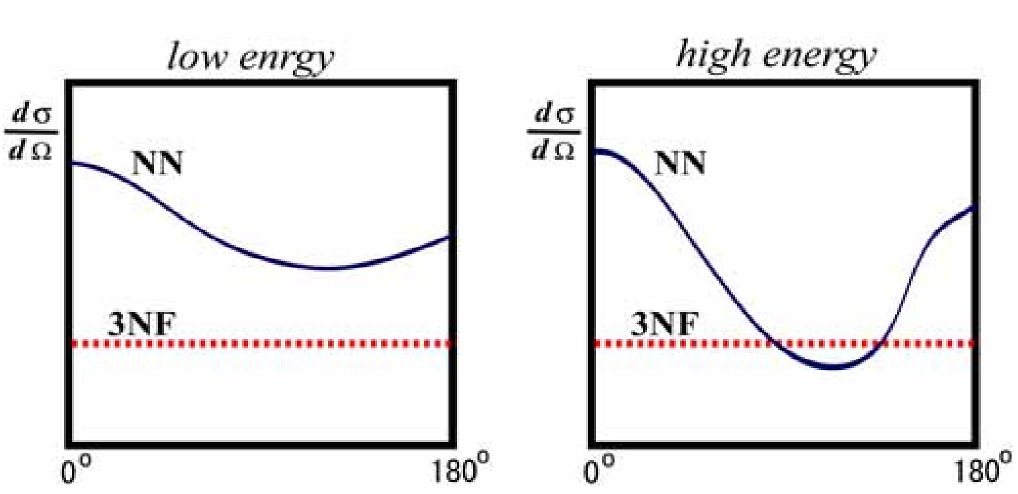
→ 3NF ?

Probably due to deficiency in ^3P_J phase shifts of NN.

To Where should we look for 3NF effects?

***Nd* elastic scattering is very attractive since it is simple and offers a rich set of spin observables.**

- **Low energy *Nd* scattering**
  - **A_y discrepancy → due to 3NF ?**
  - **Probably due to deficiency in ^3P_J phase shifts of NN.**
- **Prediction by H.Witała.** PRL **81**('98) 1183.
  - **→ go to *nd* scatt. at intermediate energy.**



- **look for *dσ/dΩ* minimum region.**

Let’s start with

135 MeV/u (E$_d$=270 MeV) data

at RIKEN by K. Sekiguchi

$\overset{\rho}{d} + p$ at 270 MeV (RIKEN)

By Kimiko Sekiguchi

$\overset{\rho}{d}$: various spin(polarization) obs.

$d\sigma/d\Omega$, $P^{y'}(= -A_y^{p})$, iT_{11}, T_{20}, T_{22}, T_{21}

K. Sekiguchi *et al.* Phys. Rev. C65 (2002) 034003.

Spin(polarization) transfer exp. by Sekiguchi

$\overset{\rho}{d} + p \to \overset{\rho}{p} + d$ **at 270 MeV (135 MeV/u)**

$K_{xx}^{y'}, K_{yy}^{y'}, K_{xz}^{y'}$

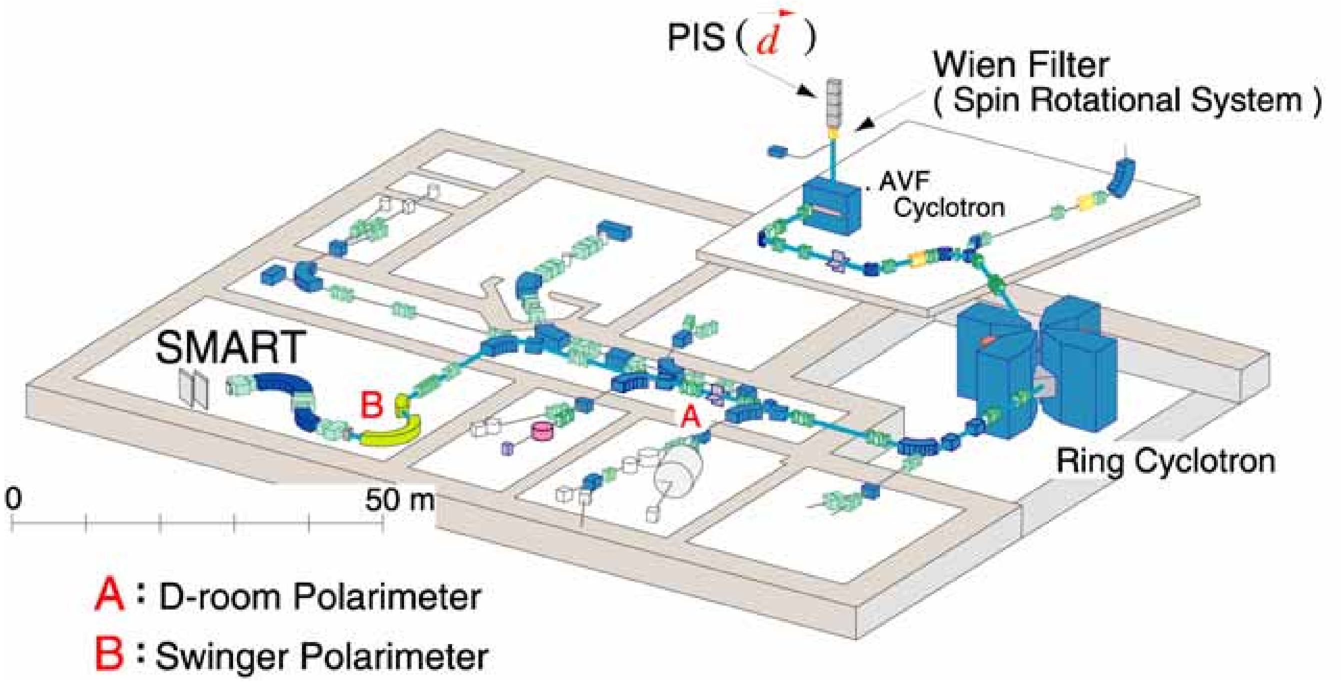
→ **K. Sekiguchi: to be published soon.**

RIKEN Accelerator Research Facility (RARF)

Directions of polarization of *d* beams are freely controlled!

- Vector and tensor polarized deuteron beams are provided by the polarized ion source(PIS).
- The Spin axis is controlled by a Wien Filter prior to acceleration.
- Single-turn extraction is available both for the AVF and Ring cyclotrons.

Beam polarizations : 60-80% of the theoretical maximum values
at D-room polarimeter (**A**) and the Swinger polarimeter (**B**)



Method of spin rotation !

magnetic moment $\mu = s\dfrac{e\hbar}{mc}(1+a)$

cyclotron frequency in magnetic field B $\omega_c = \dfrac{eB}{m\gamma}$

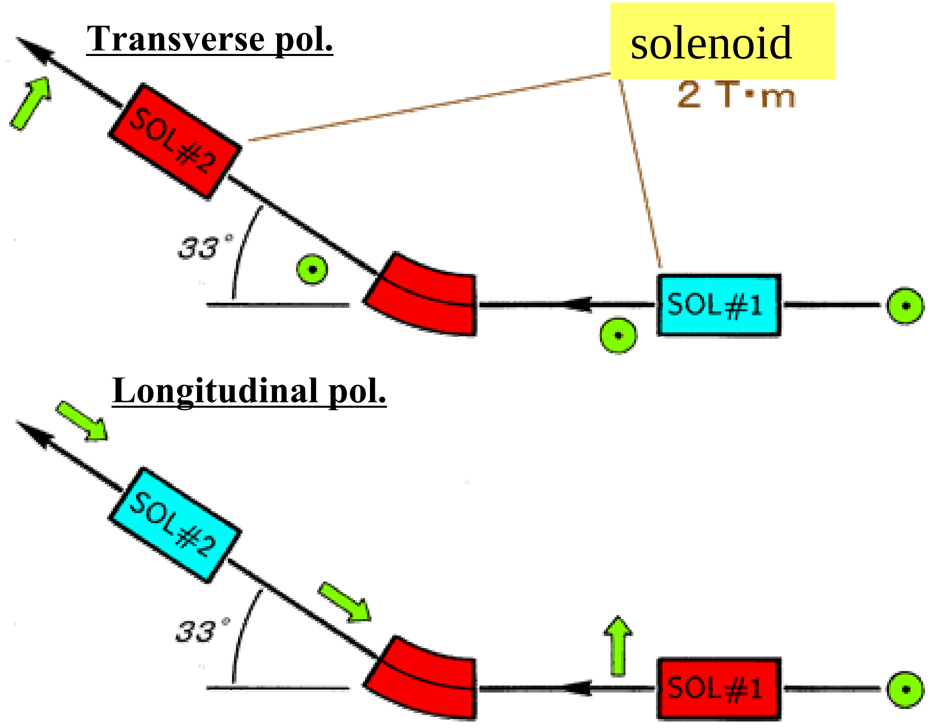
angular rotation frequency in B $\omega_s = \dfrac{eB}{m\gamma}(\gamma a + 1)$

Larmor freq. + Thomas precession (rel. effects)

Dirac particle $(a = 0) \Rightarrow \omega_s = \omega_c$

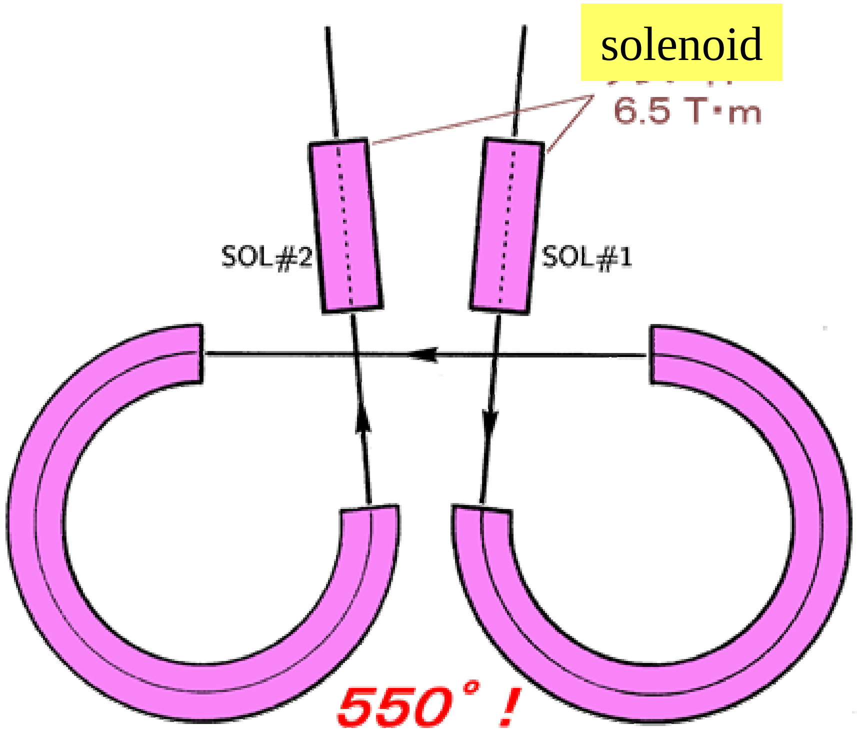
proton : $\mu_p = \dfrac{1}{2}\dfrac{e\hbar}{m_p c} \times 2.793$

500 MeV proton



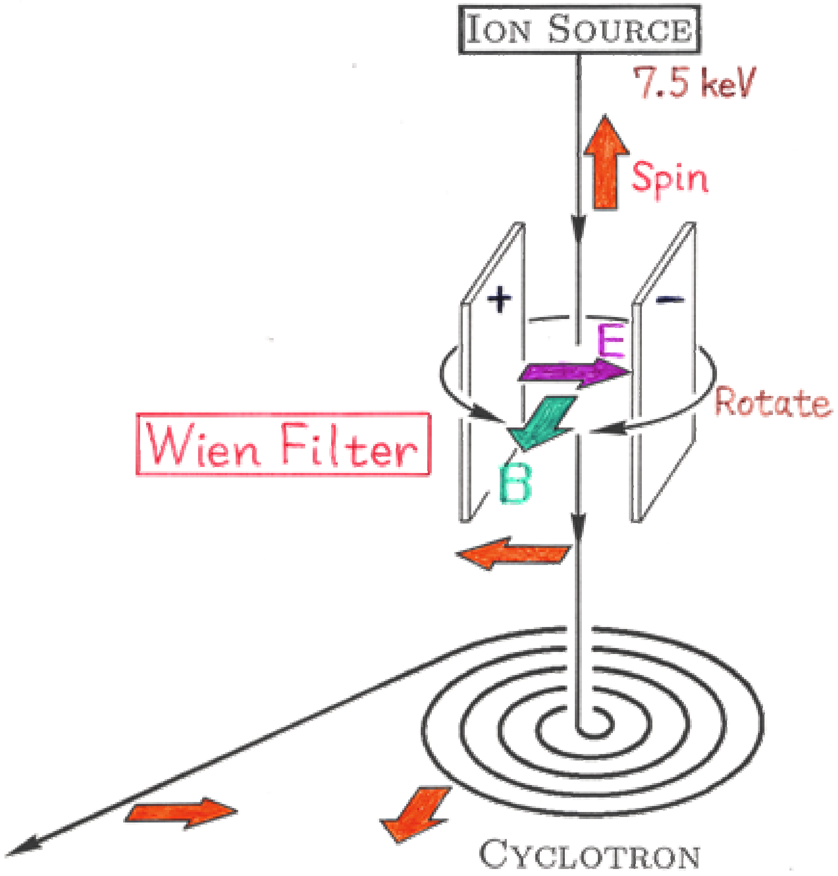
deuteron : $\mu_d = \dfrac{e\hbar}{m_d c} \times 0.857$

270 MeV deuteron



Method of spin rotation II

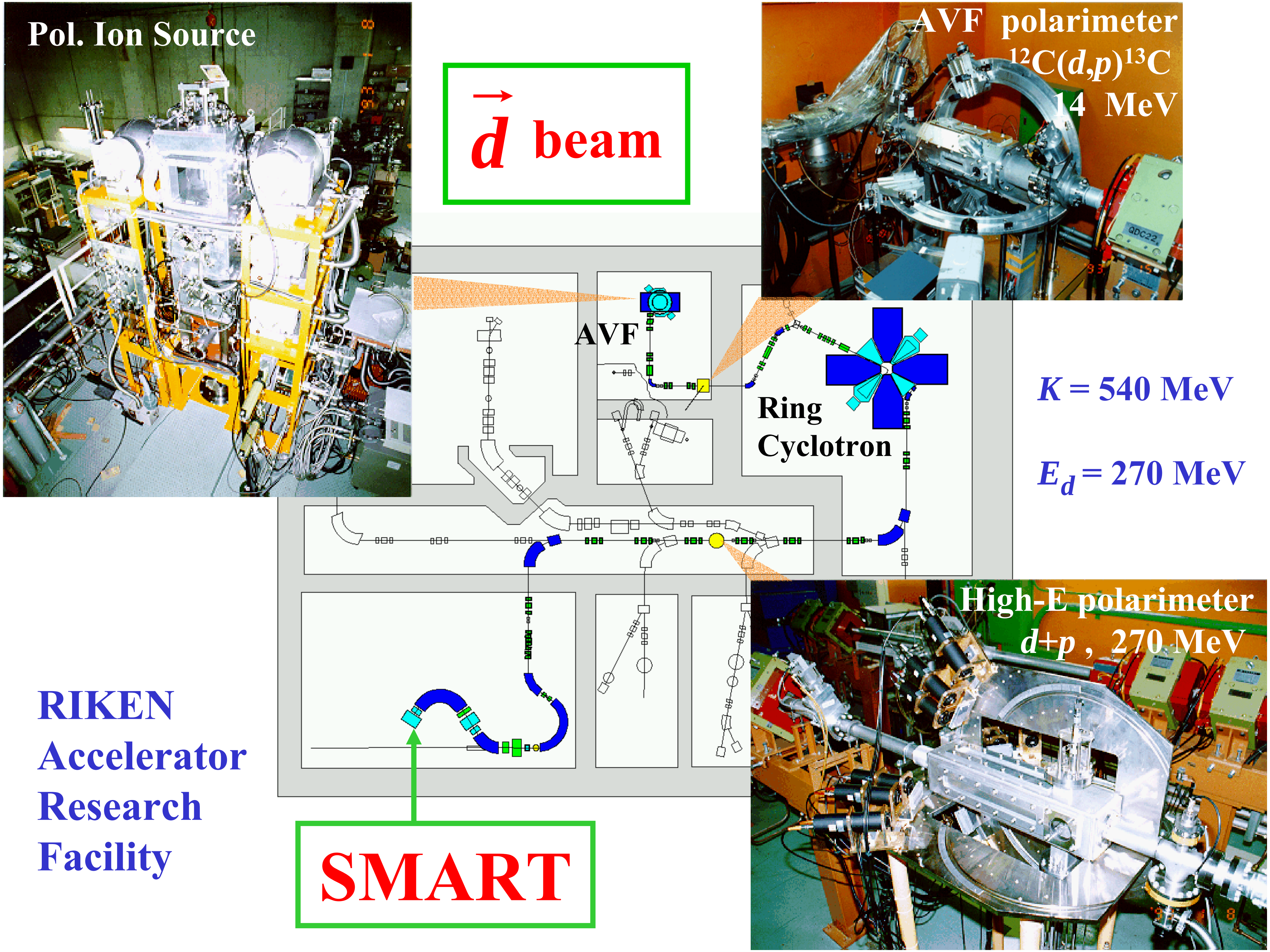
Spin rotation before injection
into cyclotron at low energy
⇒ spin precession during accel.



Familiar at Tandem VdG accel…

- **single turn extraction needed at cyclotron**
  ⇒ Thanks to RIKEN Accelerator Staff
- **spin direction moniter needed after accel. With high efficiency.**

$\vec{d}$ beam

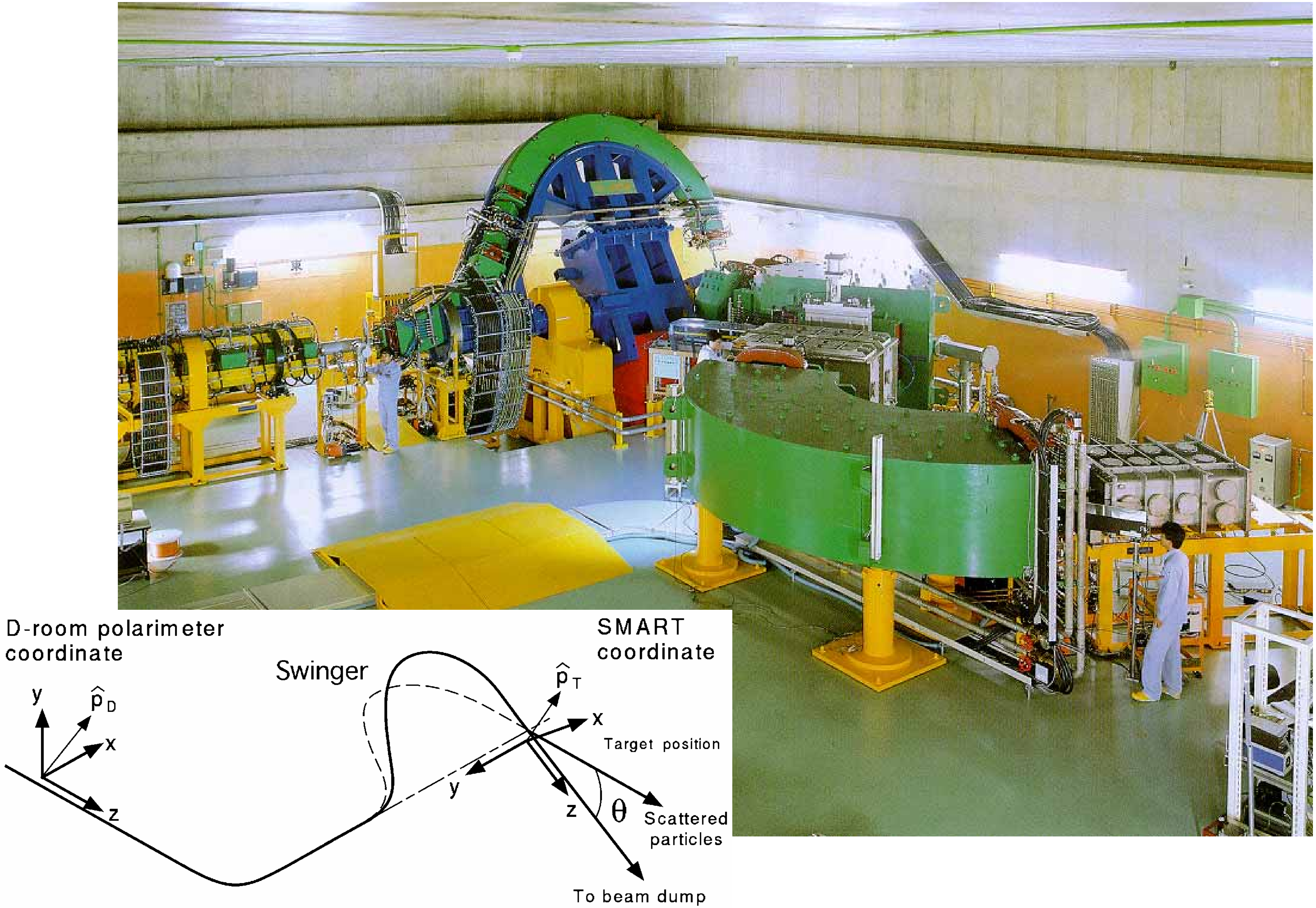


$K = 540$ MeV

$E_d = 270$ MeV

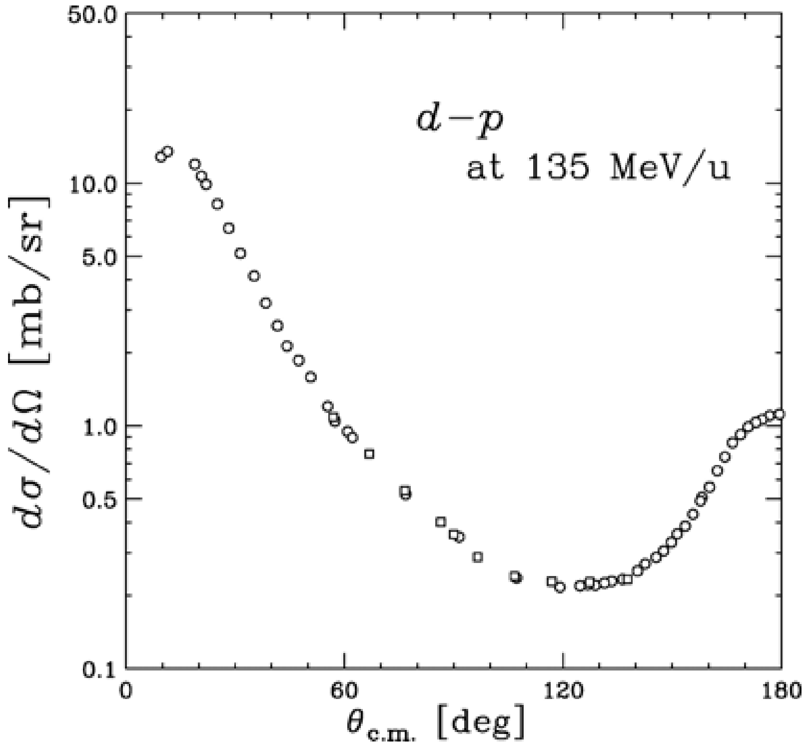
RIKEN Accelerator Research Facility

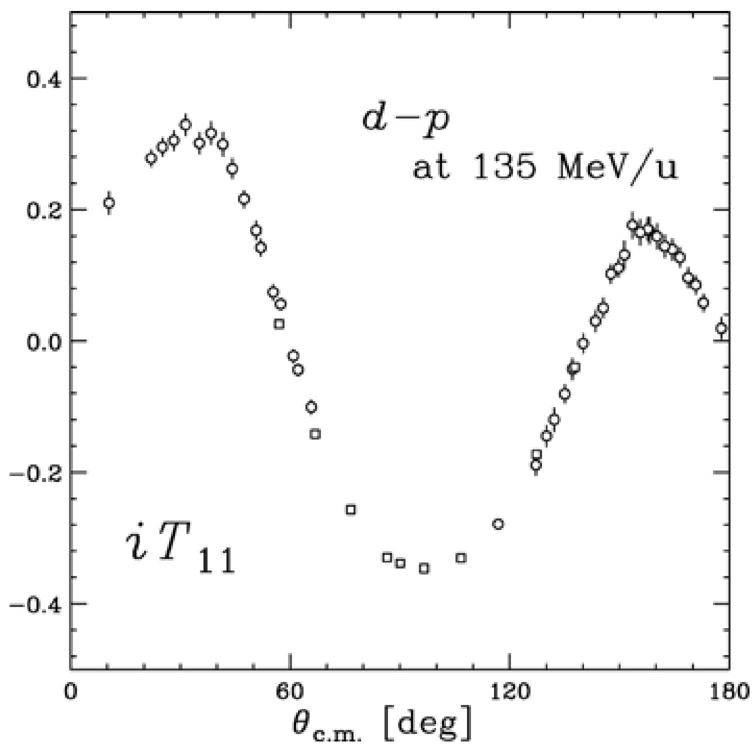
SMART



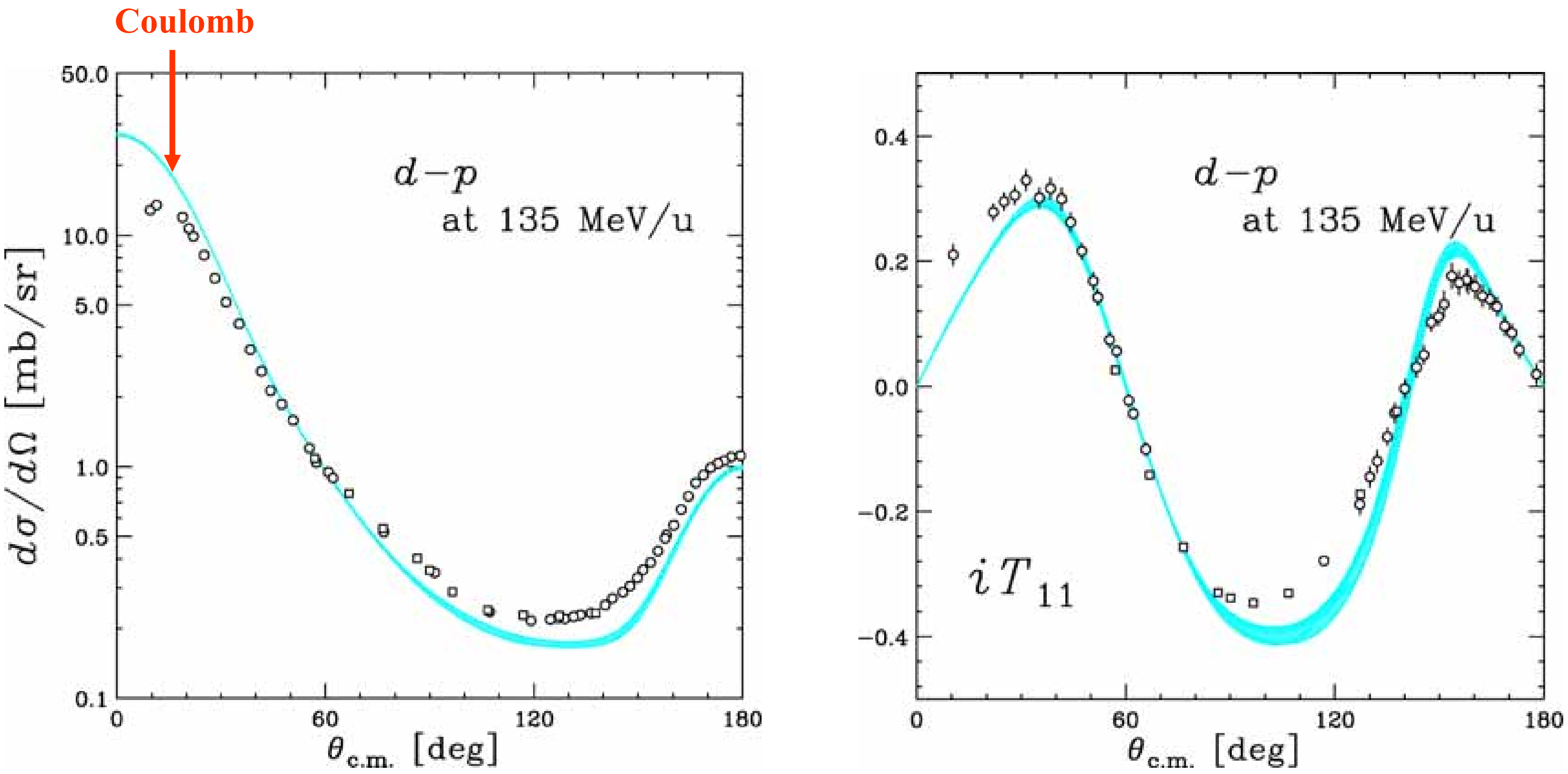
SMART: Swinger and Magnetic Analyzer with Rotator and Twister

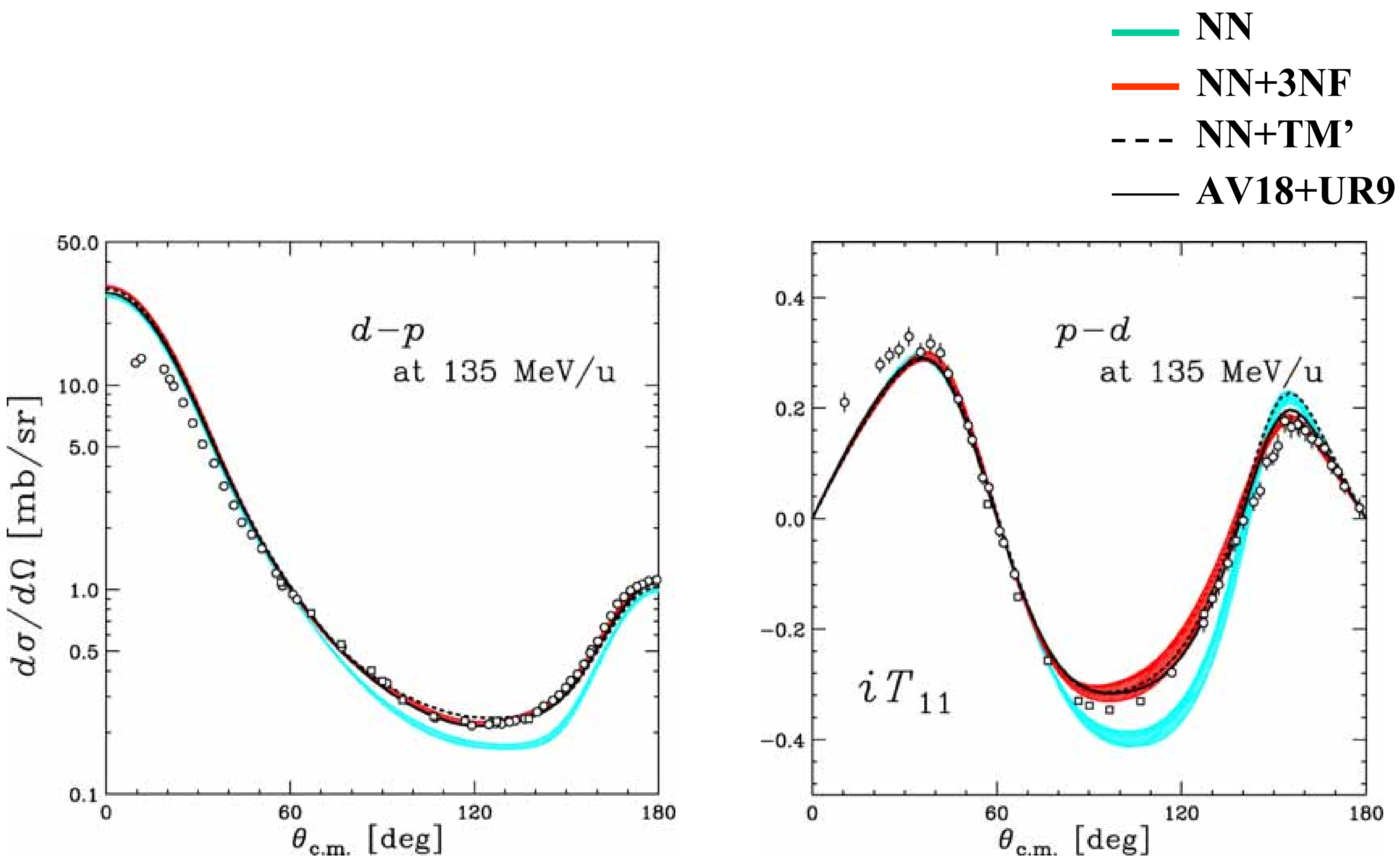
RIKEN data **270 MeV**

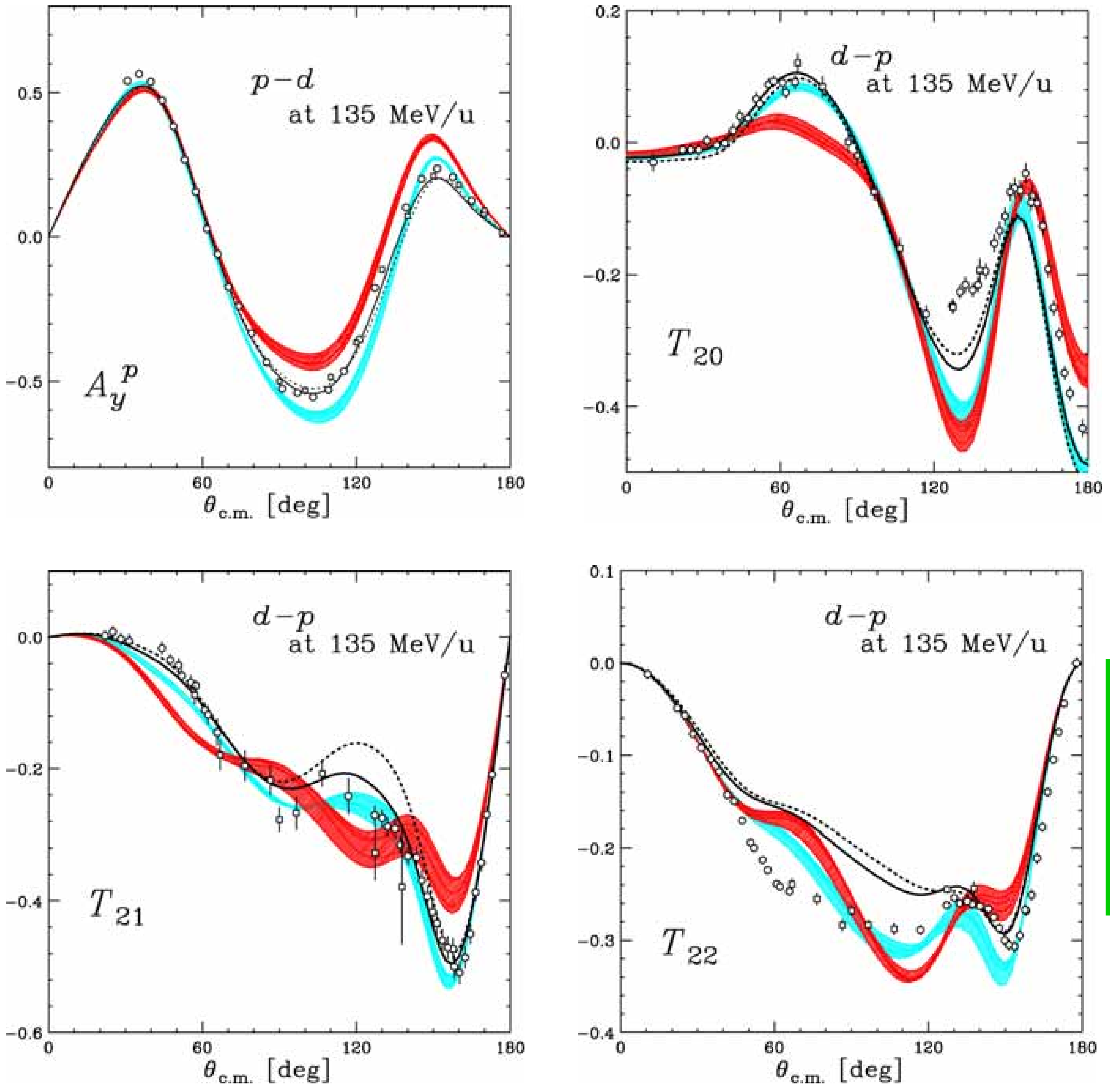




Bochum calc. — **NN**




NN
NN+3NF
NN+TM’
AV18+UR9
$d\sigma/d\Omega$ [mb/sr]
50.0
10.0
5.0
1.0
0.5
0.1
$d-p$
at 135 MeV/u
0
60
120
180
$\theta_{\rm c.m.}$ [deg]
0.4
0.2
0.0
−0.2
−0.4
$p-d$
at 135 MeV/u
iT_{11}
0
60
120
180
$\theta_{\rm c.m.}$ [deg]



🟩 **NN**
🟥 **NN+3NF**
- - - **NN+TM’**
— **AV18+UR9**

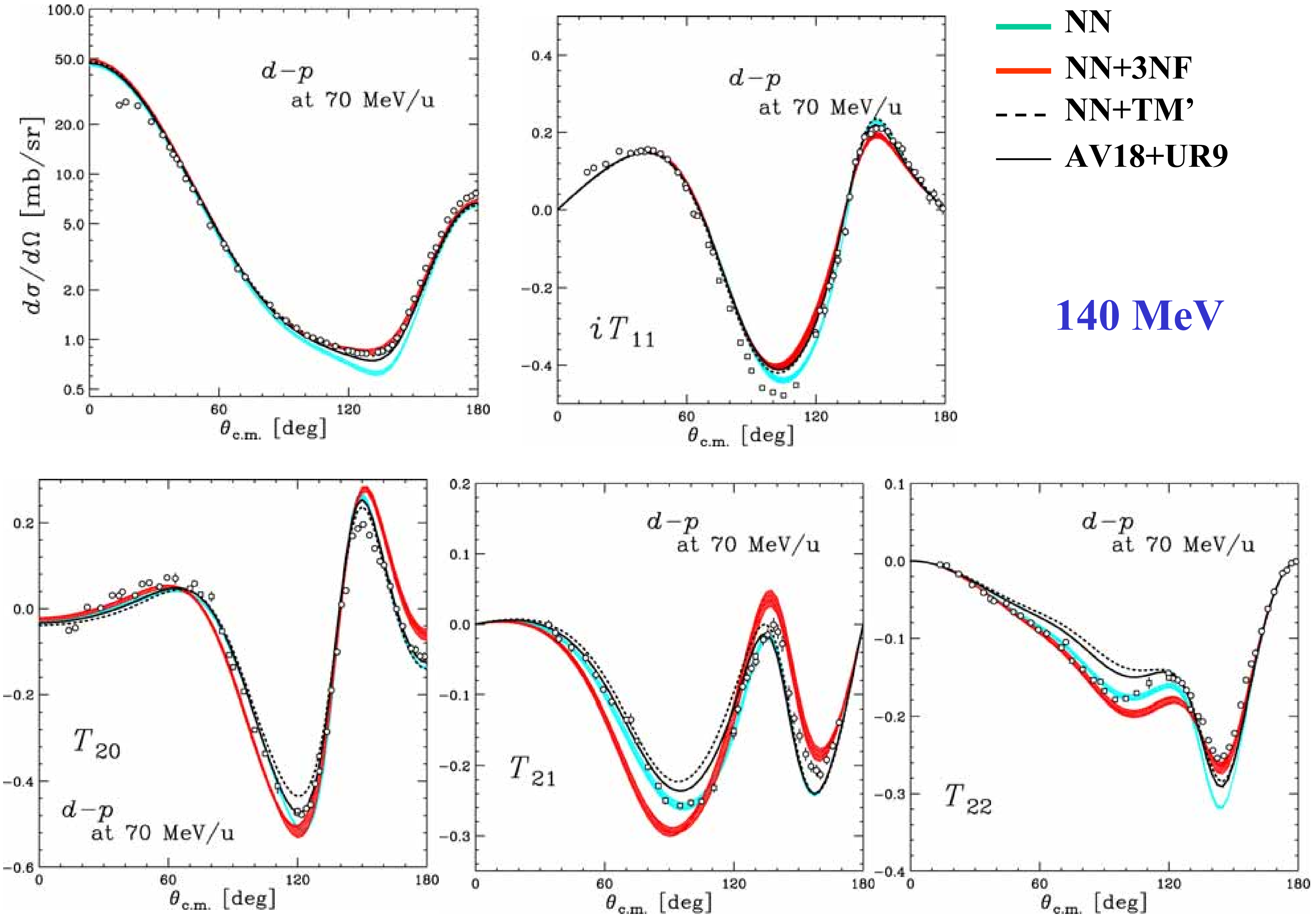
Tensor behaviour

➡ **chaotic**

How they look like if the energy is halved ?

140 MeV(70 MeV/u) data

at RIKEN


NN
NN+3NF
NN+TM'
AV18+UR9
d−p at 70 MeV/u
dσ/dΩ [mb/sr]
100.0
50.0
20.0
10.0
5.0
2.0
1.0
0.5
θc.m. [deg]
0
60
120
180
iT11
0.4
0.2
0.0
−0.2
−0.4
T20
−0.6
T21
0.1
−0.1
−0.3
T22
−0.4

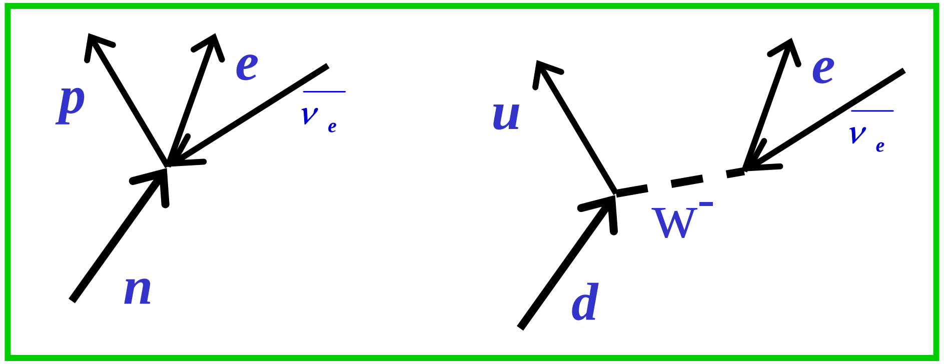
140 MeV

Chiral Effective Field Theory

- Relation with QCD

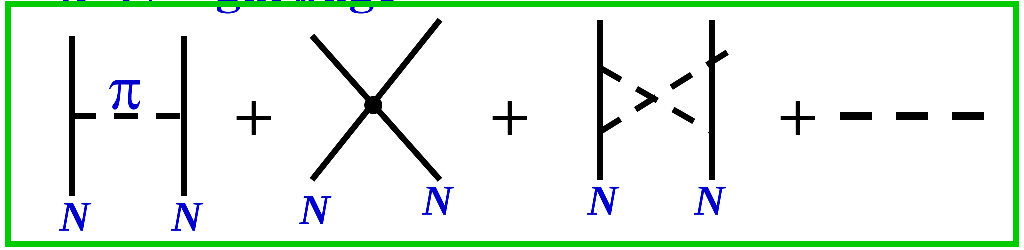
  Lagrangian *L*=. . . .
- Scale parameter Λ

  expand in power of Q/ Λ (Q=nucl. mom.)
- Chiral symmetry
- Effective theory



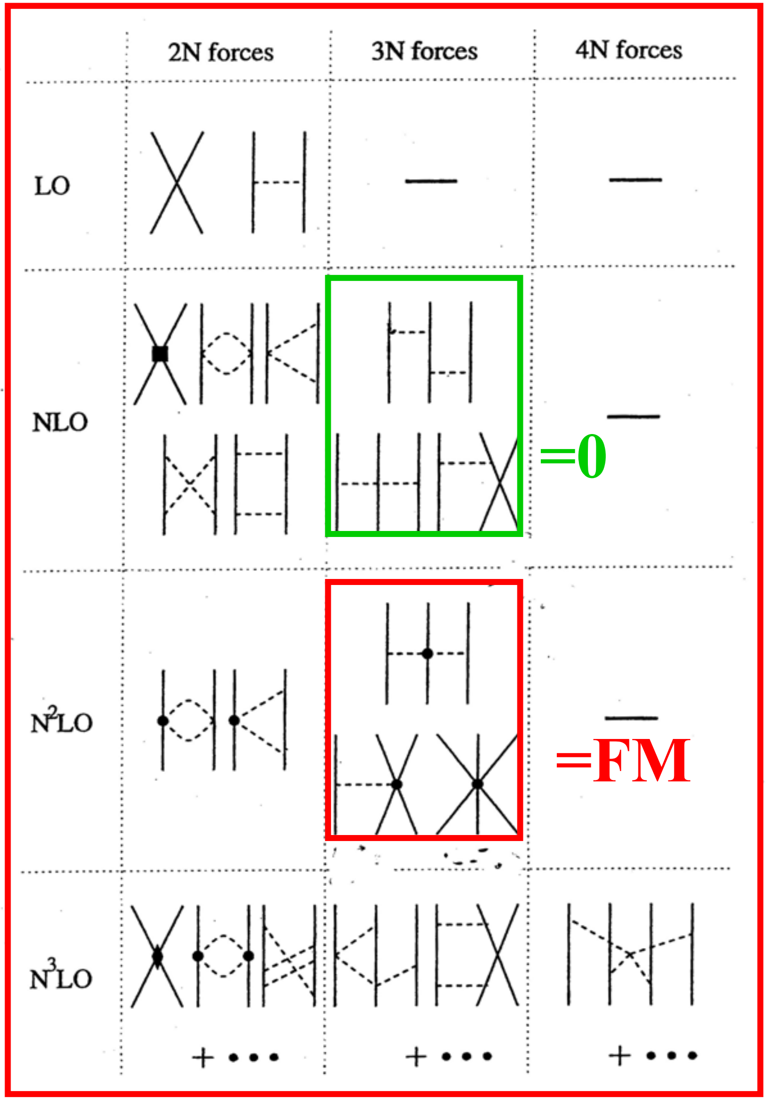
- **Chiral perturbation theory**

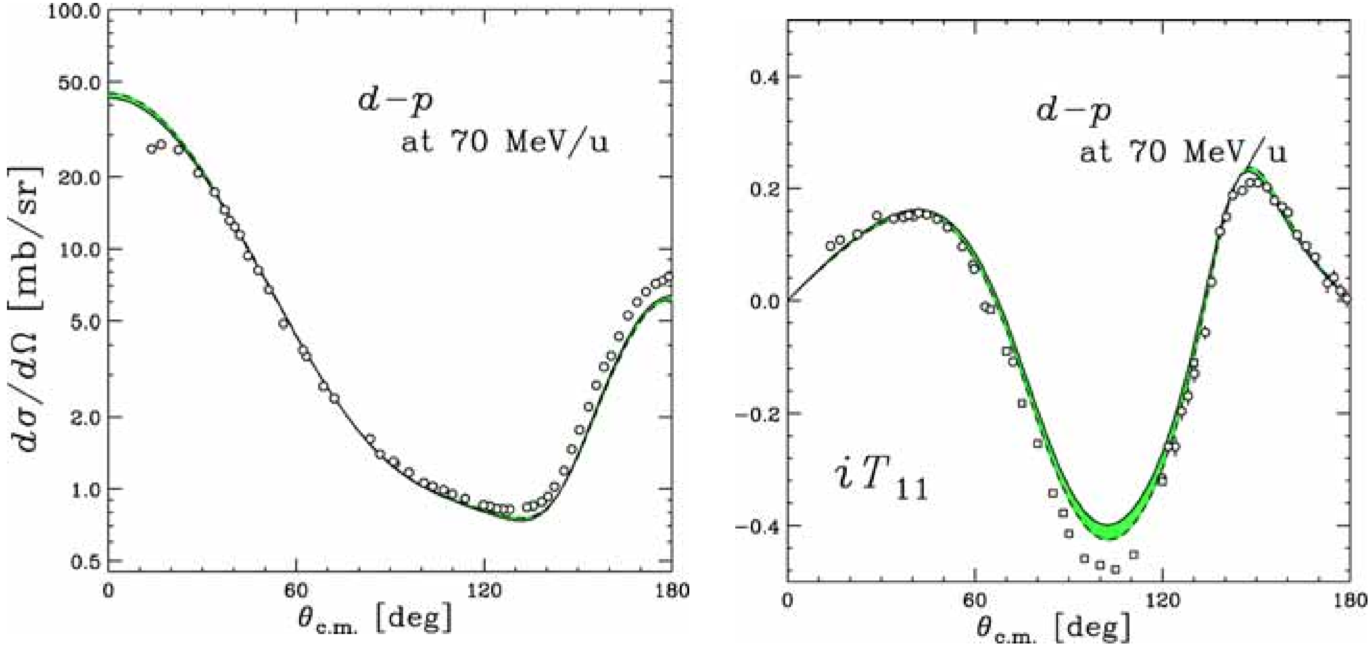
  π+N+"garbage"



"garbage"=heavy meson, Δ

2N+3N on the same footing !



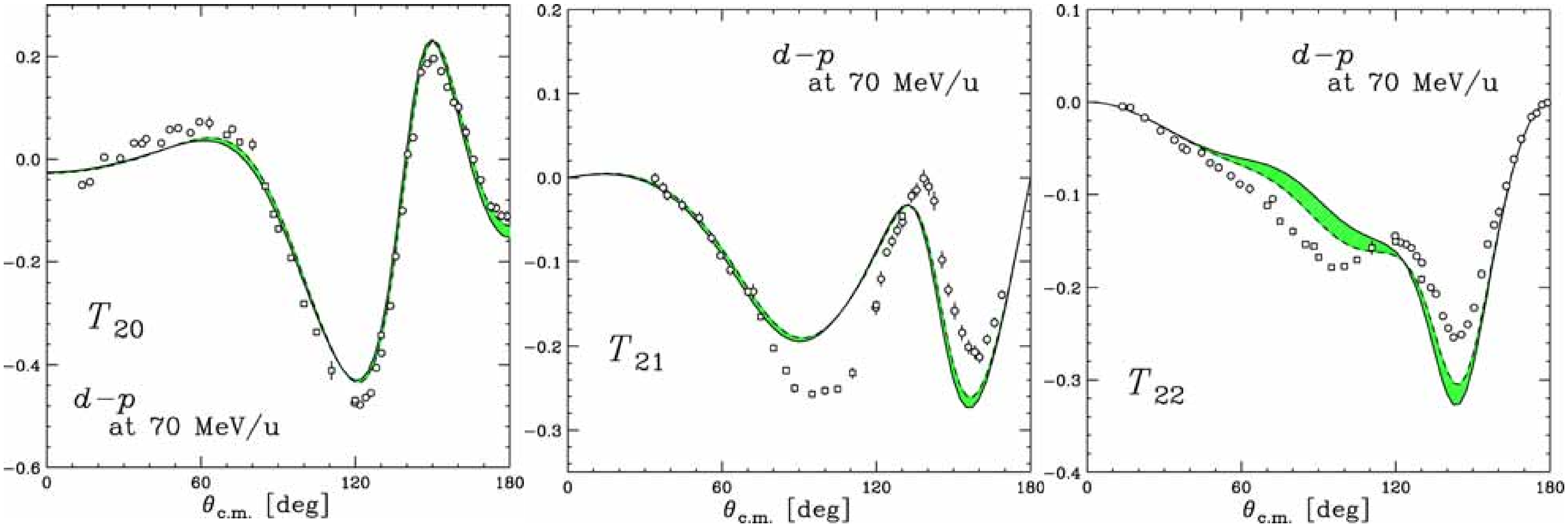


Chiral Eff. Field Theory Calc. NNLO

E. Epelbaum et al.

Phys. Rev. C66 (2002) 64001.

Cut off = 500, 600 MeV/c



Results of 270 and 140 MeV

- $d\sigma/d\Omega$, iT_{11}: **Excellent fits!**

  → clear **3NF** effects in **N*d*** scatt.

  → magnitudes of 3NF seem to be O.K.

- $A_y(=-p^{y'})$, T_{20} ,T_{22} , T_{21}: Poor fits!

  → defects in spin dependent part of 3NF.

- 3NF: TM'/ Urbana IX does better job.

  → chiral symmetry requires: The ***c*** term should be zero.

- **Chiral Eff. Field Theory calc. does reasonable job for $d\sigma/d\Omega$ but not much analyzing powers.**

How they look like if the energy is doubled

from 135 MeV/u (E_d=270 MeV) ?

250 MeV/u data

at RCNP

$\vec{n}$ + d at 250 MeV (RCNP)

by Yukie Maeda

- Coulomb free
- direct comparison is possible:

  between ***nd*** data vs. Faddeev calc.

$\vec{n}$: secondary beam exp. → very difficult.

^{7}Li(p,n)^{7}Be reaction

Forward angle : *d(n,n)d* NTOF+NPOL

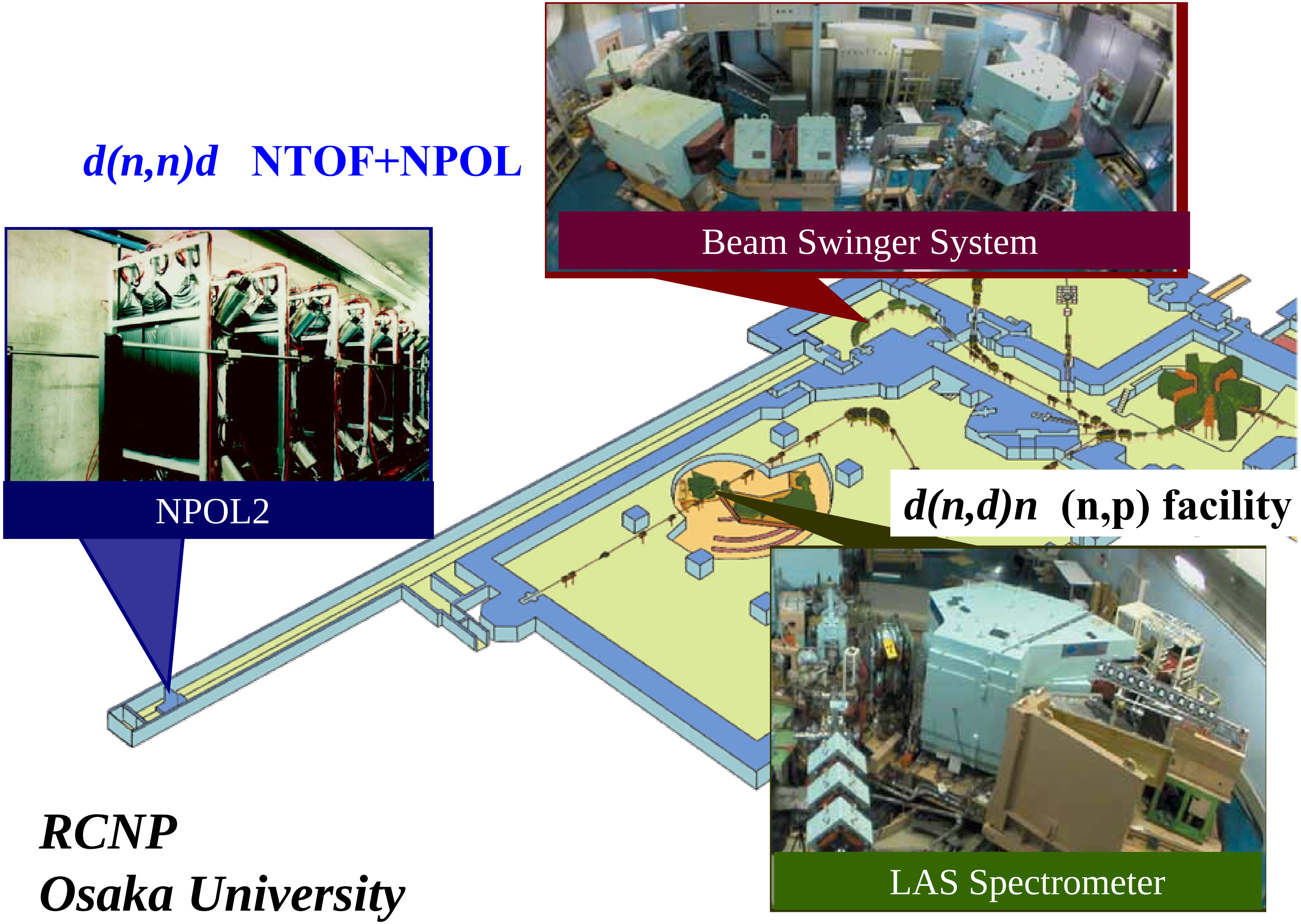
D liq. Scintillator(active target)

Backward angle : *d(n,d)n* (n,p) facility

recoiled *d* dectected

All data points are normalized by np scatt.

d(n,n)d **NTOF+NPOL**

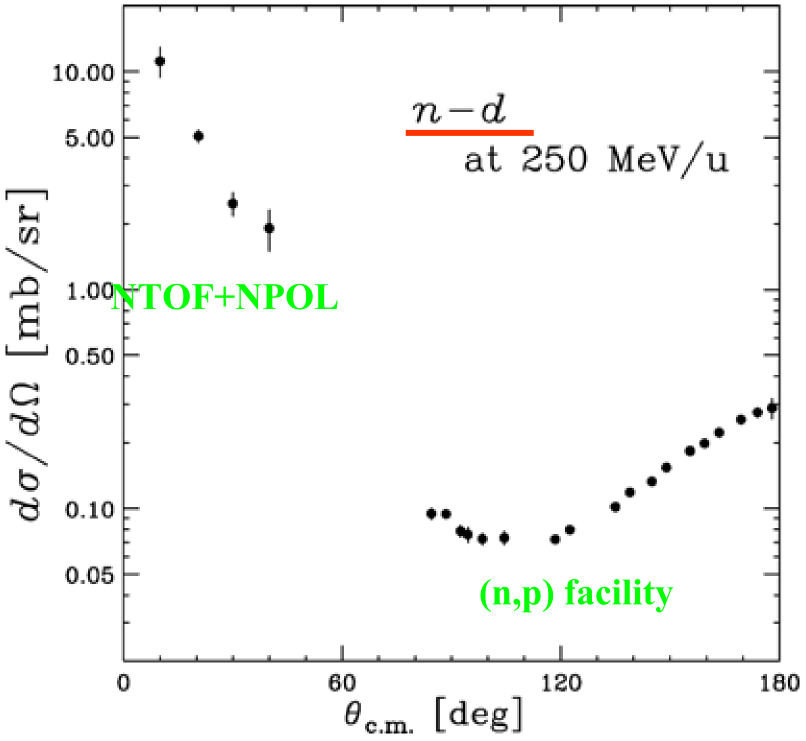


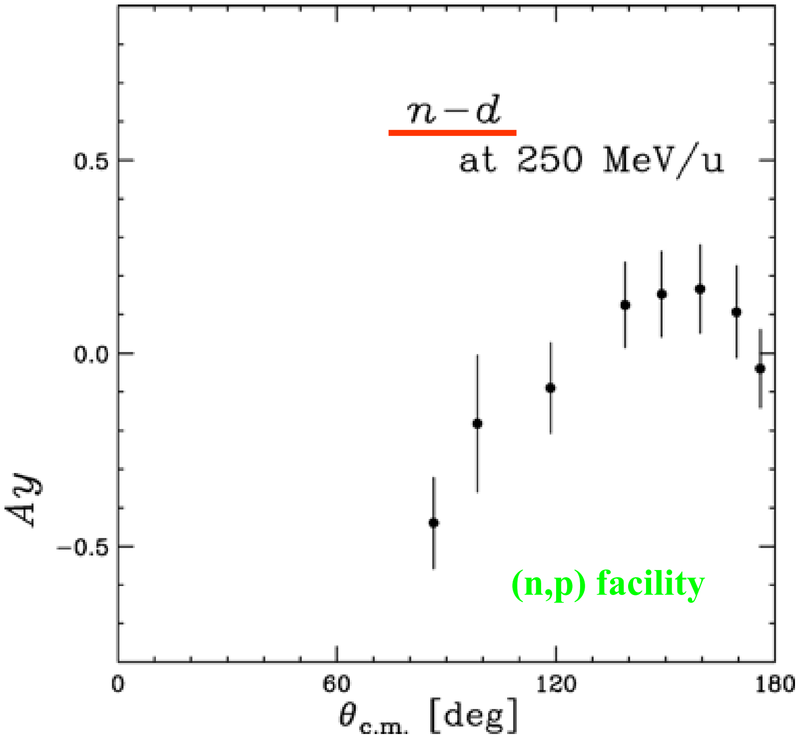
d(n,d)n **(n,p) facility**

RCNP
Osaka University

$\vec{n}$ + d at 250 MeV

by Yukie Maeda





$\vec{p}$ + d at 250 MeV (RCNP)

by K. Hatanaka

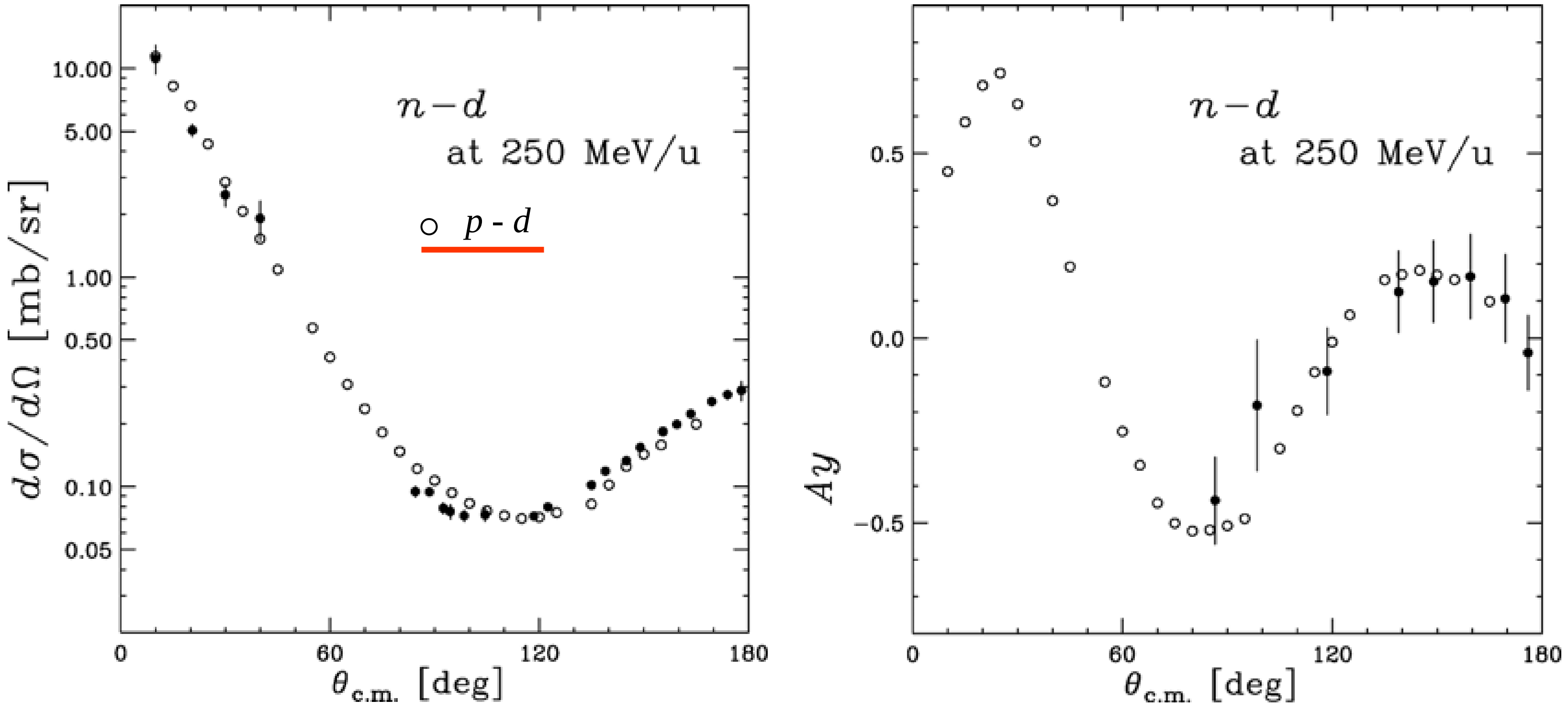
- $d\sigma/d\Omega$, A_y
- complete pol. transfer meas.: $K_x^{x'}$, $K_y^{y'}$, $K_z^{z'}$, $K_z^{x'}$, $K_x^{z'}$

  proton to proton
- direct comparison possible: between ***nd*** *vs.* ***pd***

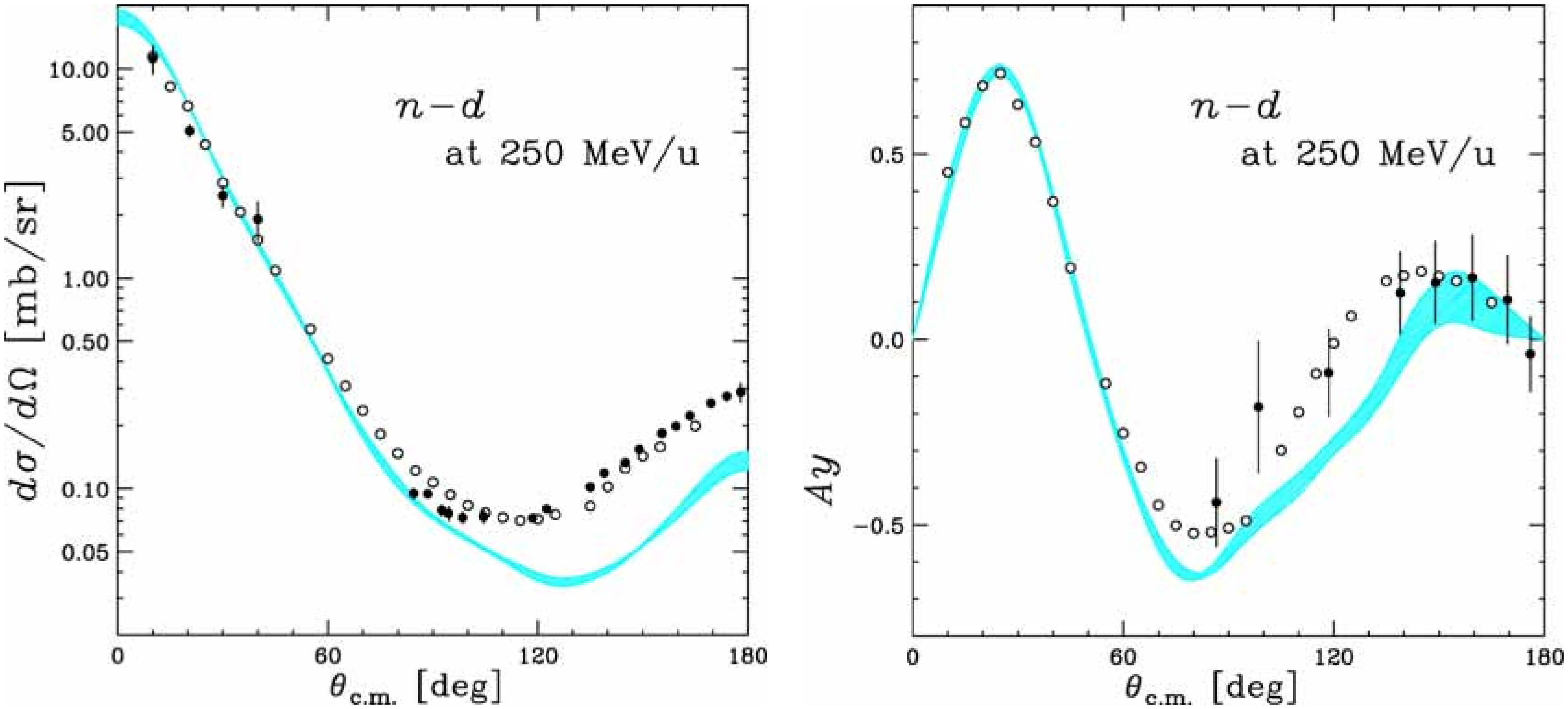
$\vec{p}+d \rightarrow \vec{p}+d$ **at 250 MeV**

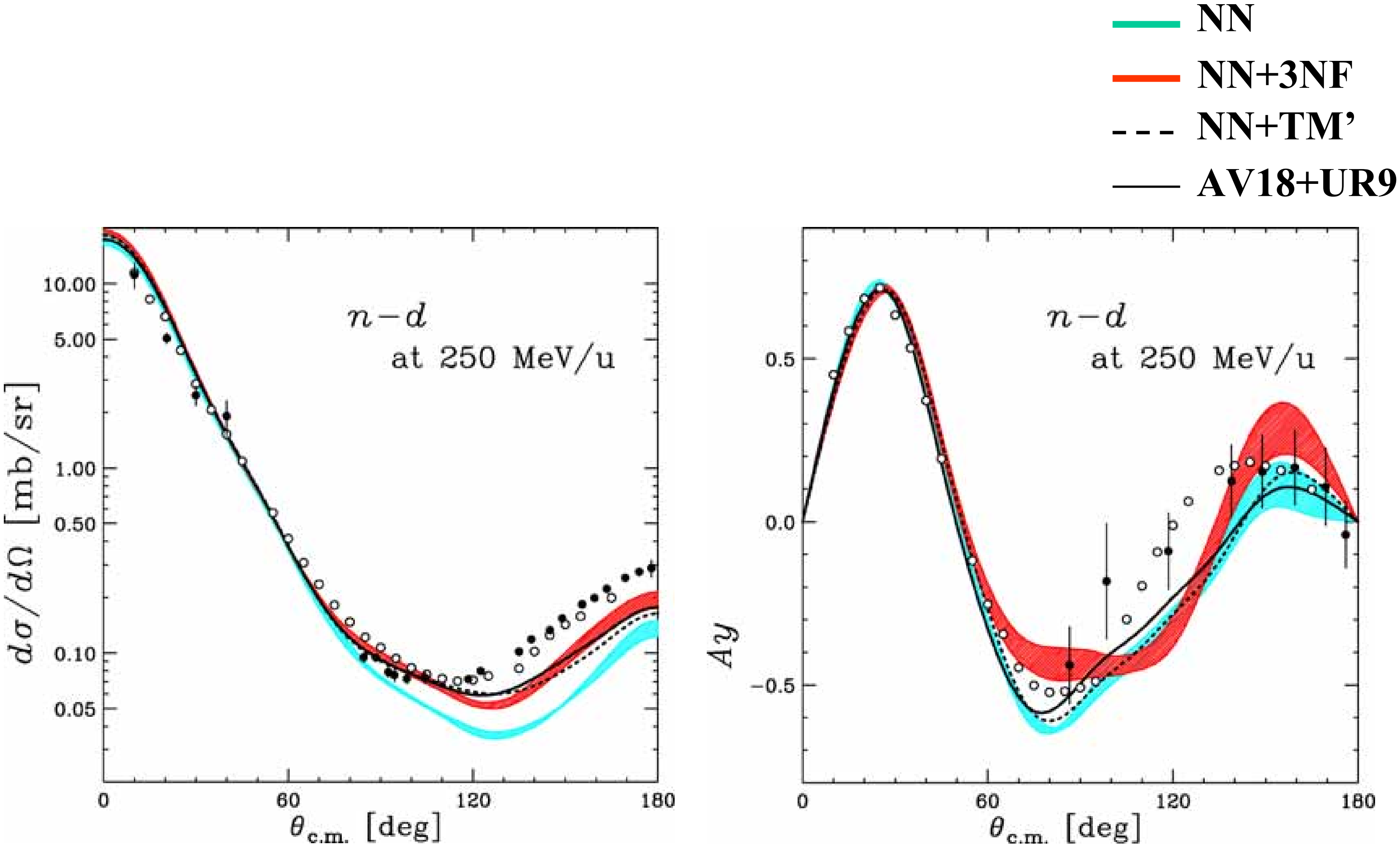
K. Hatanaka *et al.*, Phys. Rev. C66 (2002) 044002.

$\vec{n}$ + d and $\vec{p}$ + d at 250 MeV

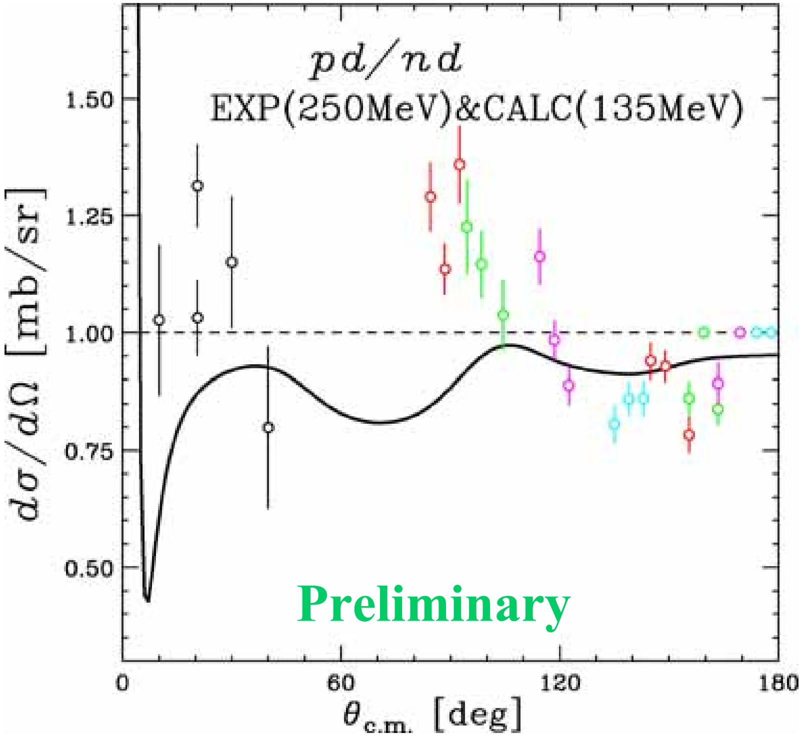


🟩 **NN**


n−d
at 250 MeV/u
$d\sigma/d\Omega$ [mb/sr]
10.00
5.00
1.00
0.50
0.10
0.05
0
60
120
180
$\theta_{\text{c.m.}}$ [deg]
n−d
at 250 MeV/u
Ay
0.5
0.0
−0.5
0
60
120
180
$\theta_{\text{c.m.}}$ [deg]


NN
NN+3NF
NN+TM'
AV18+UR9
n−d
at 250 MeV/u
dσ/dΩ [mb/sr]
10.00
5.00
1.00
0.50
0.10
0.05
0
60
120
180
θc.m. [deg]
n−d
at 250 MeV/u
Ay
0.5
0.0
−0.5
0
60
120
180
θc.m. [deg]

Data-to-data comparison between *nd vs. pd*



$$\frac{\left(\frac{d\sigma}{d\Omega}\right)_{pd}}{\left(\frac{d\sigma}{d\Omega}\right)_{nd}}$$

Coulomb effect ! ?

Calculation by Y. Koike.

***Nd* at 135/u MeV**

Coulomb force is approx. included.

Results at 250 MeV

- First $\vec{n}d$ and $\vec{p}d$ measurements at 250 MeV.
- Data-to-data comparison was m $\vec{n}d$ *vs.* $\vec{p}d$
  - → **10-20 % variation in $d\sigma/d\Omega$**
  - → **Coulomb effect ! ?**
- direct comparison was made:
  - ***nd***. **exp**. data ***vs***. Faddeev calc.
- $d\sigma/d\Omega$: **50%** disagreement in backward.
- A_y : large deviation in backward.

→ defects of 3NF or relativistic effects or both?
OR

→ defects of nucleon exchange process? OR

defects of NN interactions?

How they look like if the energy is doubled ?

400 MeV/u data

at RCNP

$\vec{p}$ + d at 400 MeV (RCNP)

by Tamii

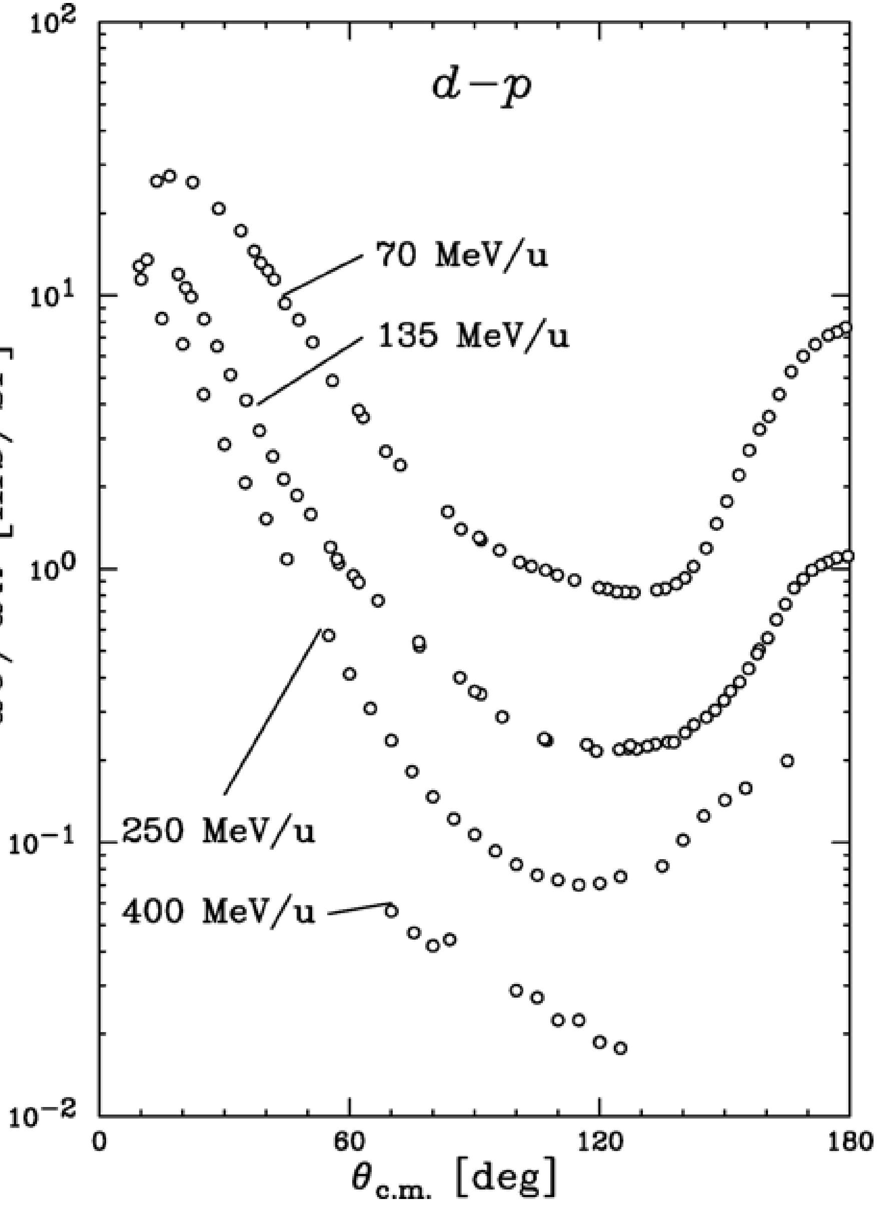
A.Tamii: $\vec{p} + d \rightarrow \vec{d} + p$ at 400 MeV

$d\sigma/d\Omega,\ A_y^{p},\ A_y^{d}\ (= - P^{y'}),\ K_y^{y'}$

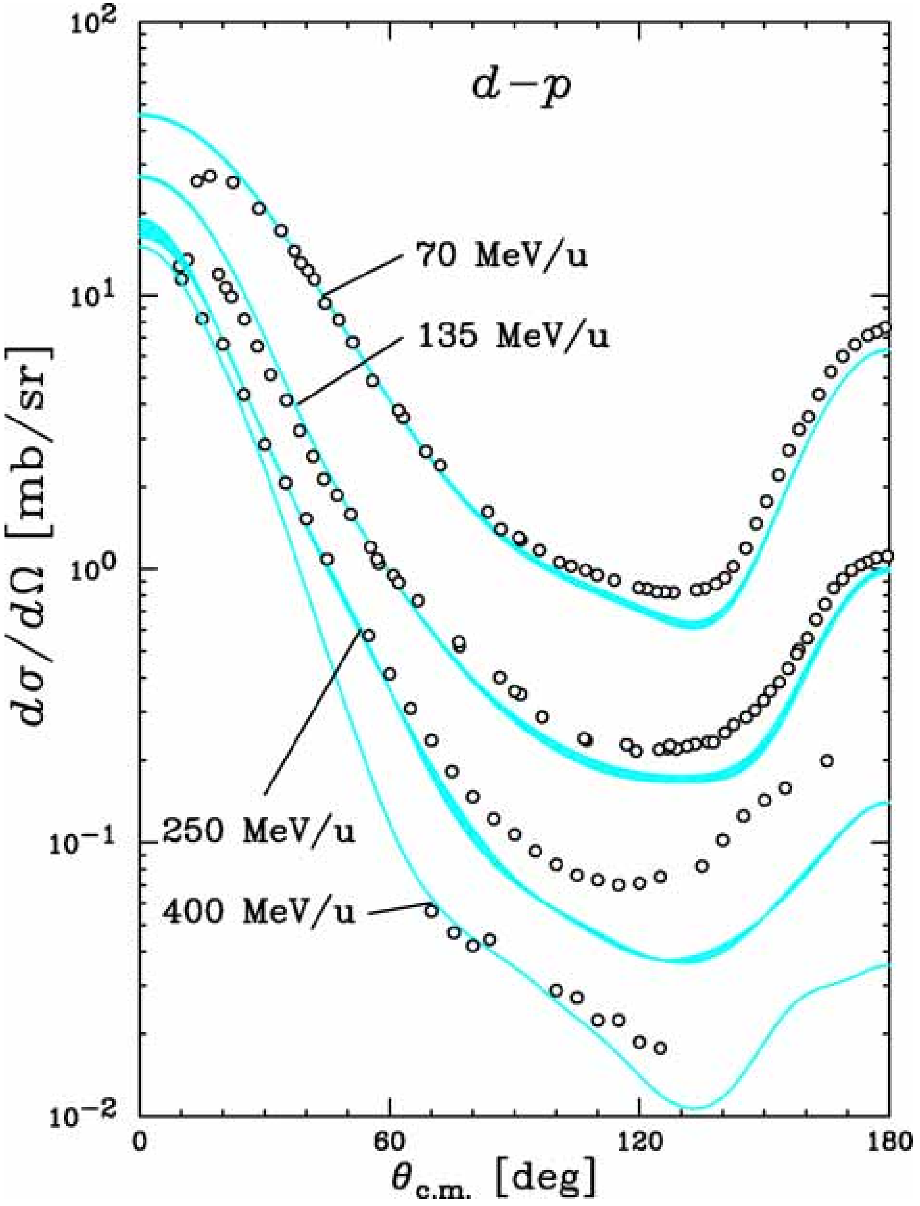
■Limited angular range

Very preliminary calc. by Kamada

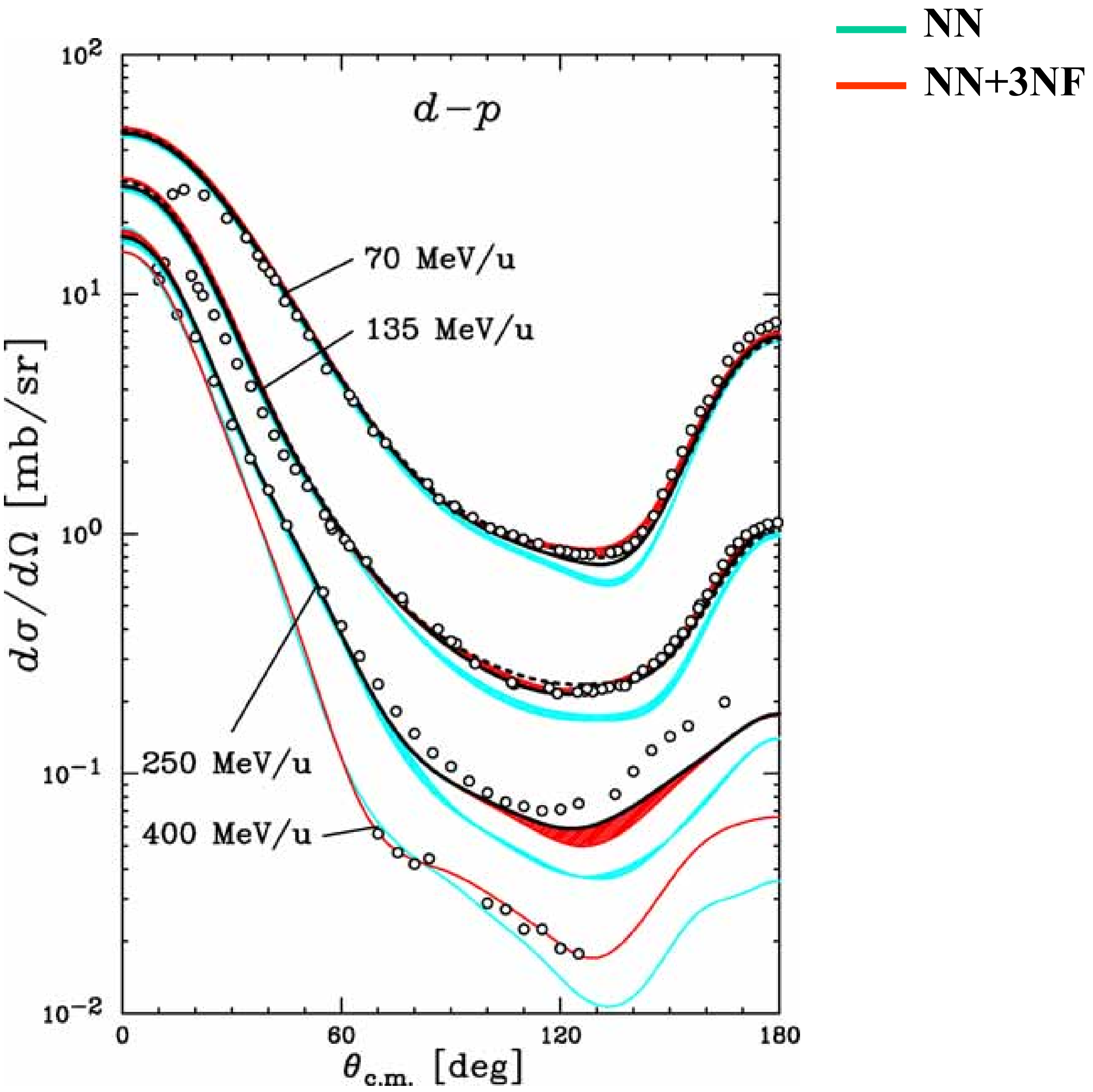
- **2NF : CD Bonn**
- **3NF : TM**


$d-p$
70 MeV/u
135 MeV/u
250 MeV/u
400 MeV/u
$d\sigma/d\Omega$ [mb/sr]
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
0
60
120
180
$\theta_{\rm c.m.}$ [deg]

— **NN**

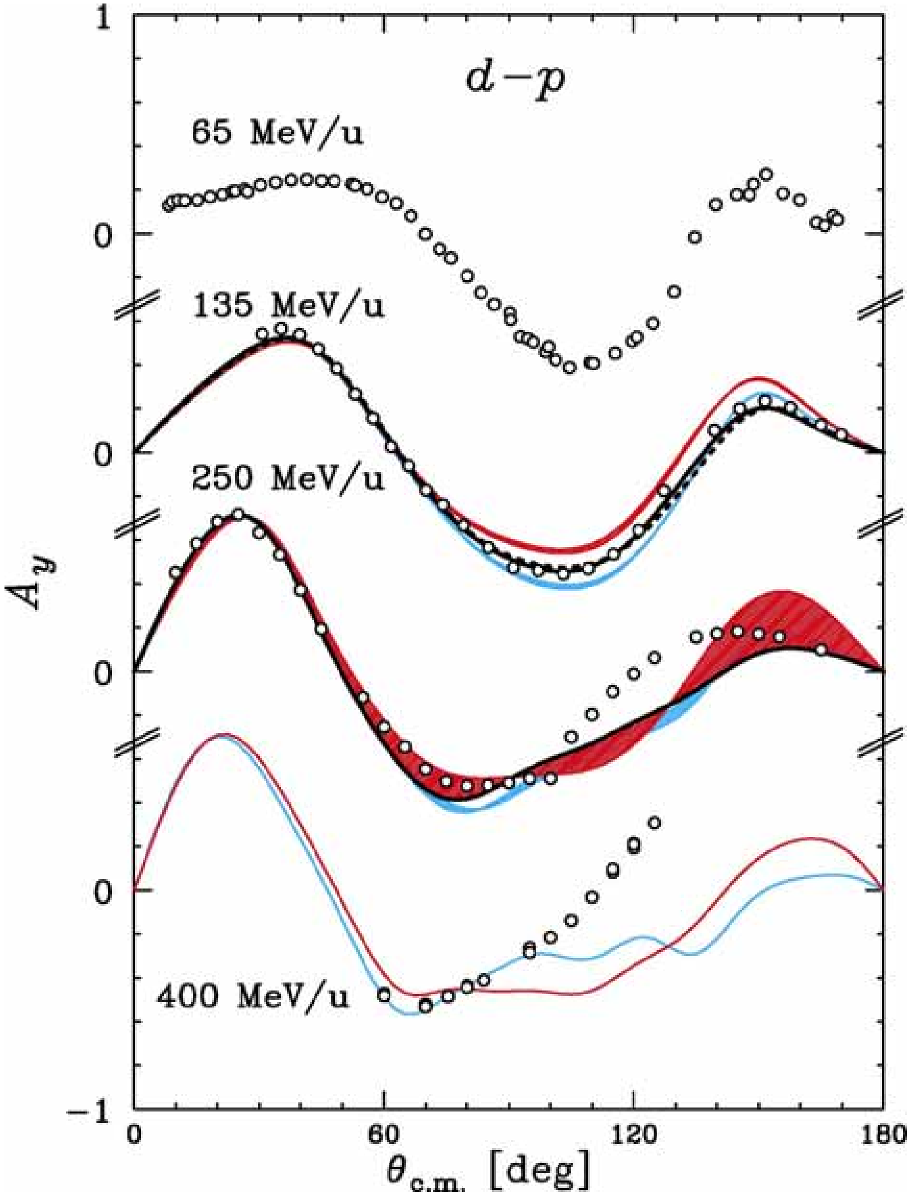


d−p
10^2
10^1
10^0
10^{-1}
10^{-2}
$d\sigma/d\Omega$ [mb/sr]
70 MeV/u
135 MeV/u
250 MeV/u
400 MeV/u
0
60
120
180
$\theta_{\mathrm{c.m.}}$ [deg]


NN
NN+3NF
d−p
70 MeV/u
135 MeV/u
250 MeV/u
400 MeV/u
$d\sigma/d\Omega$ [mb/sr]
$\theta_{\mathrm{c.m.}}$ [deg]
10^2
10^1
10^0
10^{-1}
10^{-2}
0
60
120
180

🟩 NN

🟥 NN+3NF


d−p
65 MeV/u
135 MeV/u
250 MeV/u
400 MeV/u
A_y
1
0
0
0
0
−1
0
60
120
180
$\theta_{\mathrm{c.m.}}$ [deg]

Results at 400 MeV

Calc. by H. Kamada are very preliminary!

- $d\sigma/d\Omega$: agreement?
- A_y^p, $(= -P^{y'})$, iT_{11} : large deviation.

Experimental Summary

- Precise data on $\boldsymbol{p} + \boldsymbol{d}$ elastic scattering at $\mathbf{E}_p = \mathbf{70 - 400\ MeV}$ become available now, not only $d\sigma/d\Omega$, A_y^p, $(= -P^{y'})$, iT_{11}, T_{20}, T_{22}, T_{21} but also various **P**olarization **T**ransfer **O**bservables.

- **A lot of data expected at 135 MeV/u.**
  - *** Spin-correl. data from IUCF.**
  - *** Breakup data from KVI and may be from RIKEN**

  → 135 MeV/u will be the most extensive data set.

Present status of 3NF study

- **3NF established firmly ?**

  →Yes and No.

  →Magnitudes seem to be O.K.

  Spin dependence? Chaotic.

- **Defects of 3NF ?**

  →Yes, in TM.

  The *c* term violates chiral symmetry.

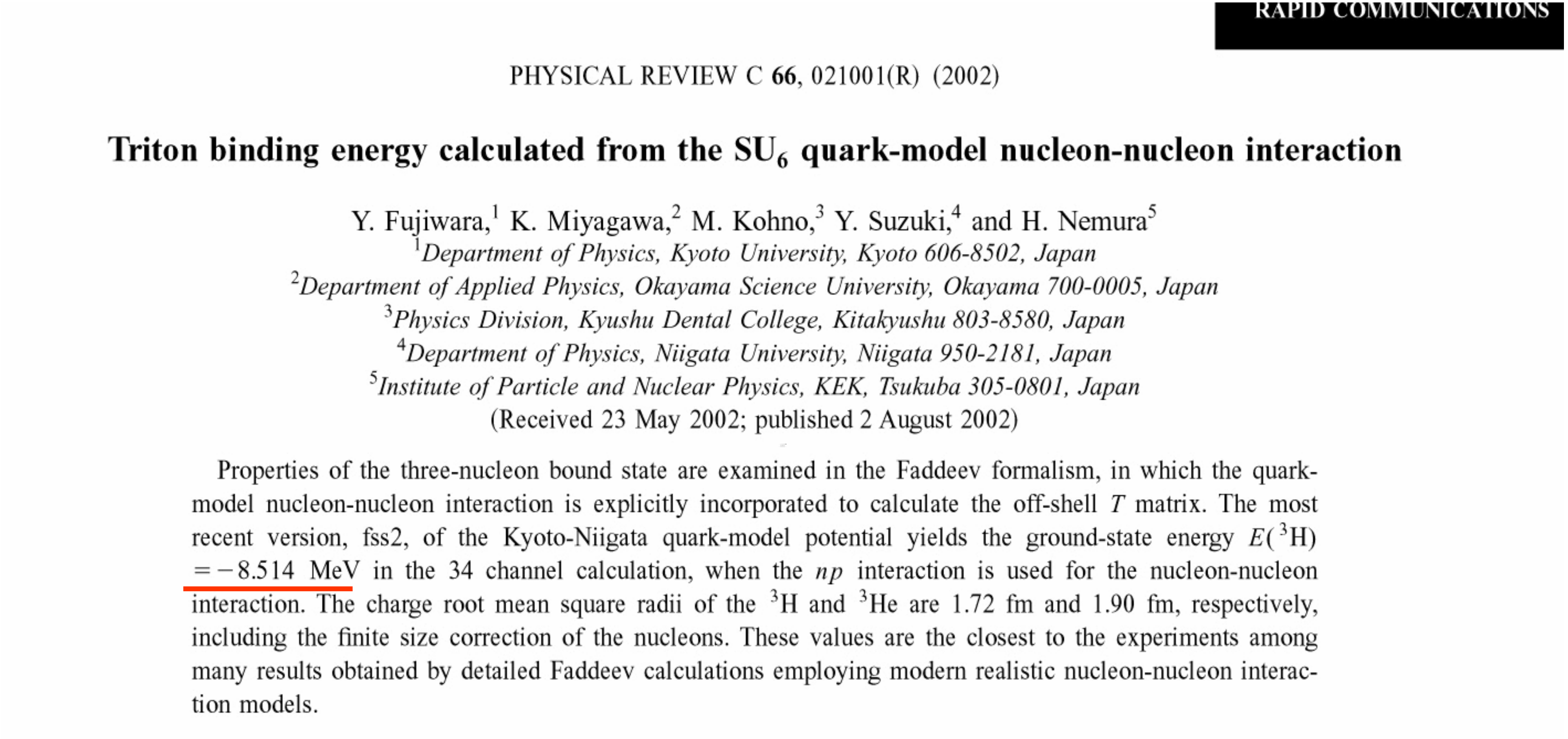
  →Need to include, $\pi\rho$ and $\rho\rho$ exch. 3NF.

- **New development of Chiral Eff. Field Theory calc. is extremely interesting.**

- **Are 2NFs reliable?**

  →Questionable in terms of off-shell properties.

  No need of 3NF in BE(^{3}H) by Y. Fujiwara!



RAPID COMMUNICATIONS

PHYSICAL REVIEW C **66**, 021001(R) (2002)

Triton binding energy calculated from the SU_6 quark-model nucleon-nucleon interaction

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[2]*Department of Applied Physics, Okayama Science University, Okayama 700-0005, Japan*
[3]*Physics Division, Kyushu Dental College, Kitakyushu 803-8580, Japan*
[4]*Department of Physics, Niigata University, Niigata 950-2181, Japan*
[5]*Institute of Particle and Nuclear Physics, KEK, Tsukuba 305-0801, Japan*

(Received 23 May 2002; published 2 August 2002)

Properties of the three-nucleon bound state are examined in the Faddeev formalism, in which the quark-model nucleon-nucleon interaction is explicitly incorporated to calculate the off-shell T matrix. The most recent version, fss2, of the Kyoto-Niigata quark-model potential yields the ground-state energy $E(^3\mathrm{H}) = -8.514$ MeV in the 34 channel calculation, when the np interaction is used for the nucleon-nucleon interaction. The charge root mean square radii of the ^{3}H and ^{3}He are 1.72 fm and 1.90 fm, respectively, including the finite size correction of the nucleons. These values are the closest to the experiments among many results obtained by detailed Faddeev calculations employing modern realistic nucleon-nucleon interaction models.

●Are 2NFs reliable?

→Questionable in terms of off-shell properties.

No need of 3NF in BE(^{3}H) by Y. Fujiwara!

→ Should be tested by scatt. Data.

→Exchange term might be problematic.

Finnaly,

after a century of Tolstoy's novel, the 3NF study has reached a new era of 'the Renaissance'.

This is due to recent harmonious development of both experiments and theories.

I am very happy, if I could convince you such Renaissance after my lecture.

Experiments were carried out under the collaboration of researchers from University of Tokyo, RIKEN, CNS, RCNP, Saitama University, CYRIC and TIT.

This talk is supported by

Kimiko Sekiguchi

Yukie Maeda

for preparing figures.