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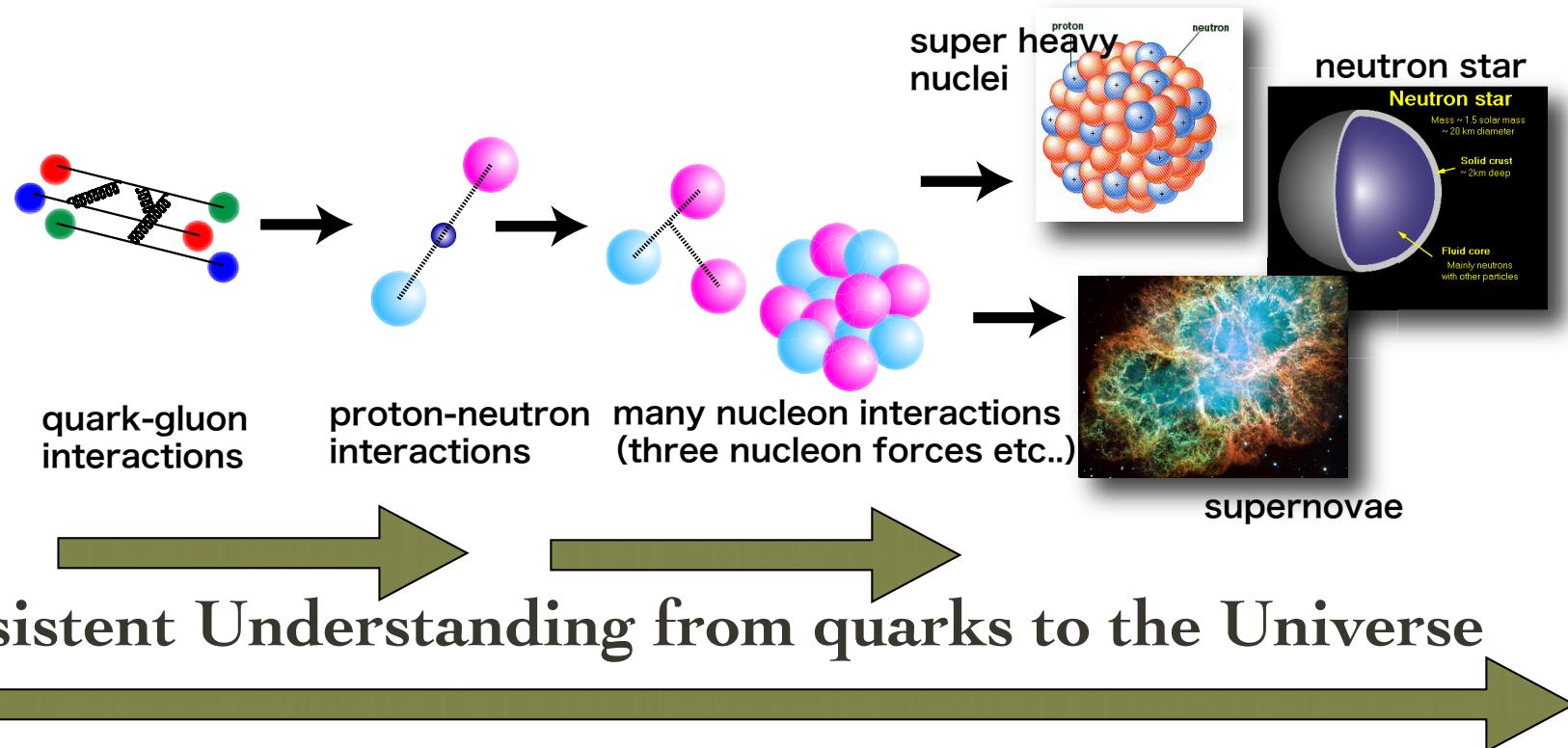
Study of Three-Nucleon Force Effects in p+³He elastic scattering

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Kimiko Sekiguchi**

第四回クラスター階層領域研究会, 2020年5月28日, オンライン

Frontier of Nuclear Force Study

- To understand Nuclear Forces from Quarks (elementary particles)
- To understand Nuclei and Nuclear Matter from bare Nuclear Forces
~ 2NF & 3NF ~



Three-Nucleon Forces in Nucleus

Three-Nucleon Force (3NF)

key element to fully understand properties of nucleus.

- First evidence of 3NF : Binding Energies of Triton (^3H)



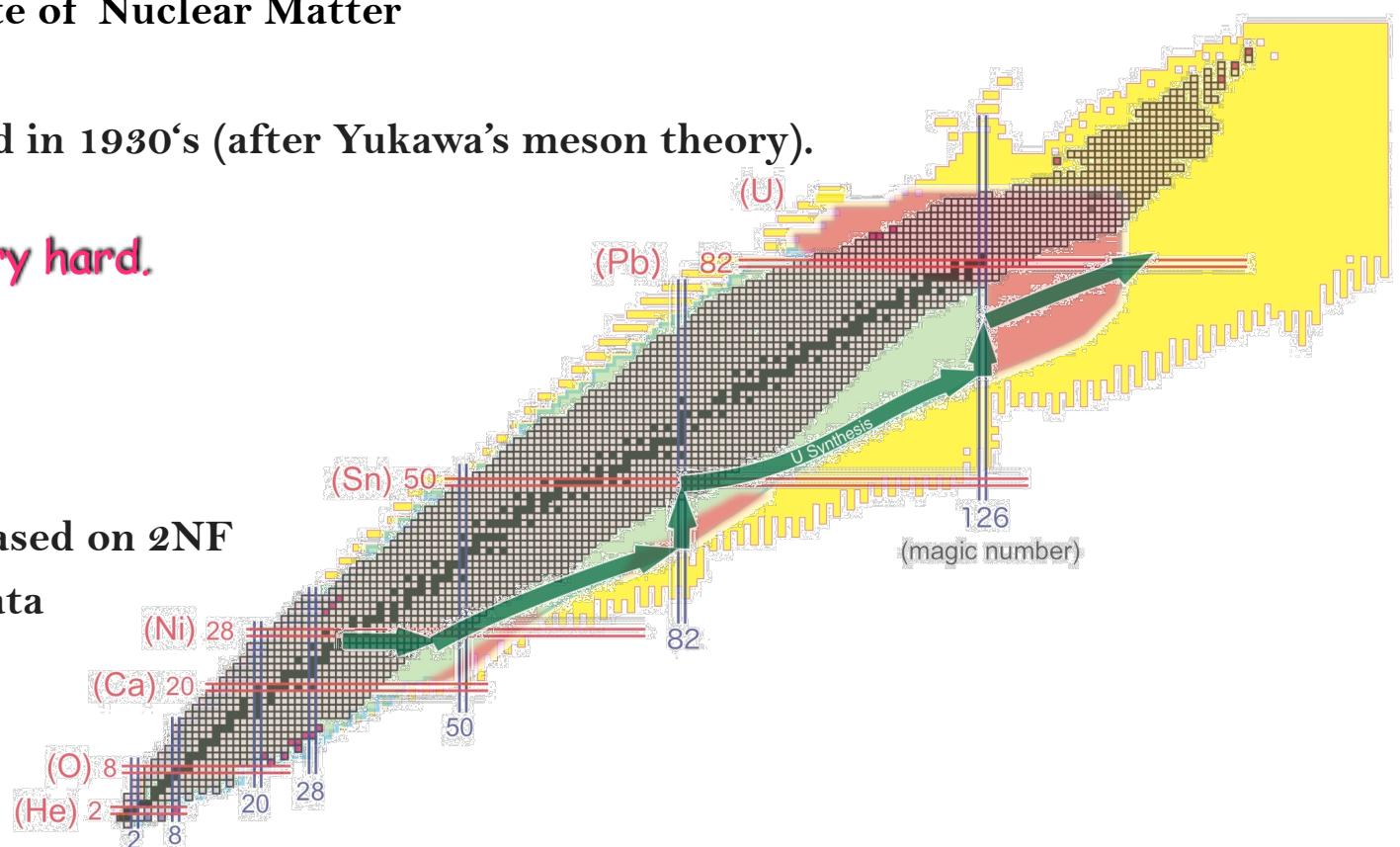
'90~

- Nucleon-Deuteron Elastic Scattering at Intermediate Energies
- Binding Energies / Levels of Light Mass Nuclei
- Equation of State of Nuclear Matter
- etc ...

Existence of 3NF was predicted in 1930's (after Yukawa's meson theory).

To find Evidence of 3NF is very hard.

- 3NF < 2NF
- One needs,
 1. Reliable 2NF
 2. *Ab initio* calculations based on 2NF
 3. Precise experimental data



Three-Nucleon Force (3NF)

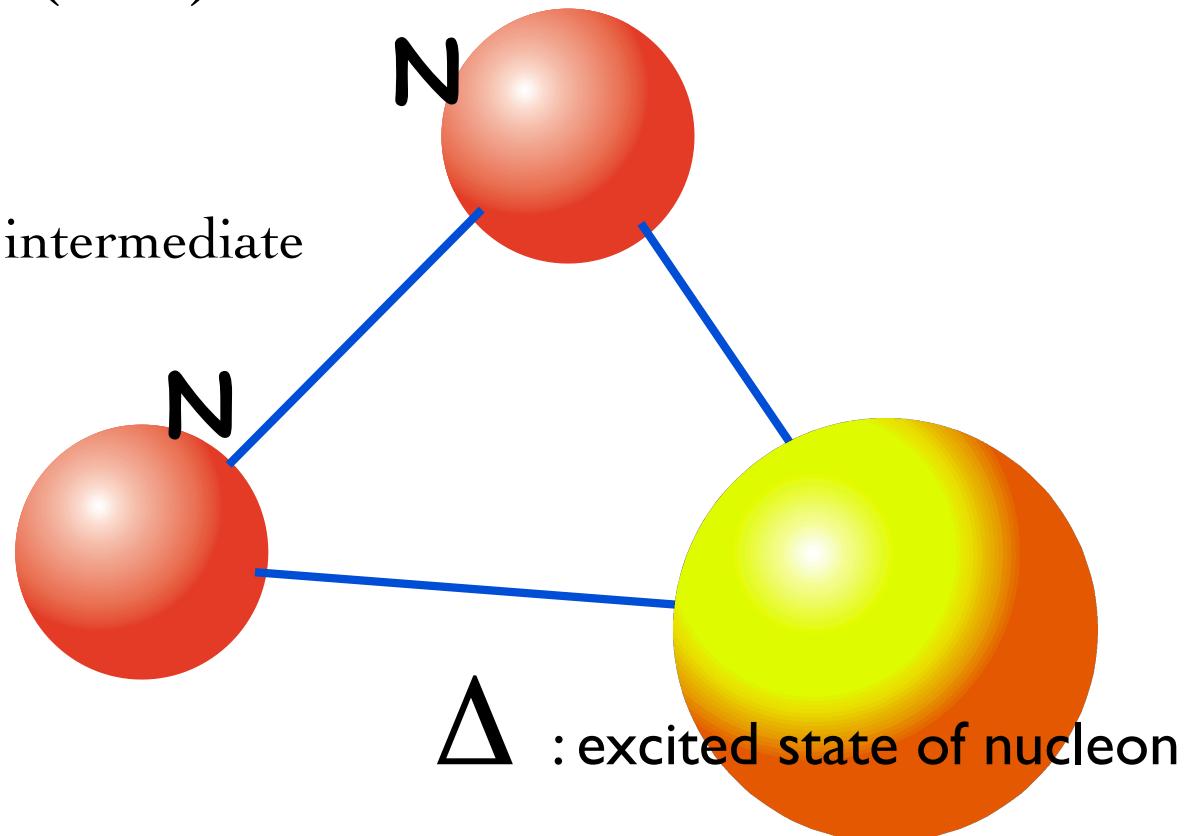
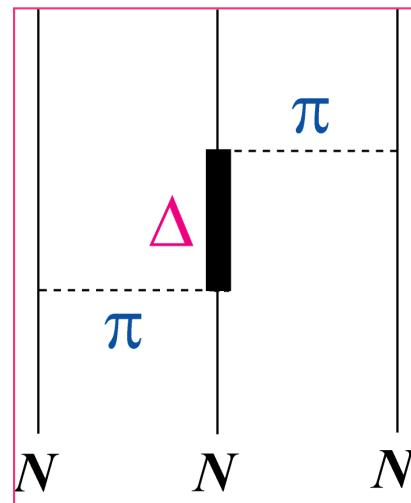
1957 Fujita-Miyazawa 3NF

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



2 π -exchange 3NF :

- Main Ingredients :
 Δ -isobar excitations in the intermediate



$$M_\Delta = 1232 \text{ MeV}$$

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

Three-Nucleon Force (3NF)

1957 Fujita-Miyazawa 3NF

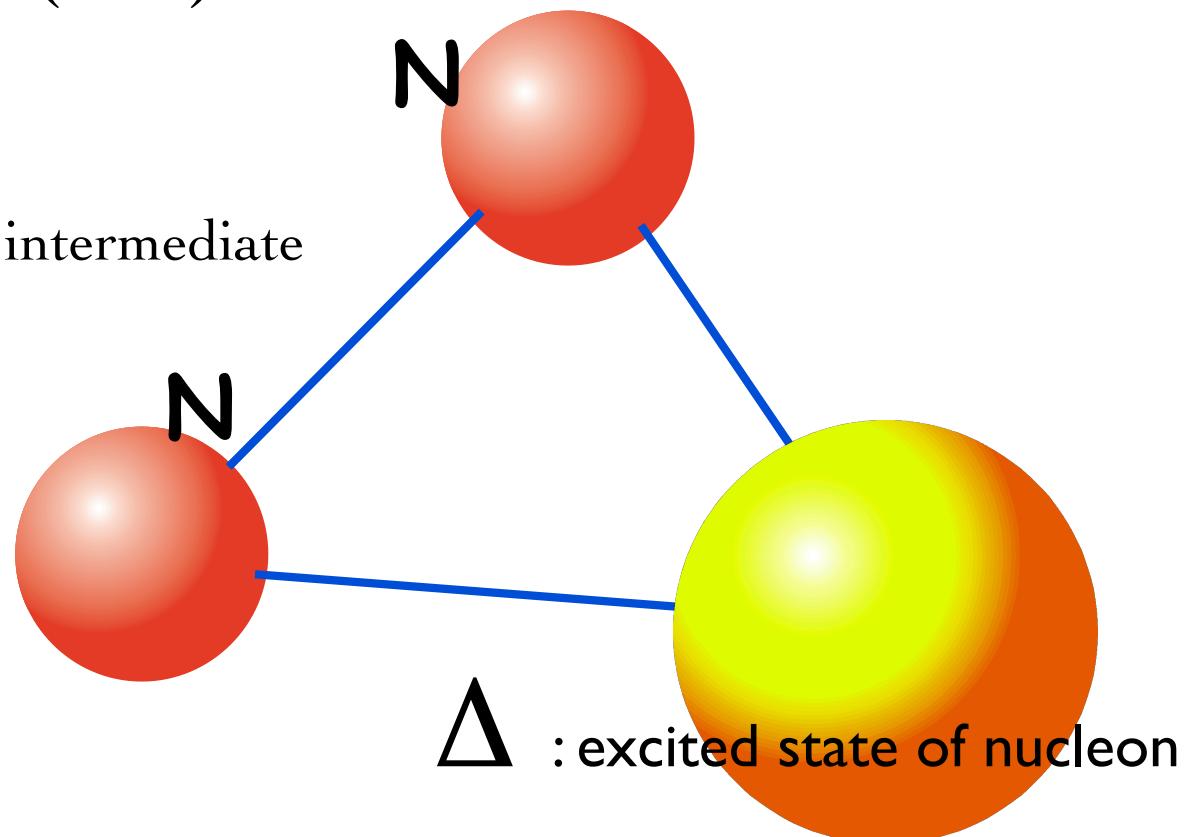
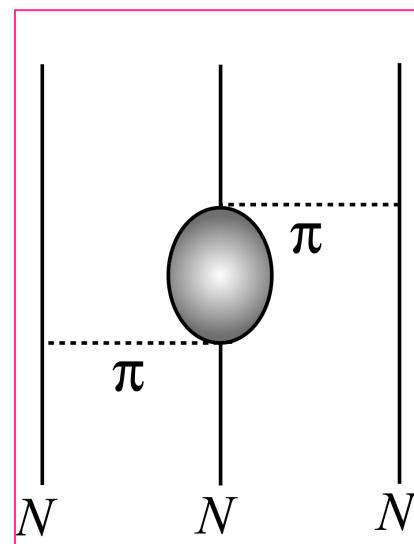
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- ⊕ Tucson-Melbourne (TM)
- ⊕ Urbana IX
- ⊕ Brazil, Texas etc...

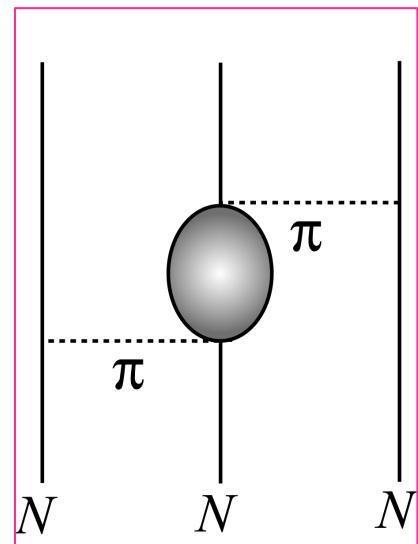
$$M_\Delta = 1232 \text{ MeV}$$
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Three-Nucleon Force (3NF)

1957 Fujita-Miyazawa 3NF

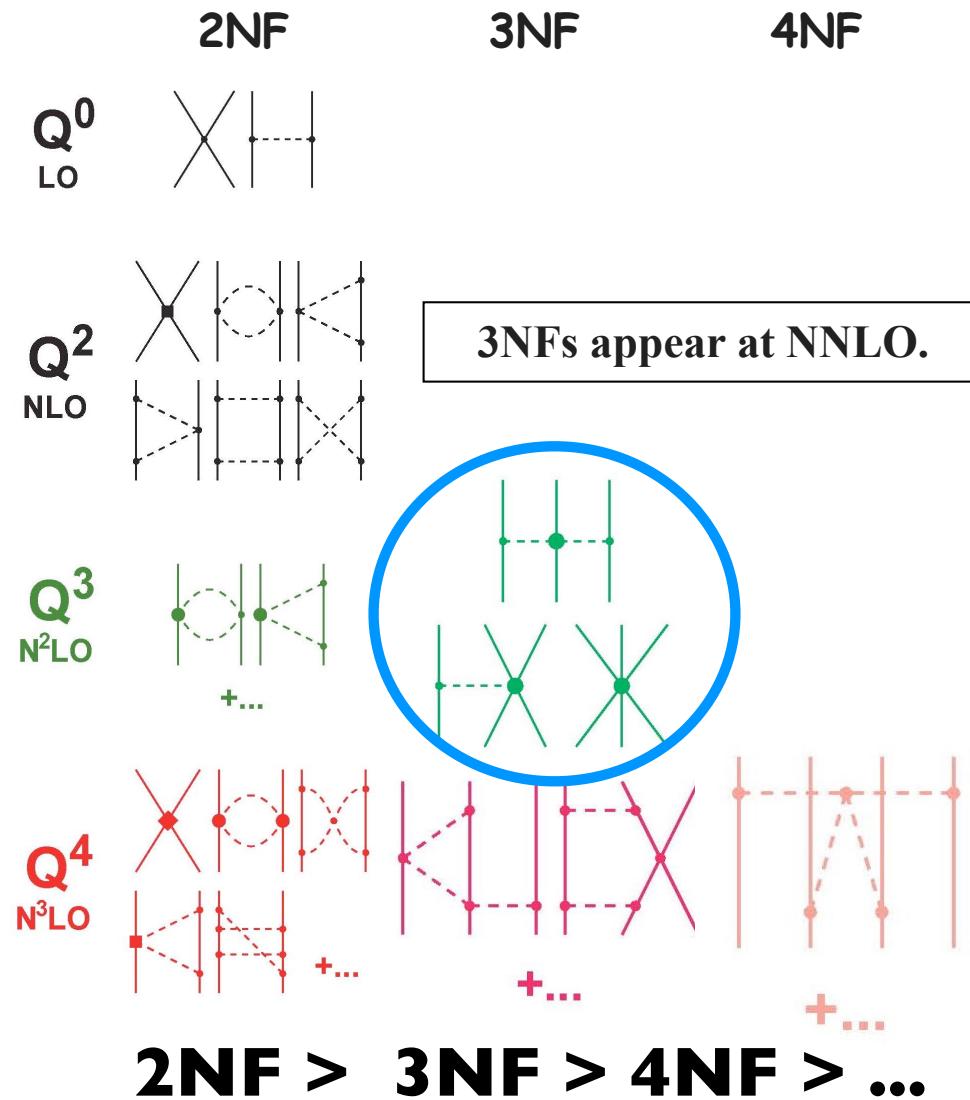
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- 2 π -exchange 3NF :
 - Main Ingredients :
 Δ -isobar excitations in the internal pion loop



- Tucson-Melbourne (TM)
- Urbana IX
- Brazil, Texas etc...

Chiral Effective Field Theory



Few-Nucleon Scattering

a good probe to study the dynamical aspects of 3NFs.

- ✓ Momentum dependence
- ✓ Spin & Iso-spin dependence

Direct Comparison between Theory and Experiment

- Theory : **Faddeev / Faddeev-Yakubovsky Calculations**
Rigorous Numerical Calculations of 3, 4N System

2NF Input

- CDBonn
- Argonne V18 (AV18)
- Nijmegen I, II, 93

3NF Input

- Tucson-Melbourne
- Urbana IX
- etc..

2NF & 3NF Input

- Chiral Effective Field Theory

- Experiment : **Precise Data**
• $d\sigma/d\Omega$, Spin Observables (A_{ij} , K_{ij} , C_{ij})

Extract fundamental information of Nuclear Forces

Summary of Precise Measurement of Few-Nucleon Scattering at RIKEN/RCNP/CYRIC

Nucleon-Deuteron Scattering

RIKEN

RCNP

- 3-nucleon scattering system
- Theory : Large 3NF effects are predicted. Isospin channel : $T=1/2$
- Energy dependent Experimental Results of cross section and analyzing powers : 70-300 MeV/nucleon

*N. Sakamoto et al., Phys. Lett. B 367, 60 (1996), H. Sakai et al., Phys. Rev. Lett. 84, 5288 (2000),
K. S. et al., Phys. Rev. C 65, 034003 (2002), K. S. et al., Phys. Rev. C 70, 014001 (2004),
K. S. et al., Phys. Rev. C 83, 061001 (2011), K. S. et al., Phys. Rev. C 89, 064007 (2014),
K.S. et al., Phys. Rev. C 96, 064001 (2017).*

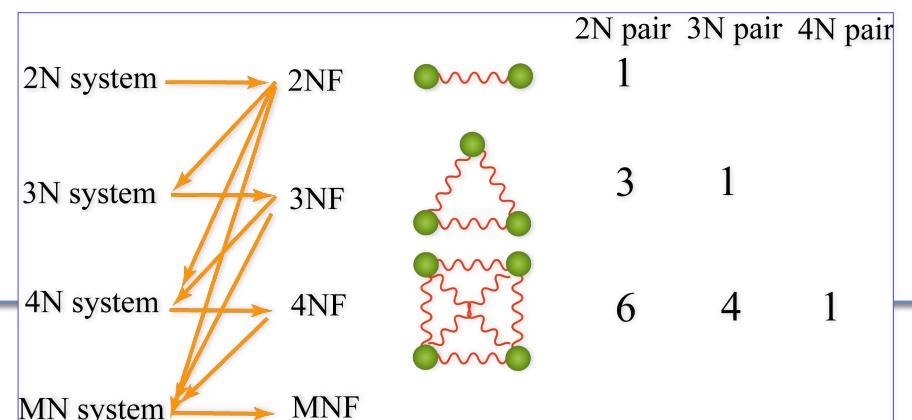
*K. Hatanaka et al., Phys. Rev. C. 66, 044002 (2002) Y. Maeda et al., Phys. Rev. C 76, 014004 (2007)
K. S. et al., Phys. Rev. Lett. 95, 162301 (2005)*

Proton- ^3He Scattering

RCNP

CYRIC

- 4-nucleon scattering system : First step from Few to Many
- Theory : Larger 3NF effects ? Isospin channel : $T=3/2$
- New Data at 65, 100 MeV

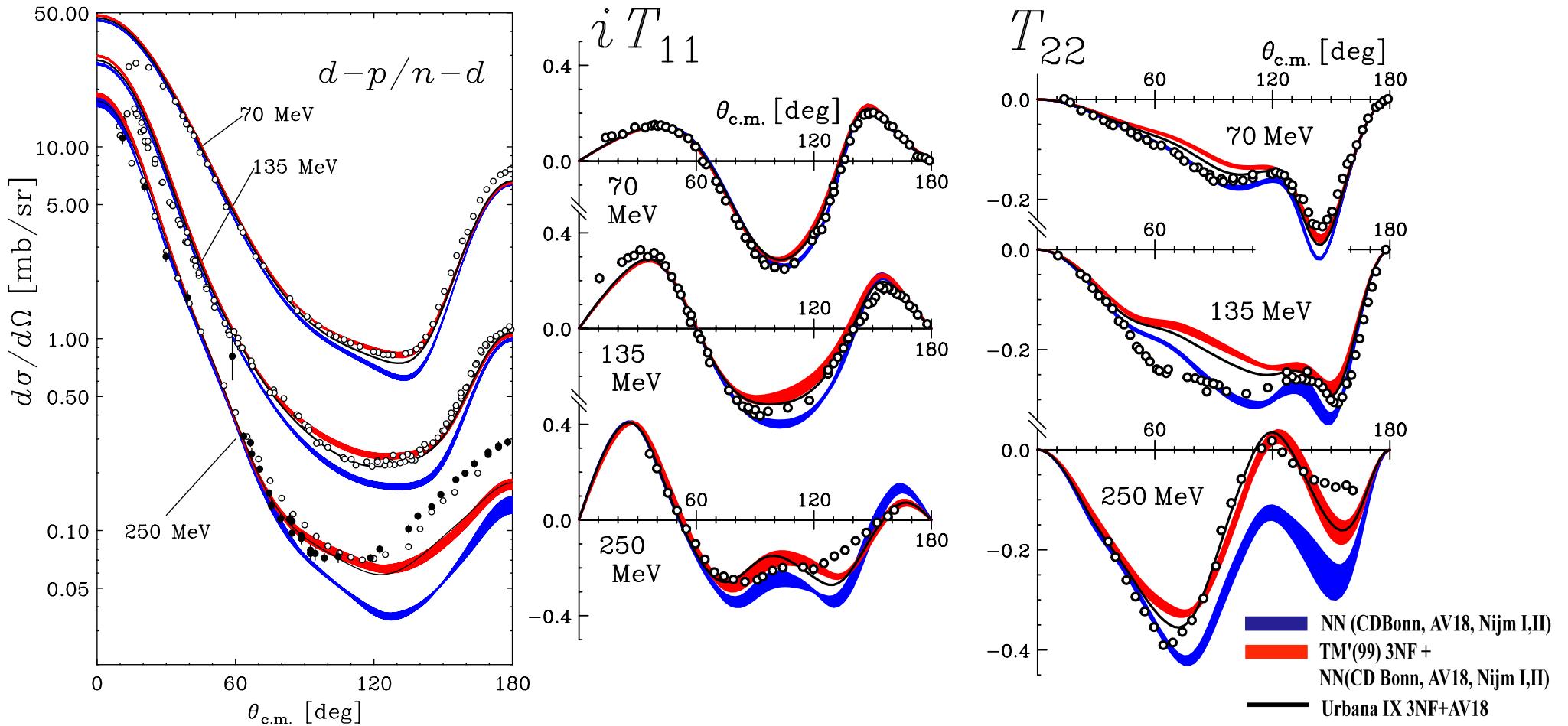


3NF effects in proton-deuteron scattering at 70-250 MeV

K. S. et al., Phys. Rev. C 65, 034003 (2002),
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Y. Maeda et al., Phys. Rev. C 76, 014004 (2007),
K. S. et al., Phys. Rev. C 89, 064007 (2014) etc...

Solid base for study of detailed properties of 3NFs

- Clear signatures of 3NF Effects in the cross section minimum.
- 3NF effects become larger with increasing an incident energy.
- Spin dependent parts of 3NFs are deficient.



Summary of Precise Measurement of Few-Nucleon Scattering at RIKEN/RCNP/CYRIC

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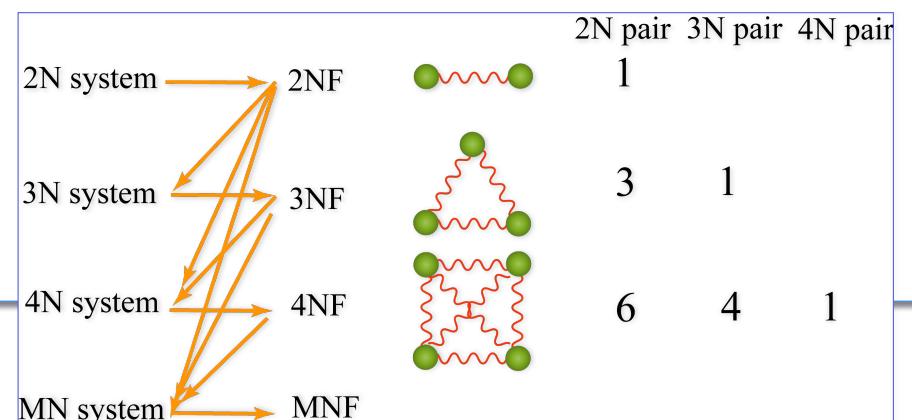
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Proton- ^3He Scattering

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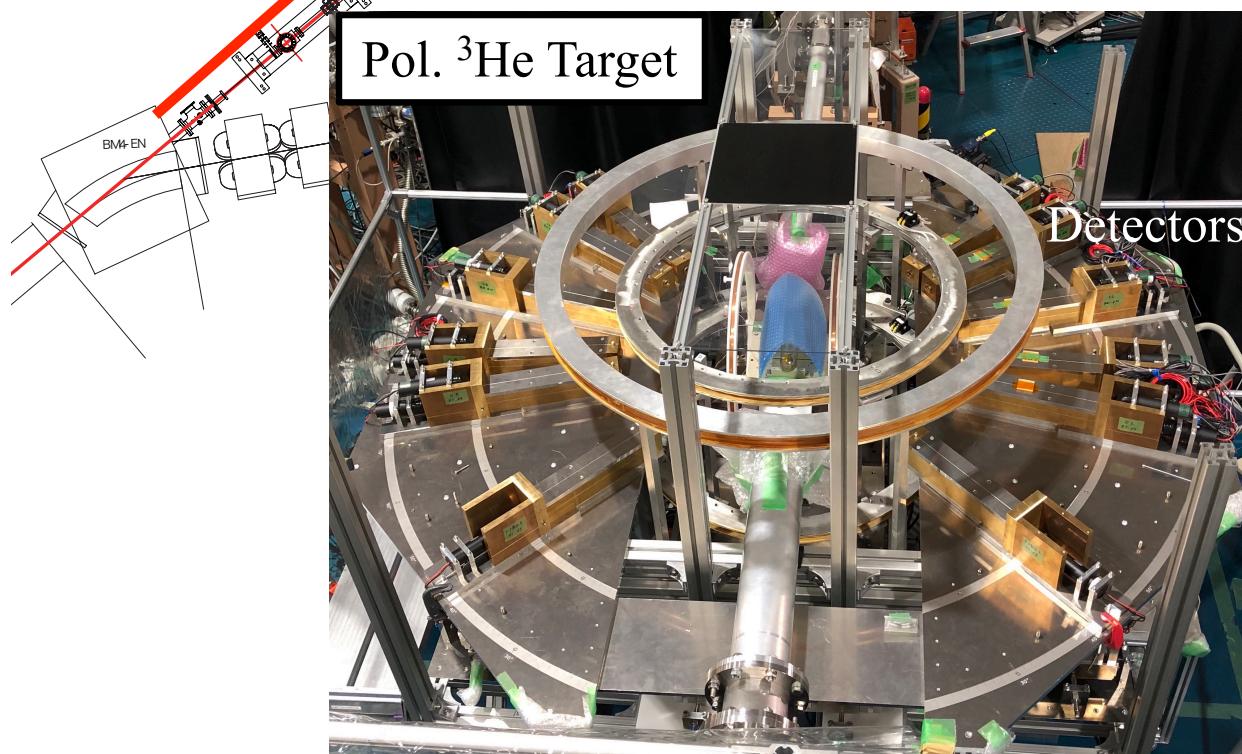


pol.p+pol. ${}^3\text{He}$ experiment at RCNP

pol. ${}^3\text{He}$ Target

pol. p beam

Pol. ${}^3\text{He}$ Target



ENN course

QM9-ENN

QM10-ENN

Faraday Cup

Beam Line Polarimeter

- Polarized p at 65, 100 MeV
 - Polarization : 40-50 %
 - B.I. = 10 - 30 nA

- Target : pol. ${}^3\text{He}$ gas target
 - polarization : 30-40%

- Observables :

$A_y(p)$, $A_y({}^3\text{He})$, $C_{y,y}$

- Measured Angles

$$\theta_{\text{c.m.}} = 47^\circ - 156^\circ$$

First high precision data set
at intermediate energies

- Detectors

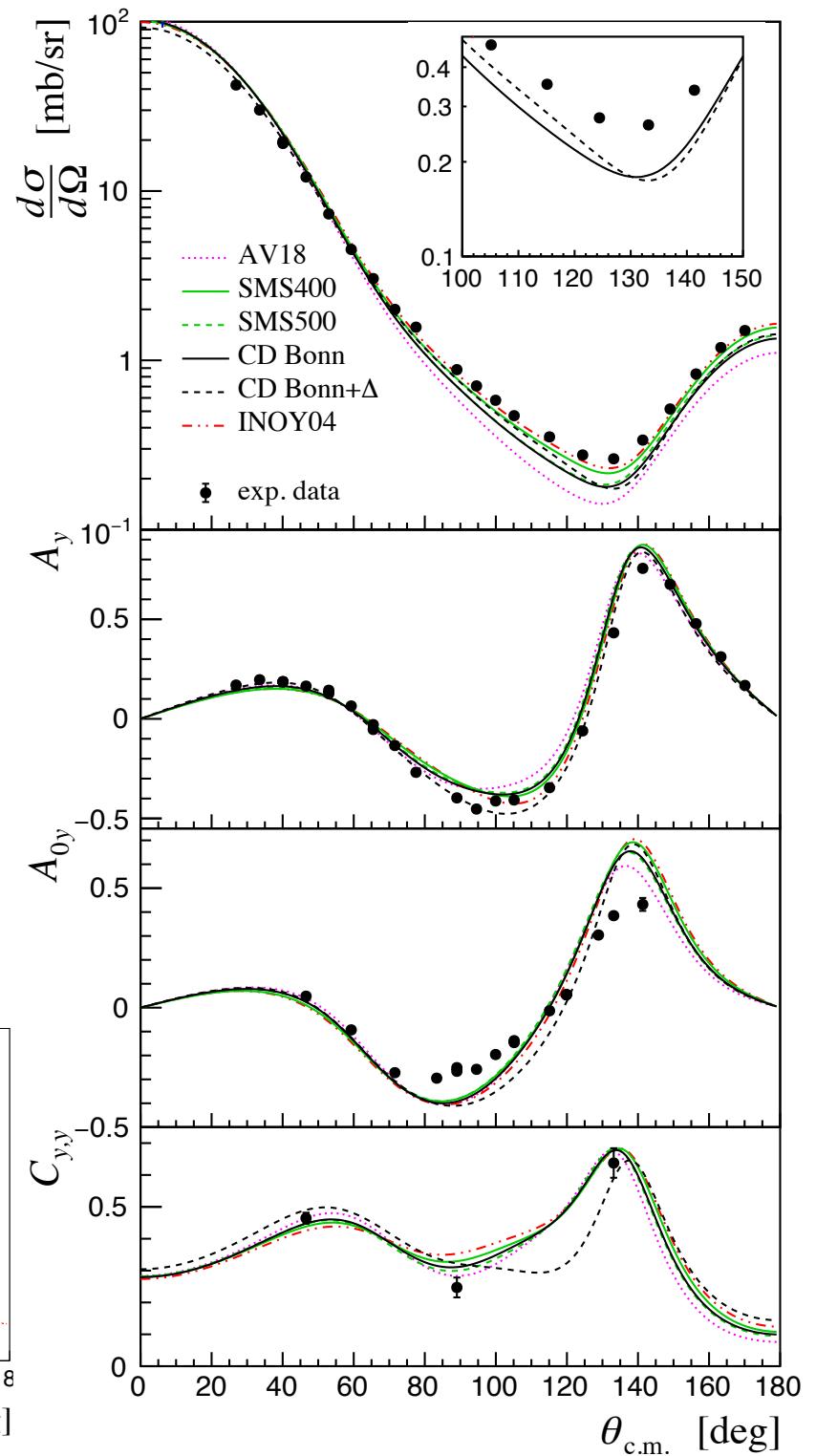
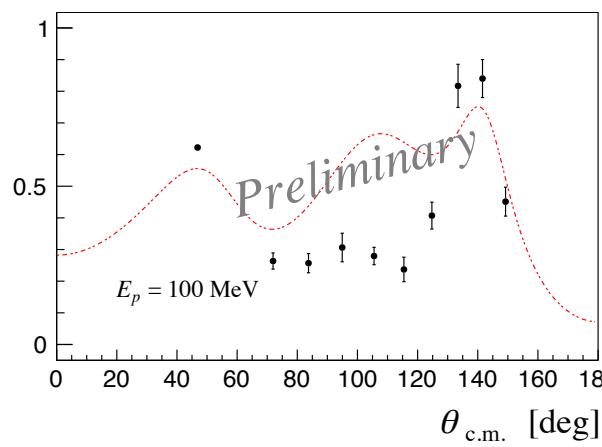
dE : Plastic Scintillator (0.5 mm t)

E : NaI(Tl) (55 mm t)

2 sets \times 6 angles = 12 sets

$p + {}^3\text{He}$ at 65 MeV

- Cross section minimum
 - rich sources to provide new features of nuclear interactions including 3NFs
- different features from Nd scattering
NN dependence
 Δ -isobar effects (3NFs)

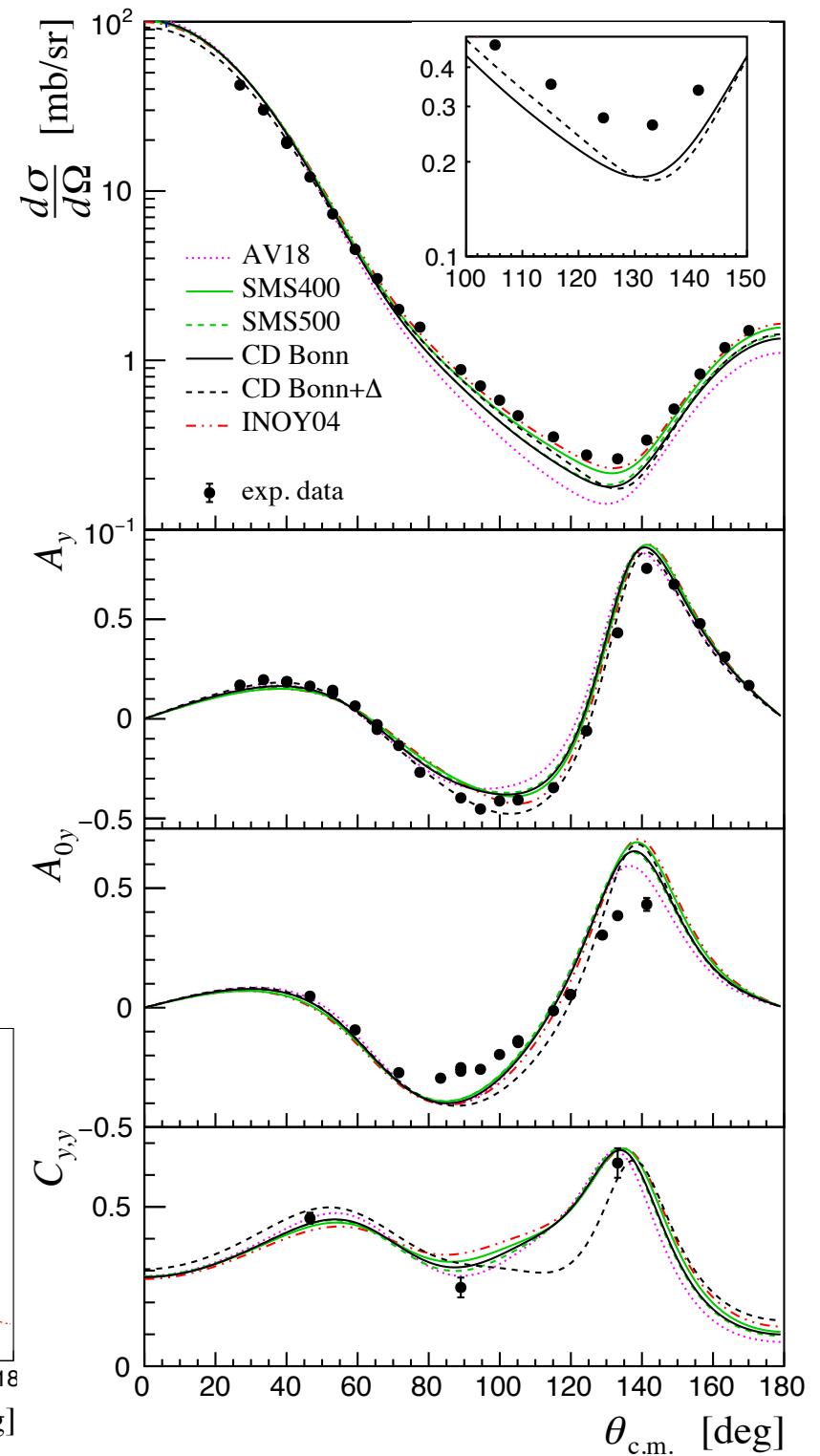
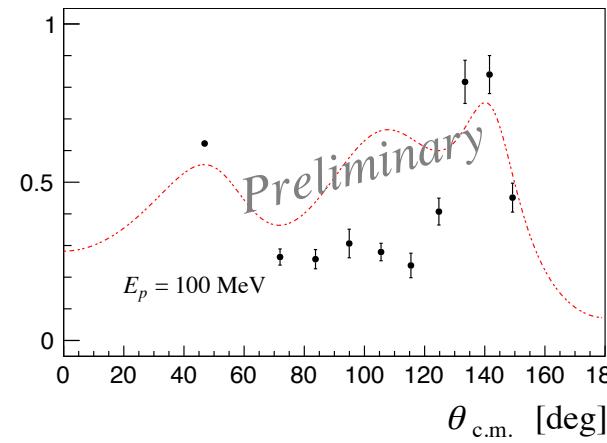


$p + {}^3\text{He}$ at 65 MeV

- Cross section minimum
 - rich sources to provide new features of nuclear interactions including 3NFs
- different features from Nd scattering

NN dependence
 Δ -isobar effect (3NFs)

High precision A_{0y} data
Watanabe, Ph.D thesis
Tohoku Univ. President Award



Summary (1/2)

Three-Nucleon Forces

are key elements to fully understand nuclear properties.
e.g. nuclear binding energies, EOS of nuclear matter

Few-Nucleon Scattering

is a good probe to investigate the dynamics of 3NFs.
- Momentum, Spin & Iso-spin dependence - .

Proton- ^3He Scattering - 4N Scattering -

- Approach to Iso-spin states of $T=3/2$ 3NF
- Rigorous numerical calculations : New possibilities for 3NF study in 4N Scatt.

New Data from CYRIC & RCNP : ^3He & p Analyzing powers, & Spin Correlation Coefficient

Cross section minimum region at 65 MeV : Source of rich information of 3NFs

Spin correlation coefficient : Very sensitive to dynamics of Nuclear forces

Very probably new features of nuclear interactions including 3NFs
which could not be accessible by Nd elastic scattering

Summary (2/2)

Future Plan

Determine 3NFs from Few-nucleon scattering experiments

- $p\text{-}{}^3\text{He}$ Scattering : Complete set of spin observables & Energy dependence
- Nucleon-Deuteron Scattering : Spin Correlation Coefficients

Study of 3NF effects in Nuclear Reaction (Spokesperson : T. Wakasa)

It could be interesting ...

How and Where 3B-Forces are defined / appear
in other hierarchical structures.

p-³He Collaboration

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K. Sekiguchi, Y. Wada, Y. Shiokawa, A. Watanabe, S. Nakai, K. Miki,
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Miyazaki University

Y. Maeda, K. Nonaka

RIKEN Nishina Center

H. Sakai, T. Uesaka

NIRS

T. Wakui

