

Measurements of the differential cross sections for pd inclusive breakup reactions at 230MeV for the study of elementary process of deuteron knock-out reactions

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Contents

- Introduction
Review of previous pd breakup reaction measurements for three-nucleon force study
- Motivation
 pd breakup reaction as an elementary process of (p, pd) knockout reaction
- Experiment
Recent measurements of $d(p, p')pn$ at RCNP



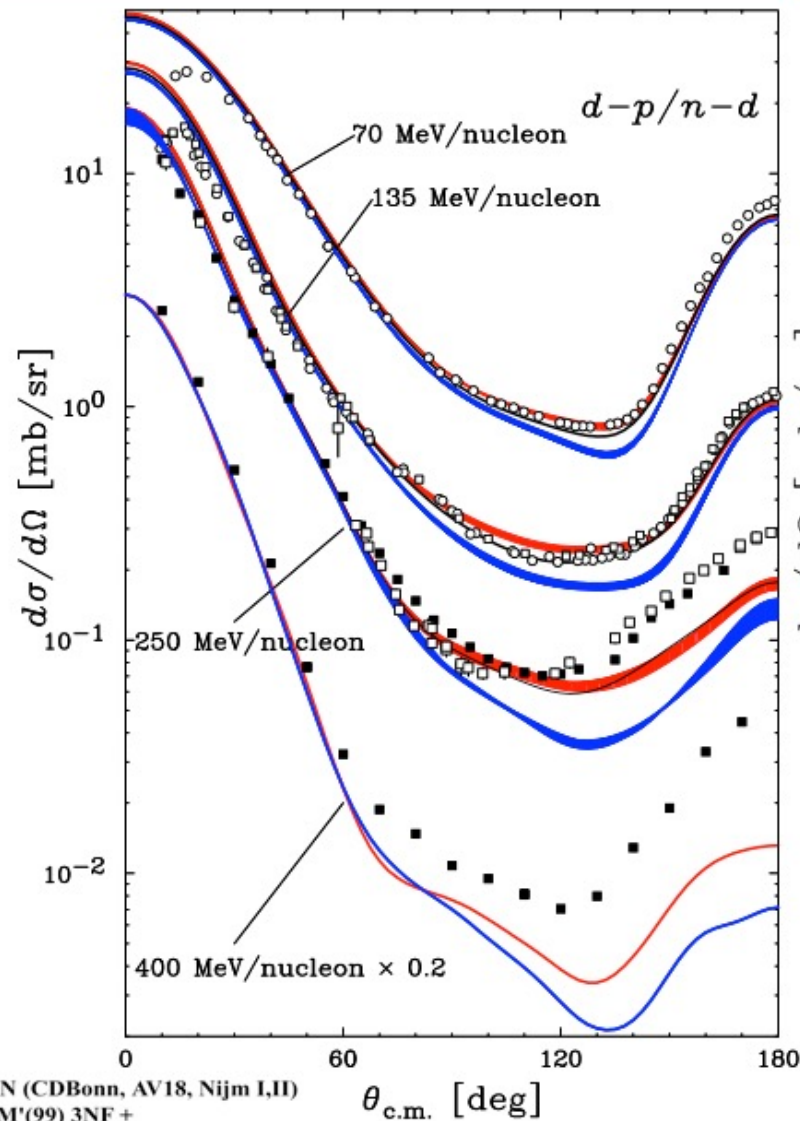
Contents

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- pd breakup reaction as an elementary process of (p, pd) knockout reaction
- Recent measurements of $d(p, p')pn$ at RCNP

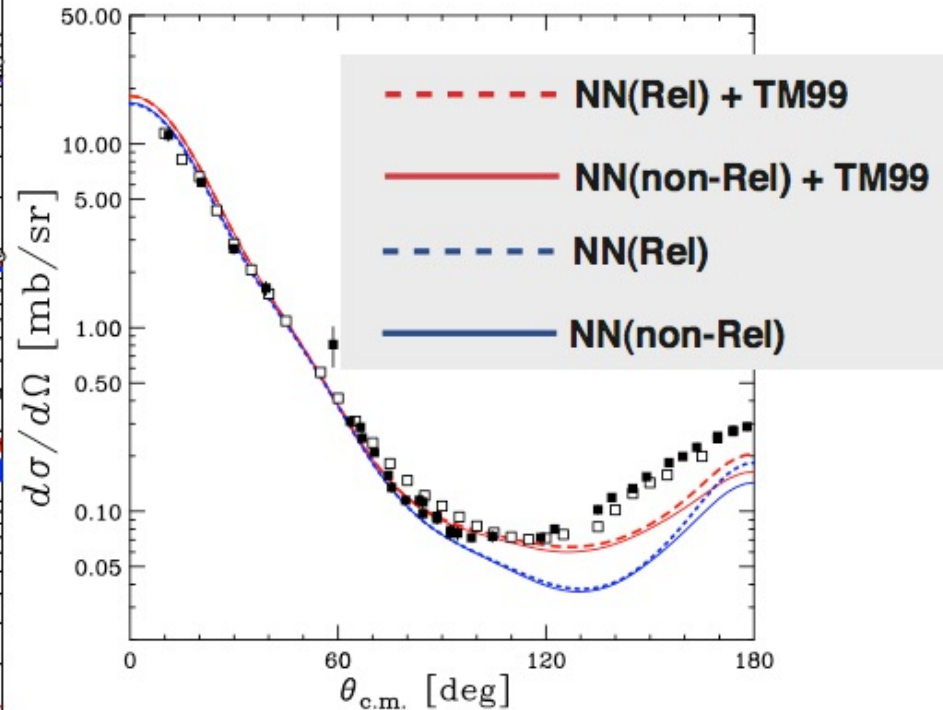


Differential Cross Section at 70 - 400 MeV/nucleon

Relativistic Faddeev Calculations
with TM'99 3NF



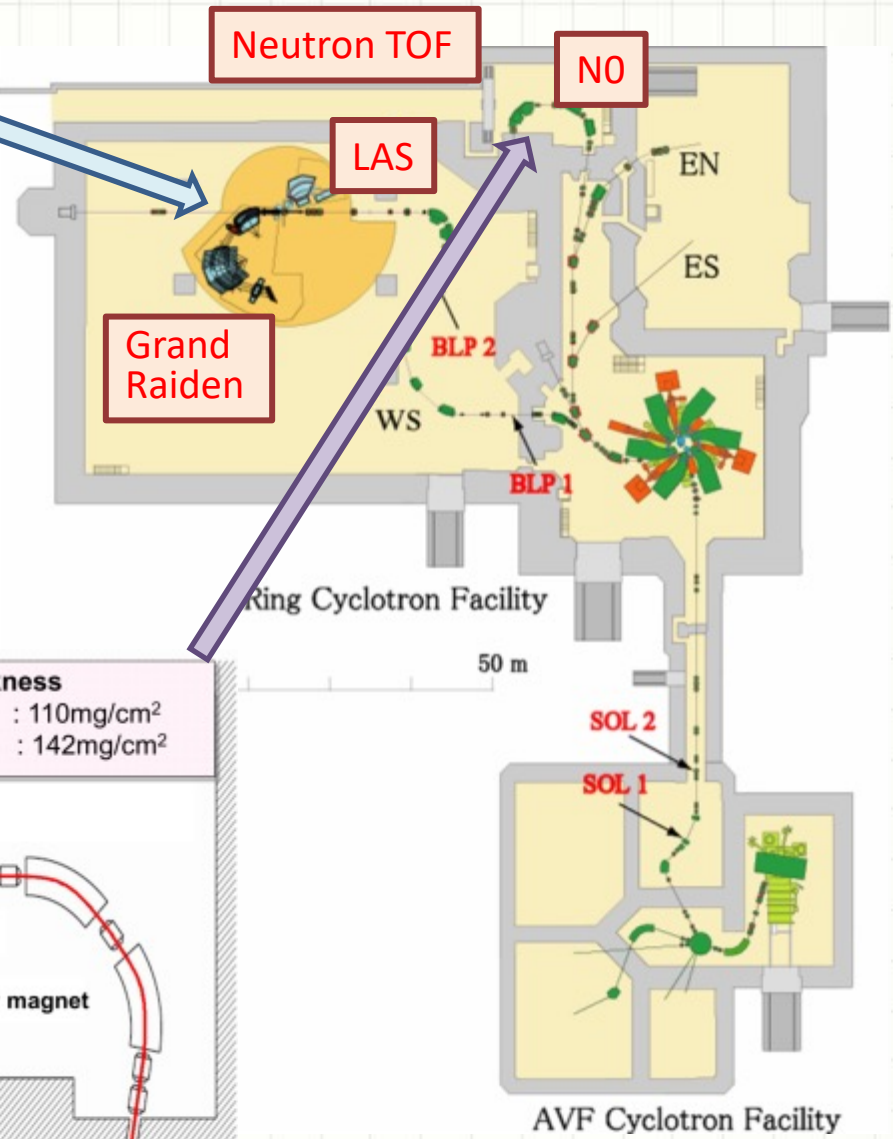
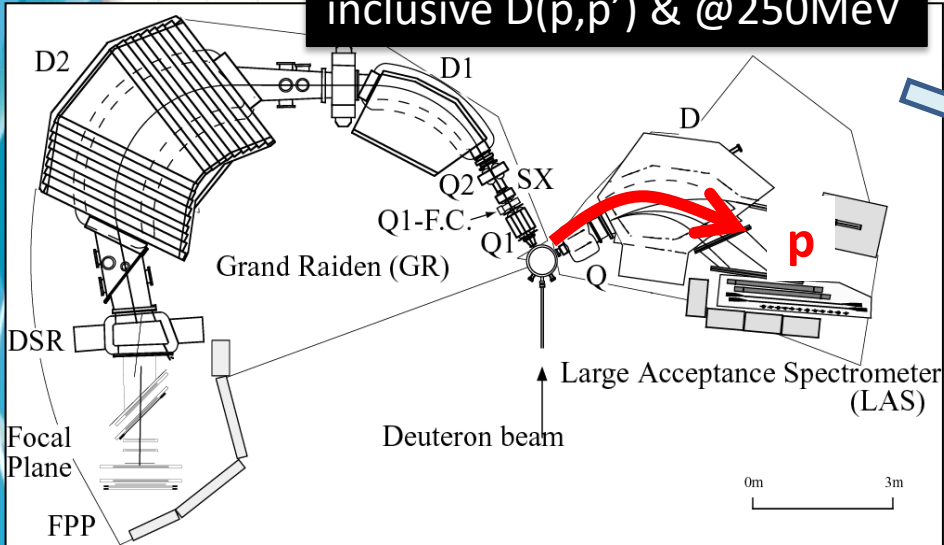
pd/nd @ 250 MeV



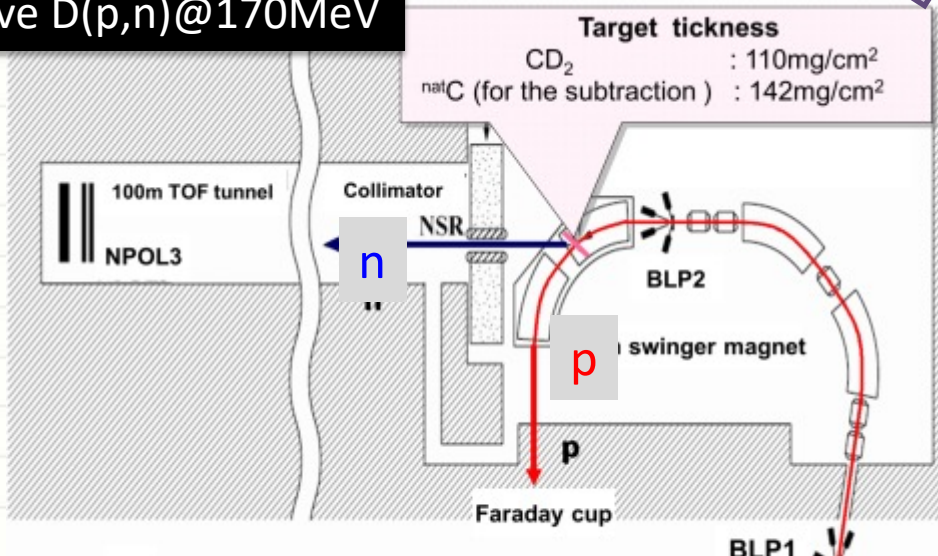
Relativistic effects are visible
at backward angles, but small.

pd inclusive breakup (BU) meas. @ RCNP

inclusive $D(p,p')$ & @250MeV



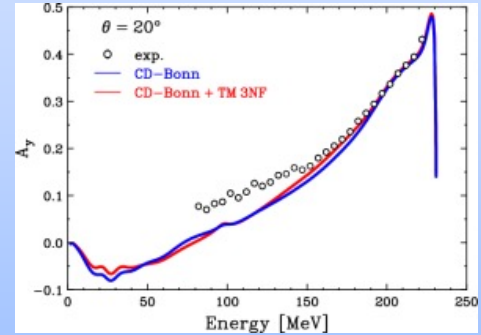
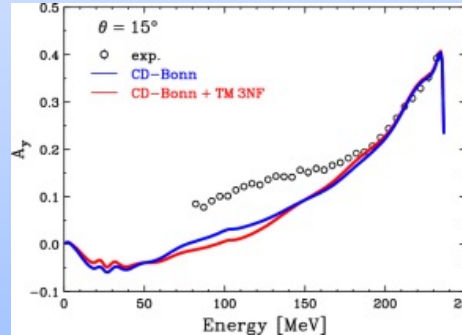
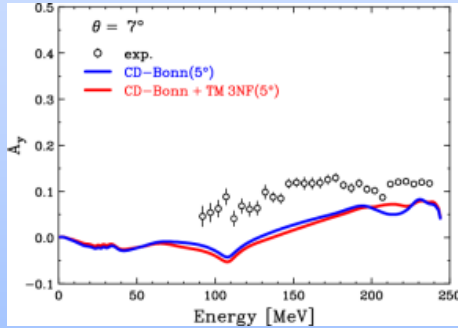
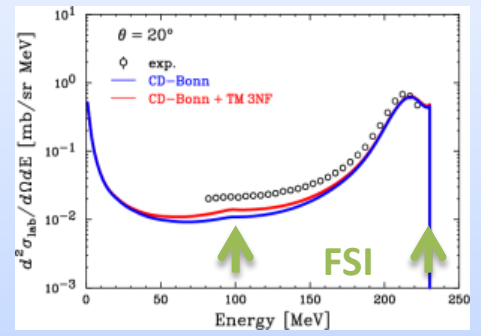
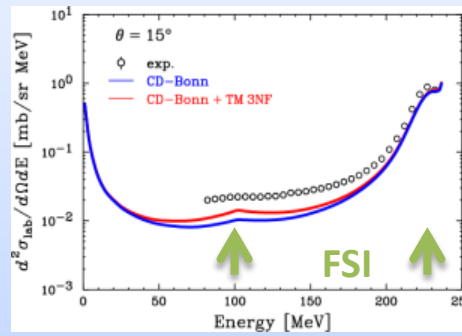
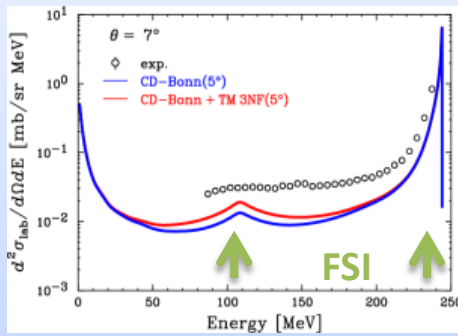
inclusive $D(p,n)$ @170MeV



$D(p,p)pn$ & $D(p,n)pp$ inclusive breakup

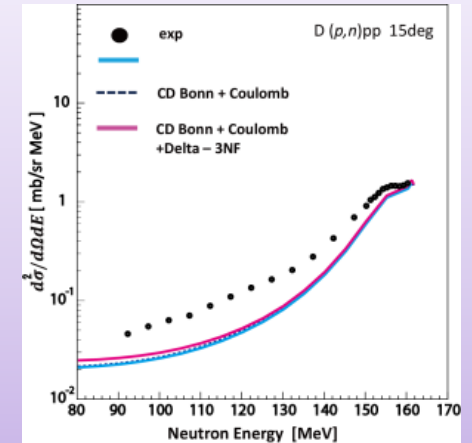
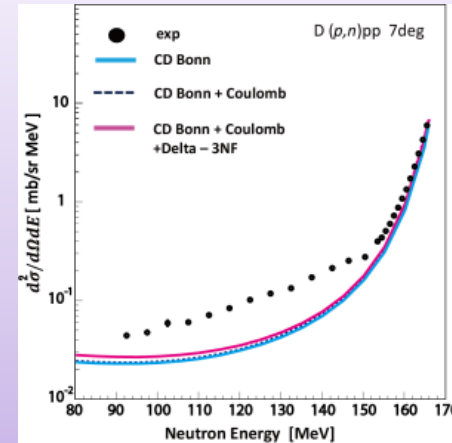
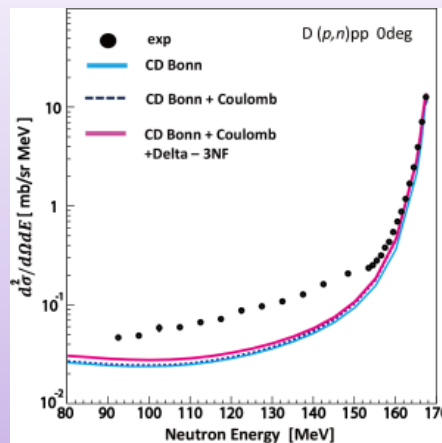
$D(p,p)pn$
@ 250MeV
S. Kuroita et al.
(Kyushu Univ.)

$\theta=7, 15, 20$ deg



$D(p,n)pp$
@ 170MeV
Y.M. et al.

$\theta=0, 7, 15$ deg



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Cluster knock-out reaction studies of nuclei

- $^{112,116,120,124}\text{Sn}(p,p\alpha) @ E_p=392 \text{ MeV}$

REPORT

J. Tanaka, Z.H. Yang, S. Typel, T. Uesaka, T. Aumann et al.,
Science 371, 260–264 (2021)

NUCLEAR PHYSICS

Formation of α clusters in dilute neutron-rich matter

We have got two hints from the experimental observation:

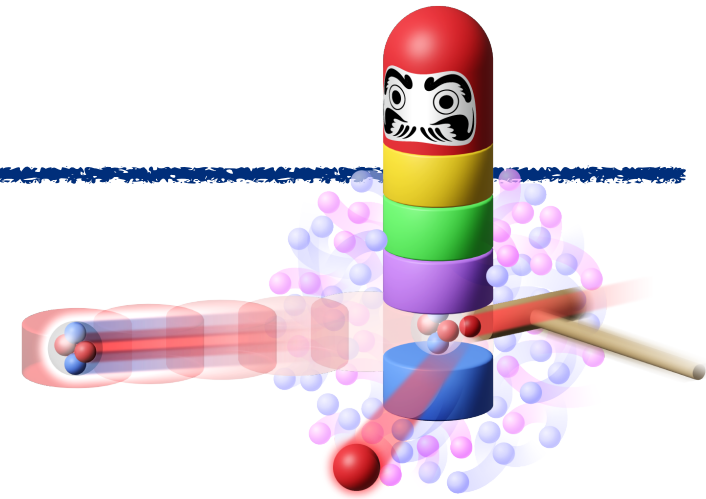
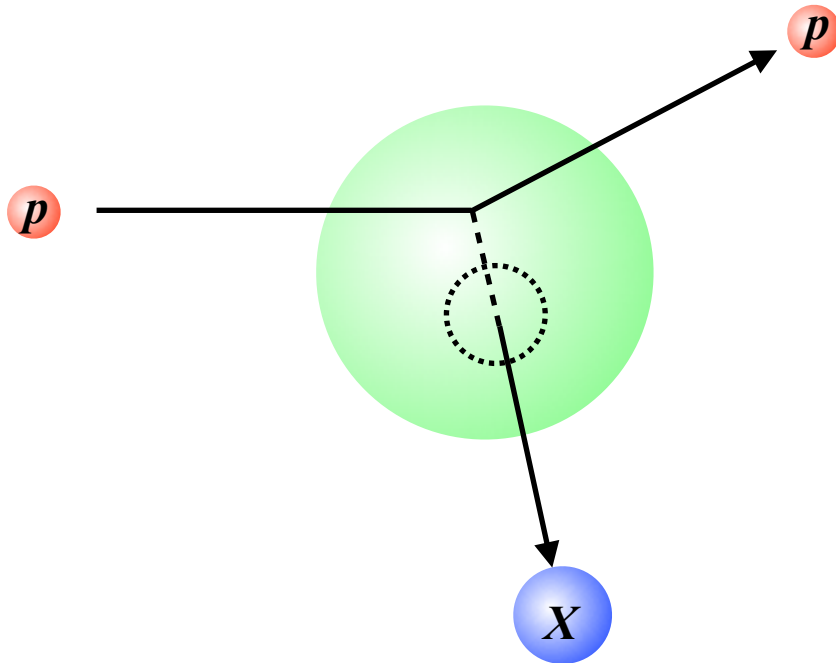
1. Cluster seems to exist in “any” nuclei
2. Knockout reaction is useful to extract information of clusters in nuclei

- ONOKORO project
 - Looking for **all the clusters** in **stable** and **unstable** isotopes
 - $(p,pX) @ E/A = 200\text{—}300 \text{ MeV}$ **$X: d, t, {}^3\text{He}, \alpha$**



(p,pX) Cluster knockout reaction

p - X elastic scattering in nuclear medium

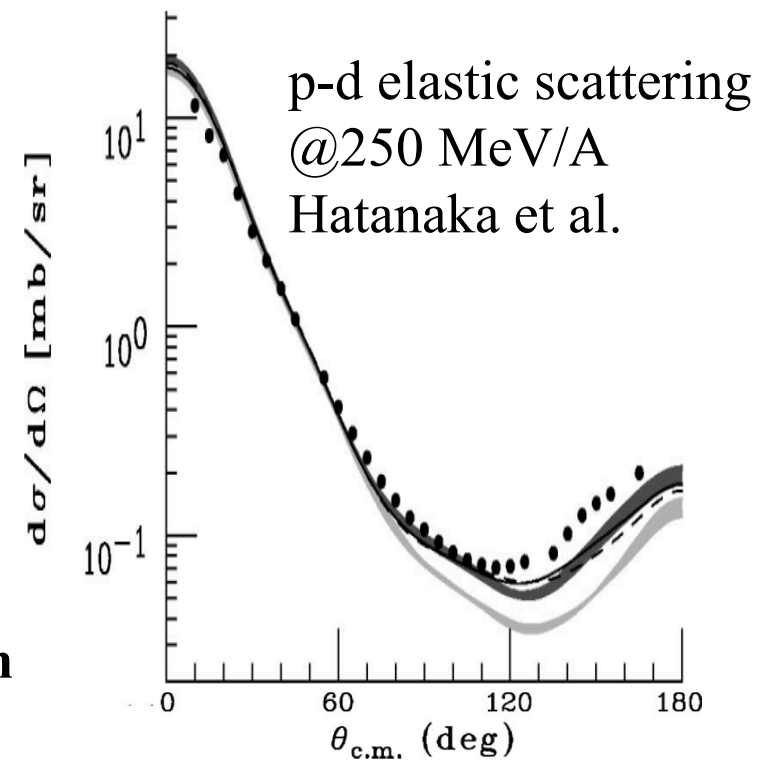


Links to few-body physics:

Accurate calculations and precise data of
the p - d , p - t , p - ^3He p - α scattering

→ reliable extraction of cluster information

Possible changes of p - X scattering amplitude
in nuclear medium?



courtesy of T. Uesaka

Reaction-mechanism studies in (p, pd) knock-out

- **Deuteron is fragile** ($B/A \sim 1\text{MeV}$)
- In order to extract information about nuclear deuteron clusters via the (p, pd) reaction, we have to know “how fragile a deuteron cluster is”. The effects of deuteron breakup channels need to be treated correctly.
- To understand the decomposition of deuteron clusters, the elementary process $p + d \rightarrow p + p + n$ needs to be quantitatively evaluated.
- Theoretical description of (p, pd) knock-out reactions

Importance of deuteron breakup in the deuteron knockout reaction

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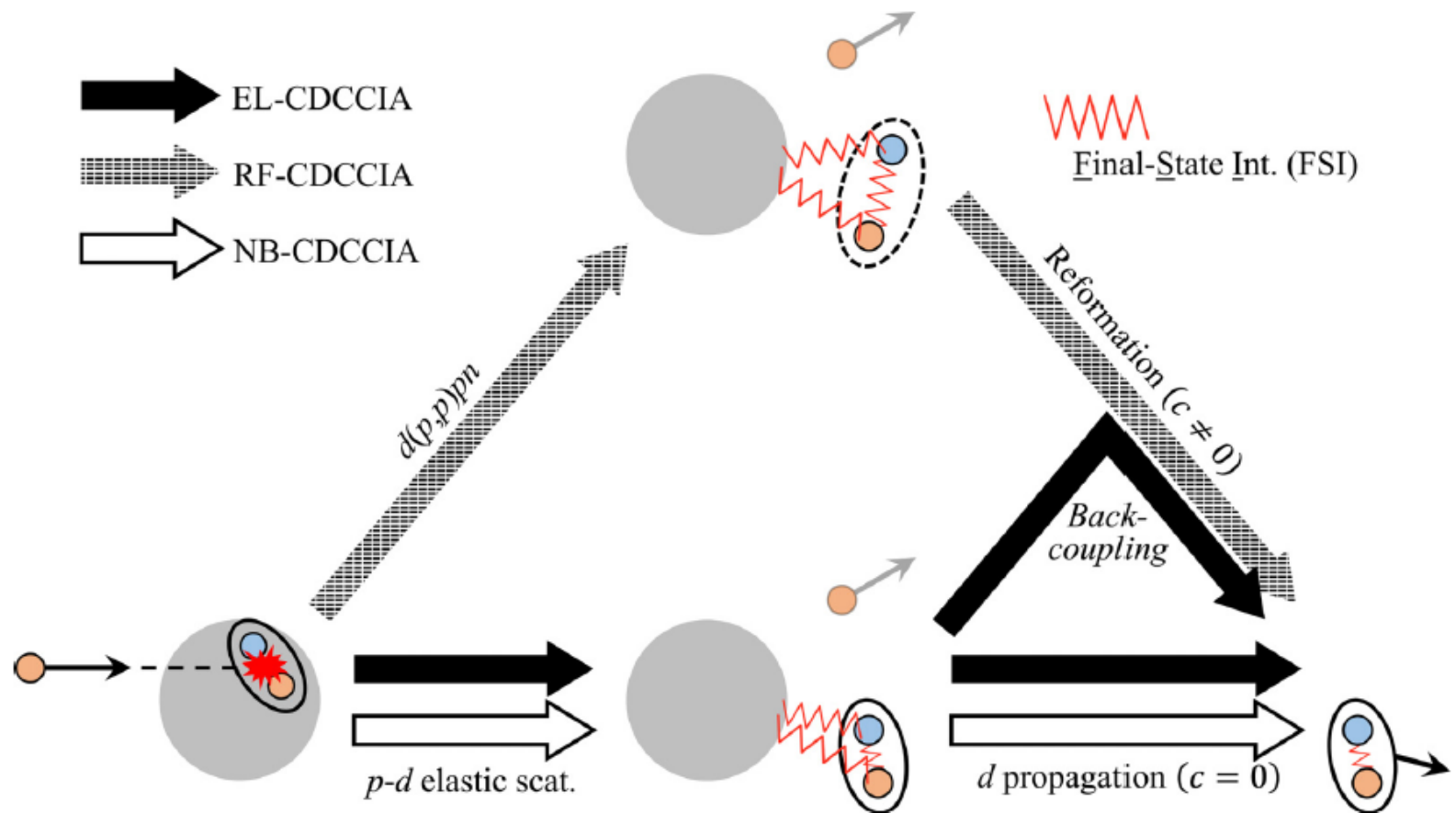
⁴Department of Physics, Kyushu University, Fukuoka 819-0395, Japan



CDCC-IA calculations

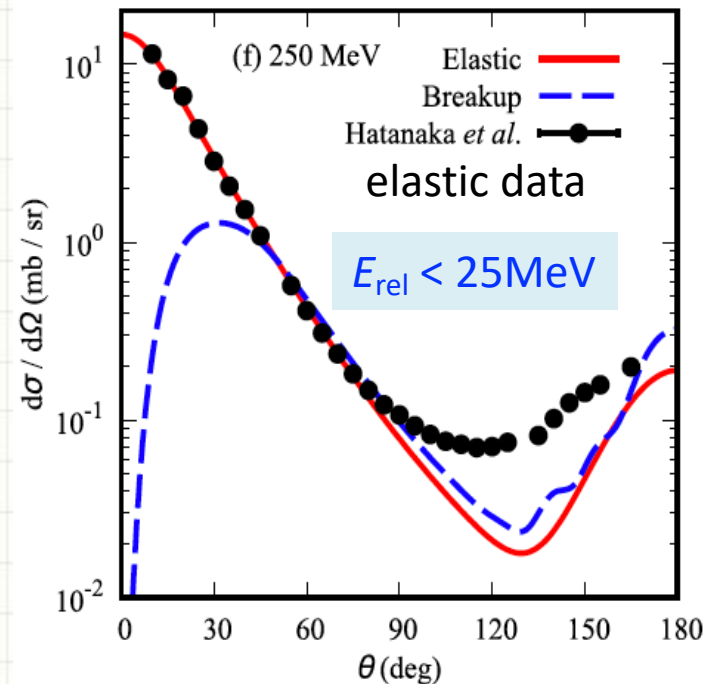
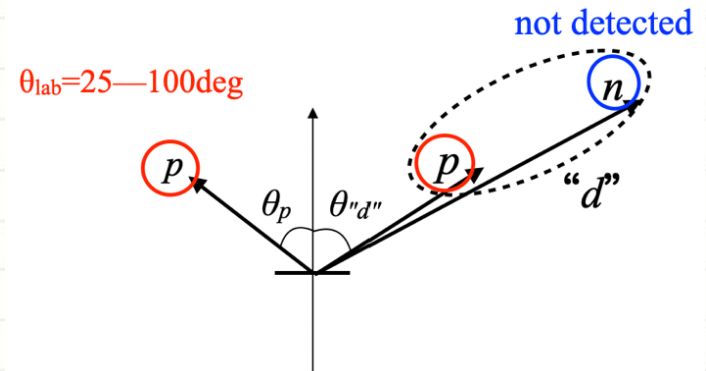
Chazono, Ogata, et al., PRC 106, 064613(2022)

- Combination of DWIA and continuum-discretized coupled channels method



Breakup reaction cross section near the FSI peak

- its kinematics similar to proton-deuteron elastic scattering.
- Inelastic scattering of deuterons to low excited states.
- $p+d$ elastic & $d(p,p')pn$ inclusive breakup reaction
 - NN effective interaction : Franey-Love, No-Coulomb
 - S-wave only for the bound and breakup deuteron states
 - DCSs of $d(p,p')pn$ are summed up to the pn relative energies E_{rel} of 25 MeV.



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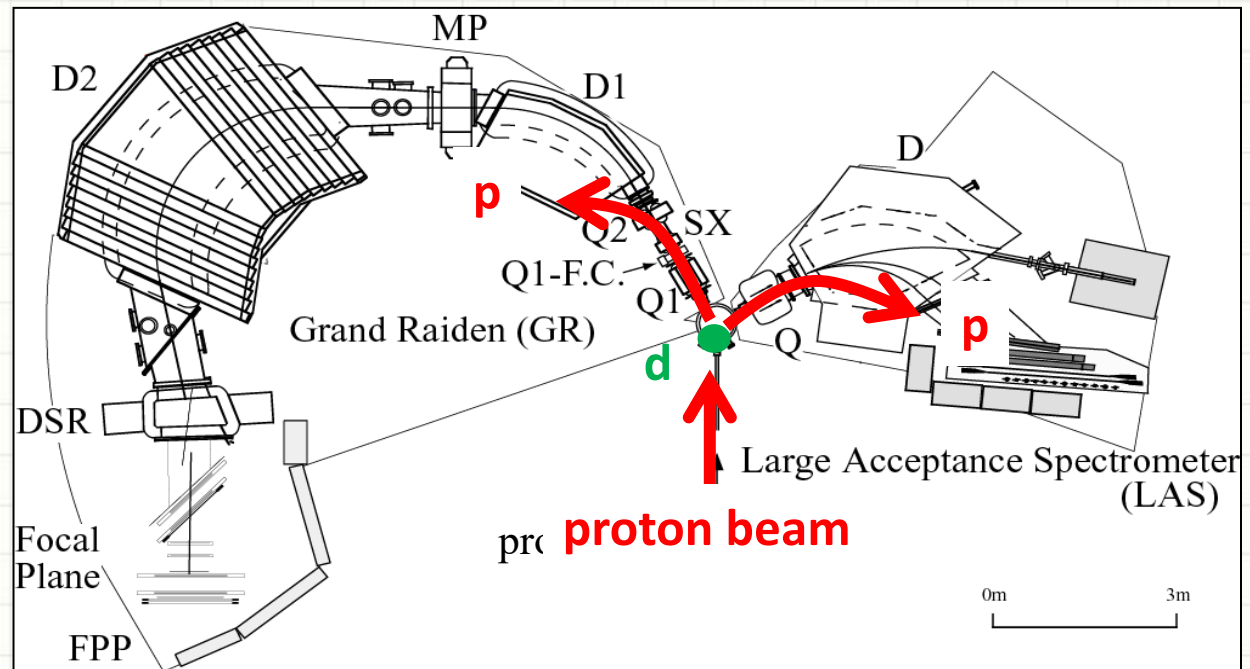
Experiment at $E_p = 230$ MeV @ RCNP (E580p, E559)

- $^2\text{H}(p,p')pn$ breakup

- target : CD_2 (24 mg/cm²) & C (15 mg/cm²)
- GR : High resolution measurements ($E_x < 10$ MeV)
 - $\theta_{GR} = 27$ -- 61 deg ($\theta_{CM}^{ela} = 40 - 90$ deg)
- LAS : Wide momentum acceptance measurement ($E_x < 60$ MeV)
 - $\theta_{LAS} = 27$ -- 98 deg ($\theta_{CM}^{ela} = 40 - 130$ deg)

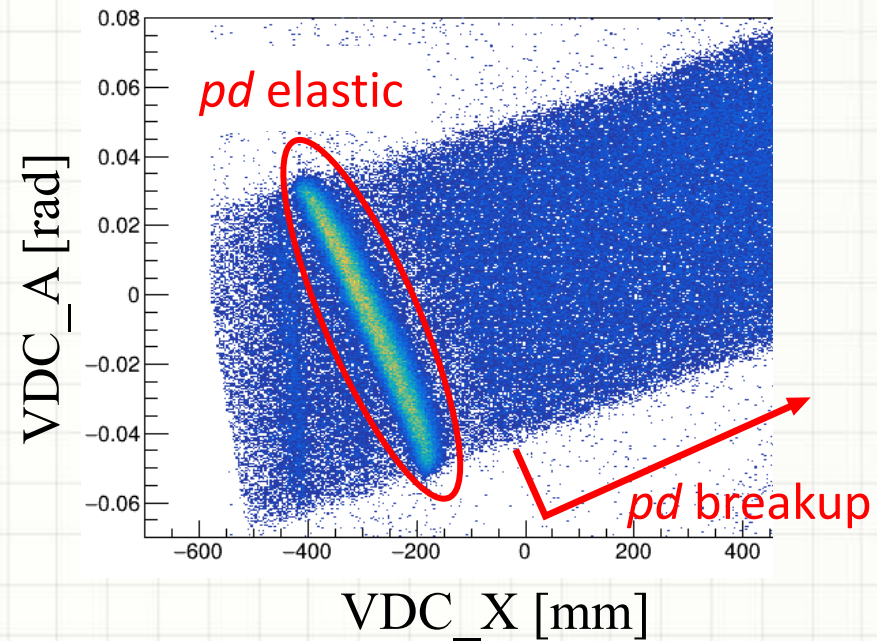
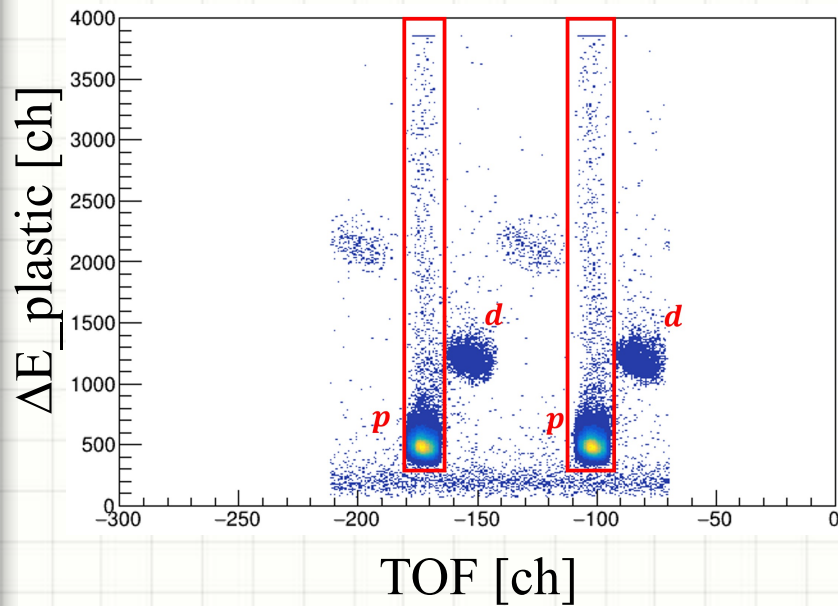
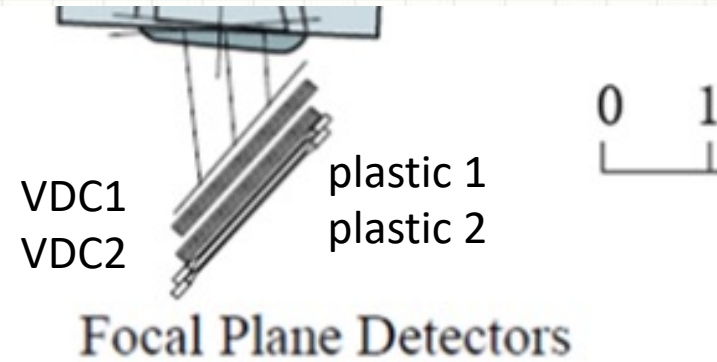
Today's talk

To be analyzed



Analysis of GR detectors data

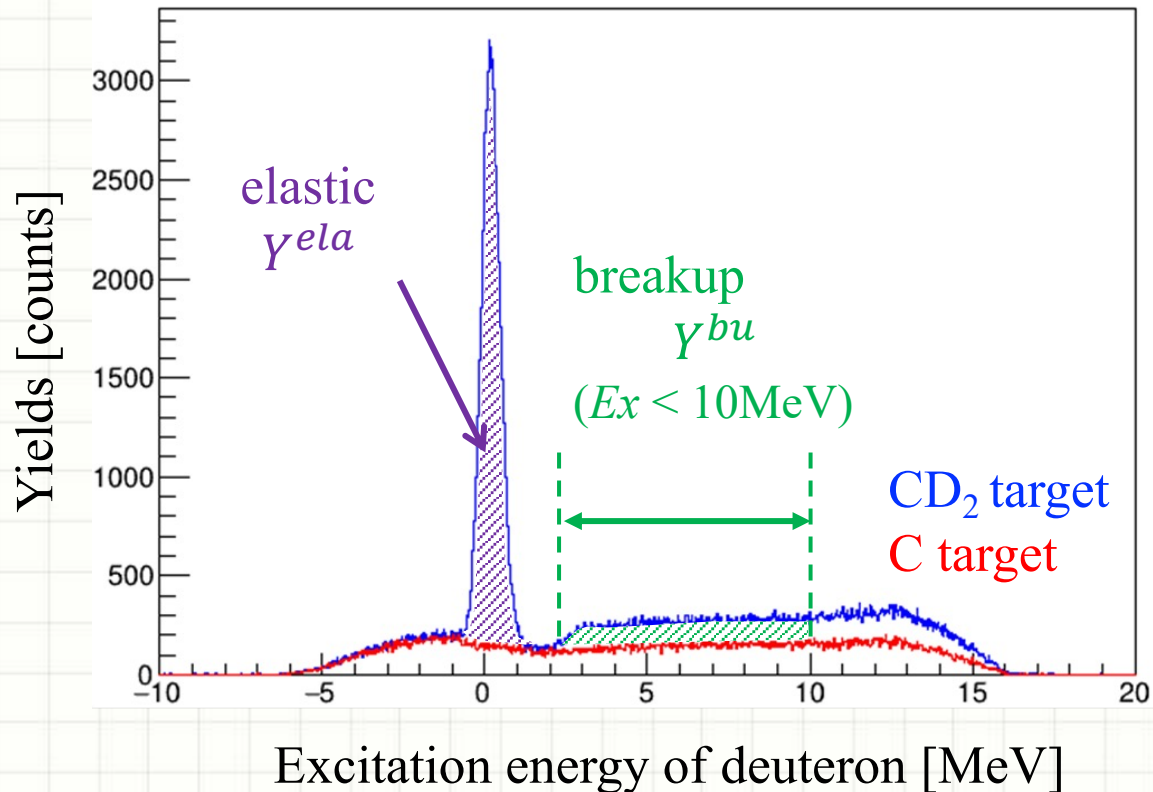
- Particle Identification & tracking



Spectrum

Yields of $p+d$ and $d(p,p)pn$ are obtained after subtraction

Y_{bu} is summed up to $E_x = 10$ MeV, which correspond to $E_{rel} = 7.8$ MeV
(because GR acceptance $\frac{\Delta p}{p} = 5\%$)



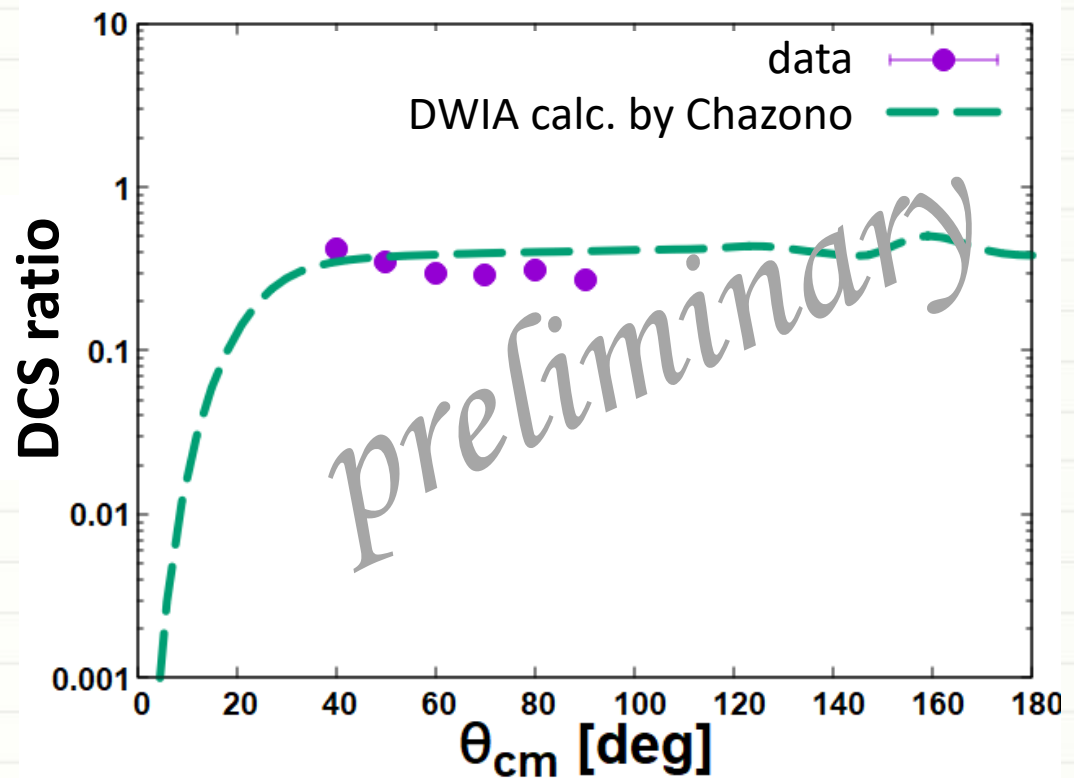
Preliminary results of DCS ratio (breakup/elastic)

- Ratio of $\left(\frac{d\sigma}{d\Omega}\right)^{bu} / \left(\frac{d\sigma}{d\Omega}\right)^{ela}$

$$- \left(\frac{d\sigma}{d\Omega}\right)^{ela} = \frac{\gamma^{ela}}{Q \times N \times \Delta\Omega \times \epsilon_{eff}}, \quad \left(\frac{d\sigma}{d\Omega}\right)^{bu} = \frac{\gamma^{bu}}{Q \times N \times \Delta\Omega \times \epsilon_{eff}} \quad \therefore \text{DCS ratio} = \frac{\gamma^{bu}}{\gamma^{ela}}$$

- statistical error :
1.0 -- 3.5 %

- Data is well reproduced by the DWIA calculation.
- The respective data for elastic and breakup reactions are under analysis.



Collaboration

- **ONOKORO $d(p,p)pn$ measurement (E580p, E559)**
Y. Maeda, **M. Mitsui** (Univ. of Miyazaki)
T. Uesaka, J. Tanaka, Y. Kubota, K. Higuchi, T. Sugiyama, Y. Li, Y. Chazono (RIKEN)
J. Zenihiro, R. Tsuji, S. Ogio, M. Dozono, Y. Hijikata, T. Yano, (Kyoto Univ.)
A. Tamii, S. Ota, N. Kobayashi, N. Endo, K. Kawata, J. Cai, F. Furukawa, R. Iwasaki, H. Shibakita (RCNP)
T. Kawabata, T. Furuno (Osaka Univ.)
S. Kawase (Kyushu Univ.)
D. Beaumel, S. Franchoo (IJCLab Orsay)
D.S. Ahn, S. Kim (CENS, IBS)
Z.H. Yang, S. Huang, Q Li, Z. Du, J. Bian, C. Liu (Pekin Univ.)





Summary

- pd BU reaction data are a mandatory input for the quantitative evaluation of the deuteron breakup effects in the study of cluster structure via knock-out reaction (ONOKORO project).
- $d(p,p)pn$ inclusive BU measurements @230MeV were carried out as a first step. Data of the ratio DCS_{BU}/DCS_{ela} is well described by the DWIA calculation.
- In future :
 - DCS_{BU} data including higher E_{rel} region or backward angles will be analyzed.
 - $d(p,pp)n$ exclusive BU will be obtained for some kinematical conditions which include FSI region.
 - Data will be compared with not only DWIA calculations, but also Faddeev calculations for the study of 3 nucleon systems.

