RCNP-HST15 Symposium @ ONC
November 18, 2015

Understanding effect of tensor interactions in light nuclei via high momentum neutron-transfer reactions

Hooi Jin ONG (RCNP, Osaka University)

On behalf of

- RCNP-E314
- GSI-S436
- RCNP-E396
- RCNP-E443

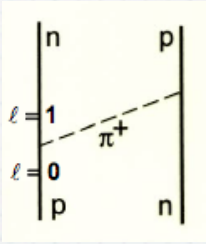
collaborations

Tensor Interactions in Nucleus

Effective nucleon-nucleon potential
(e.g. Hamada-Johnston):

$$V(r)=\begin{cases} V_{\mathrm{C}}(r)+V_{LS}\dfrac{(\mathbf{L}\cdot\mathbf{S})}{\hbar^2}+V_{\mathrm{T}}(r)S_{12}+V_{L^2}\dfrac{(L_{12})}{\hbar^2} & , \quad r>r_{\mathrm{C}} \\ +\infty & , \quad r<r_{\mathrm{C}} \end{cases}$$

Tensor force: $V_{\mathrm{T}}(r)S_{12}$



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

$$=\sqrt{24\pi/5}\left([\vec{\sigma}_1\times\vec{\sigma}_2]^{(2)}\cdot Y^{(2)}\right)$$

Originated mainly from One-Pion Exchange Potential:

$$S_{12}\frac{q^2}{m_\pi^2+q^2}$$

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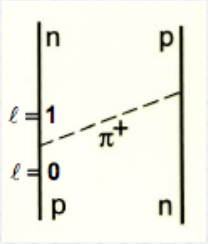

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⇨ **ΔS=2, ΔL=2**

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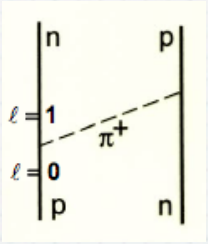

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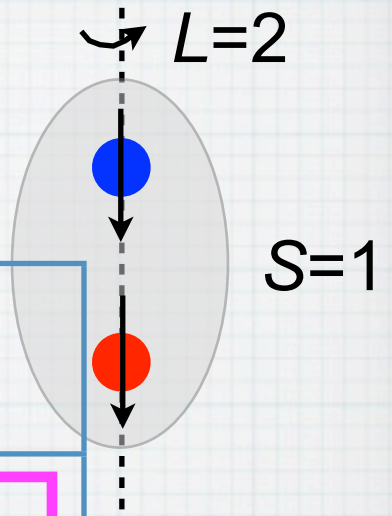
High-momentum components in nuclei

Deuteron

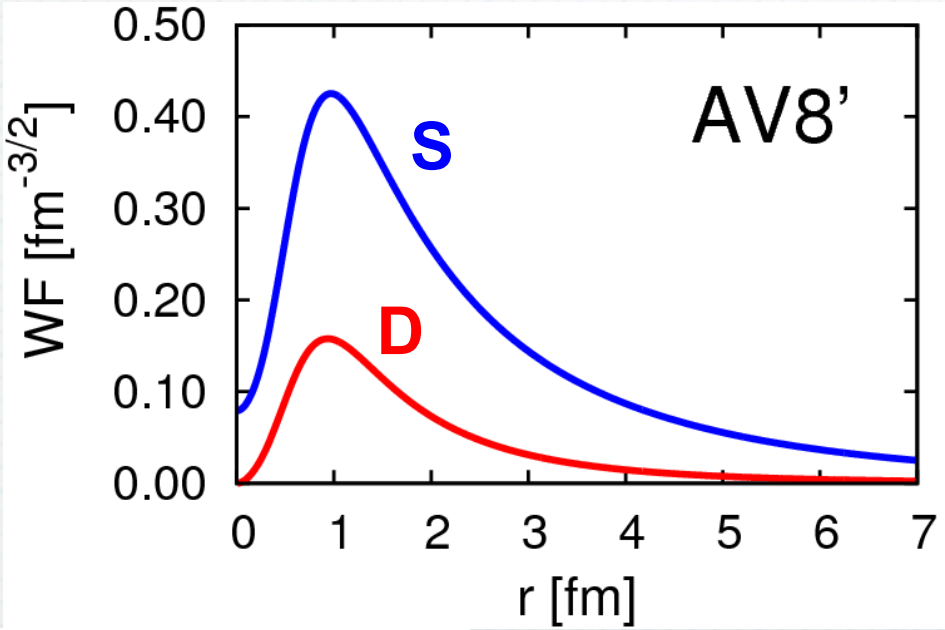


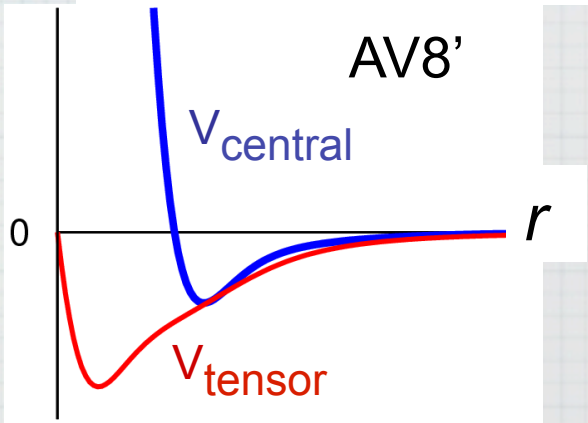
Measured proton, neutron and deuteron properties†

	Proton	Neutron	**Deuteron**
Binding energy (MeV)	-	-	-2.22452(20)
Spin-parity	$1/2^+$	$1/2^+$	1^+
Magnetic moment (μ_N)	+2.79276(2)	-1.91335(4)	+0.8574114(4)
Electric quadrupole moment (b)	0	0	+0.002738(14)

† Experimental data taken from 八木浩輔(1971)『原子核物理学』朝倉書店

Deuteron (continued)





Energy	-2.24 MeV
Kinetic	19.88
Central	-4.46
Tensor	**-16.64**
LS	-1.02
P(L=2)	5.77%
Radius	1.96 fm

$R_m(s)$=2.00 fm

$R_m(d)$=1.22 fm

d-wave is
“**spatially compact**”

(High momentum components)

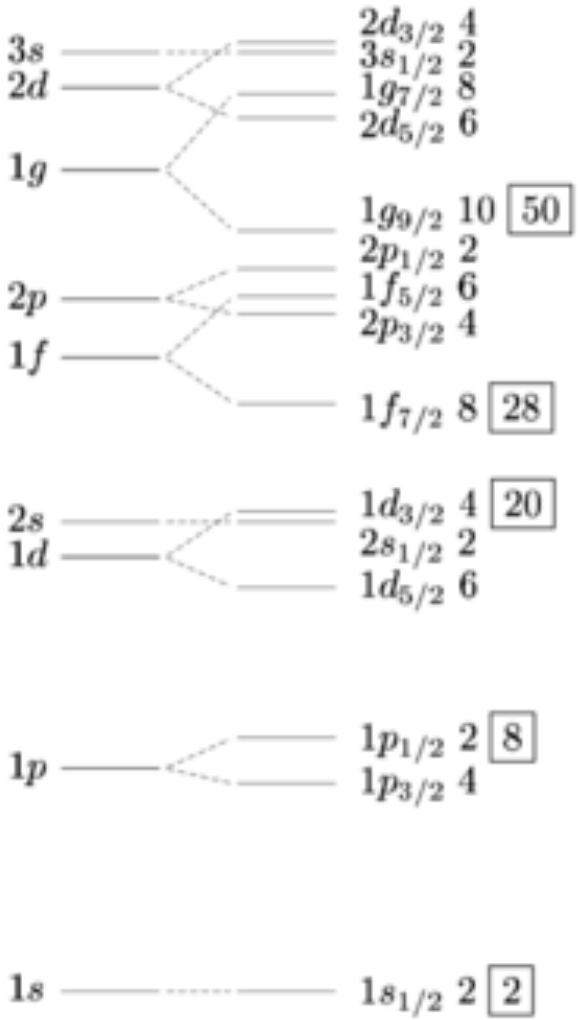
† Figures, theoretical data courtesy of T. Myo

Alpha Particles

	Faddeev-Yakubovsky†	TOSM + UCOM‡	Exp.
Energy (MeV)	-25.94	-22.30	-28.2957¶
Kinetic (MeV)	102.39	90.50	
Central (MeV)	-55.26	-55.71	
Tensor (MeV)	-68.35	-54.55	
LS (MeV)	-4.72	-2.53	
Radius (fm)	1.49	1.55	1.6755(28)§

† H.Kamada *et al*. PRC 64 ('01) 044001
‡ T.Myo *et al.* PTP 121 ('09) 511
¶ AME2012
§ I. Angeli *et al*. ADNDT 99 ('13) 69

Independent Particle Model (IPM)



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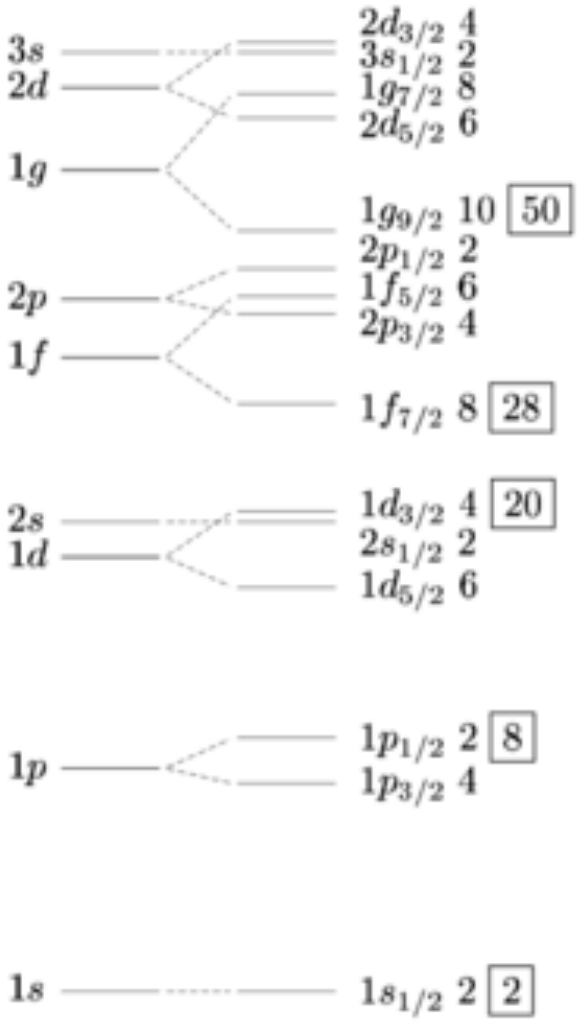

- **Nuclear Shell Model (1949)**
  - developed by Mayer, Jensen, Wigner
  - complex many-body nucleon-nucleon interactions

    ⇒ average potential:

    i) **3 dimensional harmonic oscillator**

    ii) **spin-orbit interactions**
  - reproduces nuclear **magic numbers**
  - enhances understanding of nuclear structures, predicts energy levels and other observables
  - helps to understand/predict (direct) nuclear reactions
    - spectroscopic factor

Limitation of IPM

- Underestimates (direct) nuclear reactions, especially those that involve transfer/knockout of high momentum nucleons

  ⇒ the need to consider explicitly **tensor** and **short-range correlations**.

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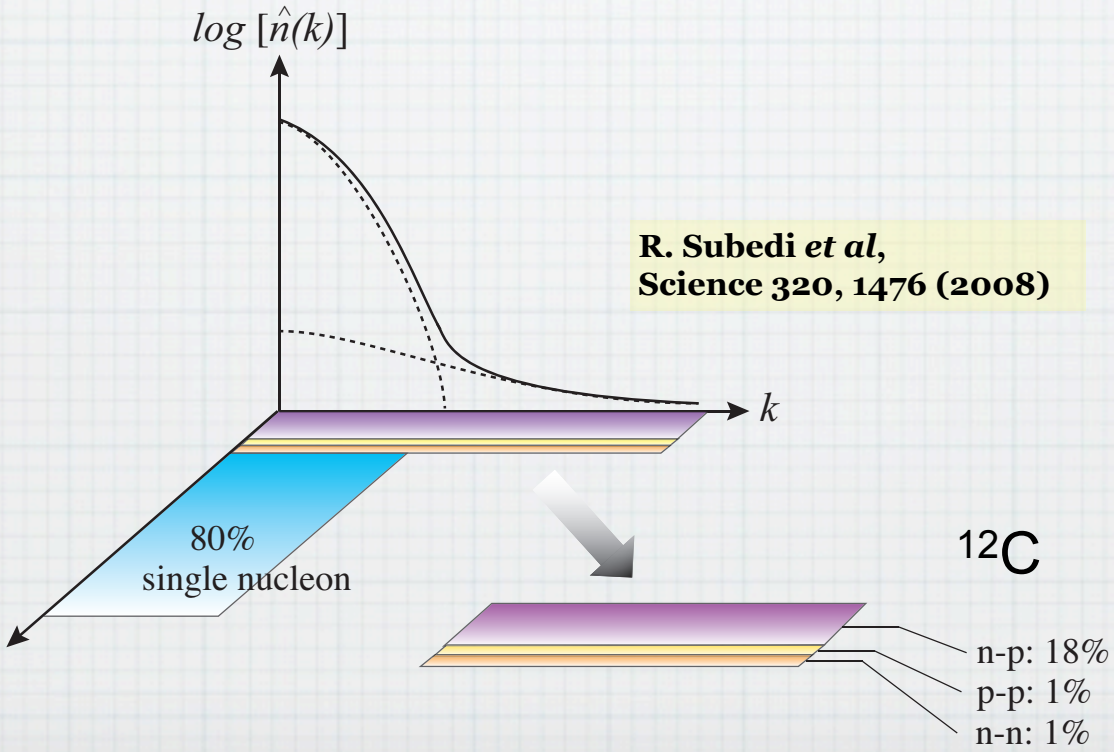

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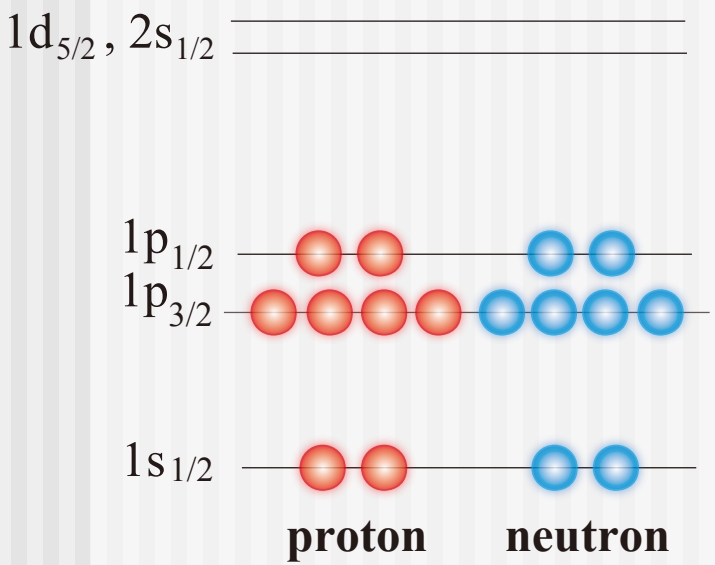
YES!



Ground state of ^{16}O

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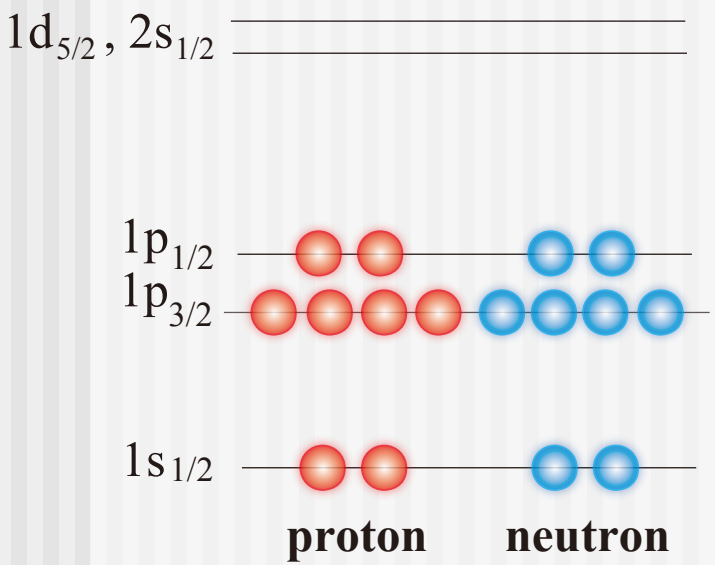

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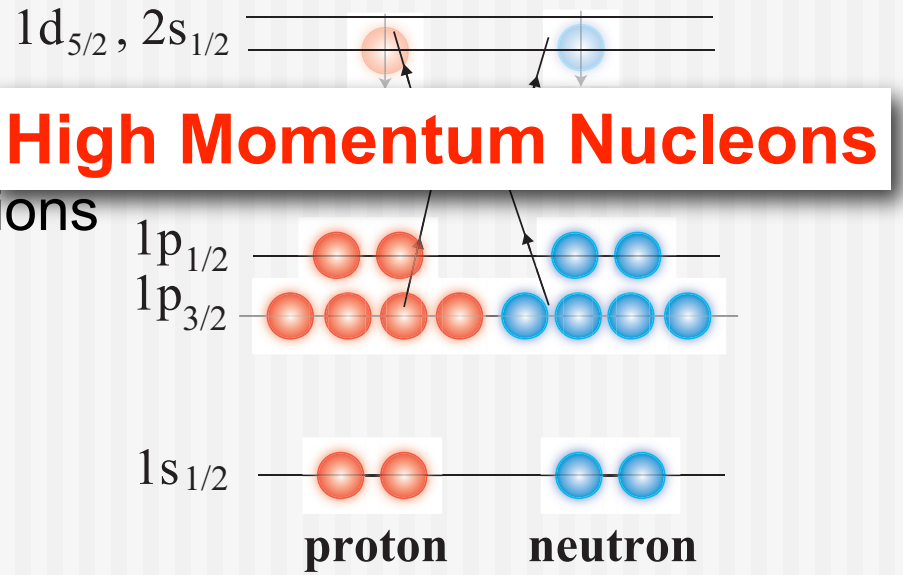
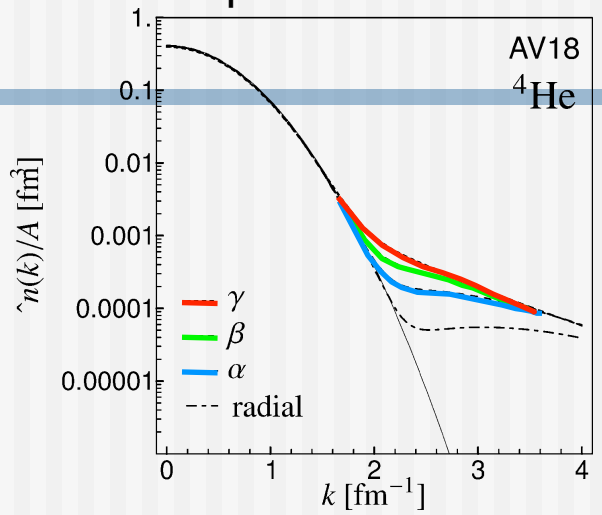
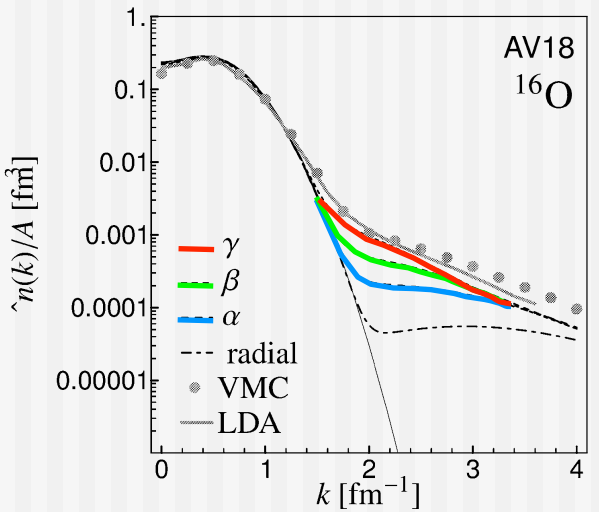


Ground-state of ^{16}O:
mixing of 2p-2h configuration

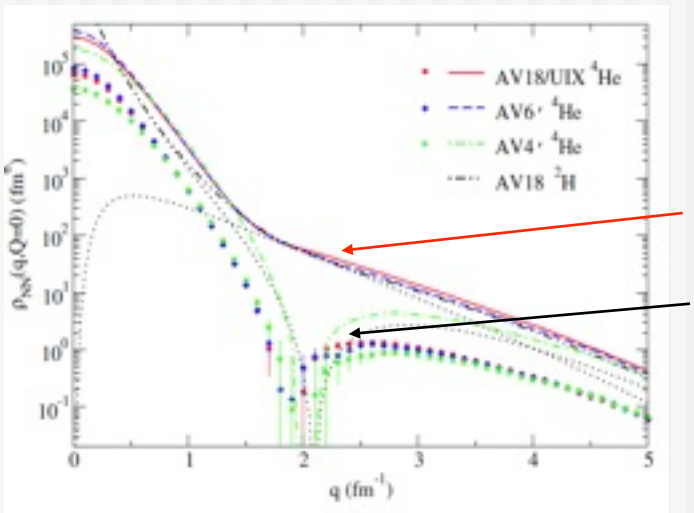
Predicted Momentum Distribution of Nucleons

Unitary Correlation Operator Method





T. Neff and H. Feldmeier, NPA713, 311(2003)



pn pair (lines)

pp pair (symbols)

R. Schiavilla et al., PRL 98, 132501 (2007)

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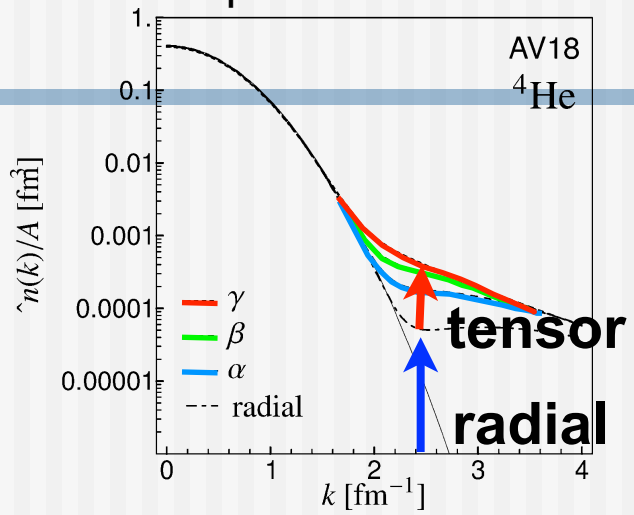

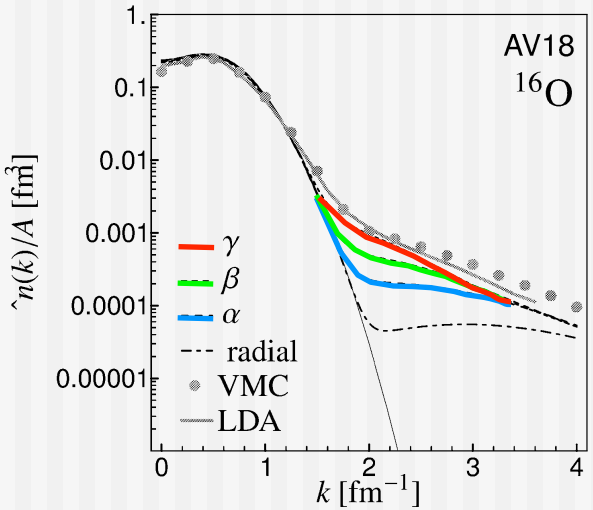

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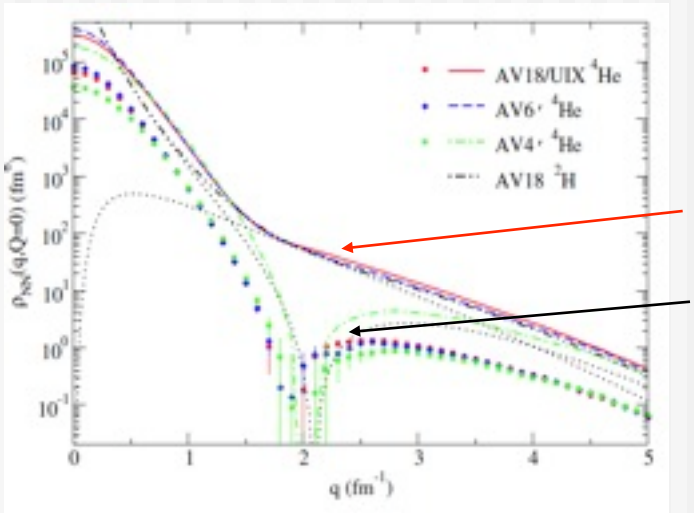

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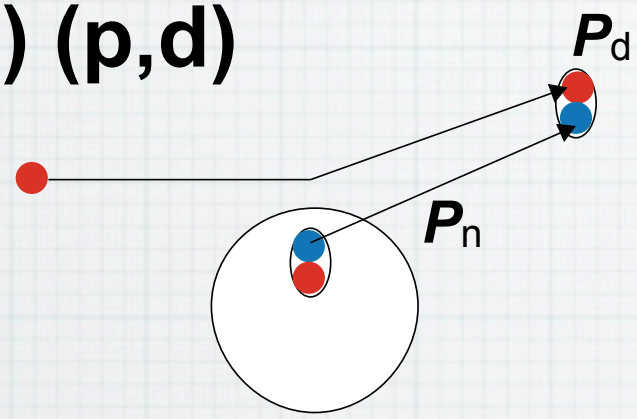
Probe internal momentum of nucleon by neutron-transfer reactions

(i) (p,d)



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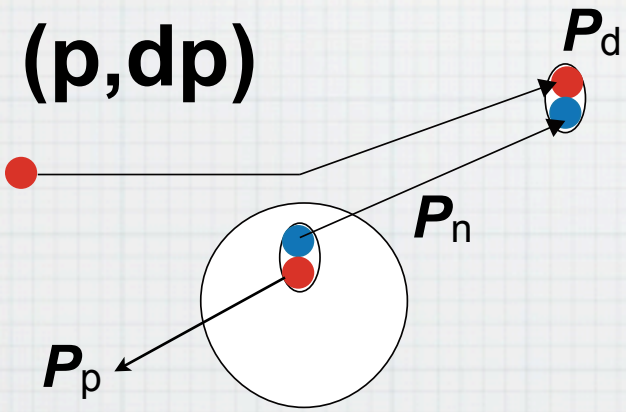

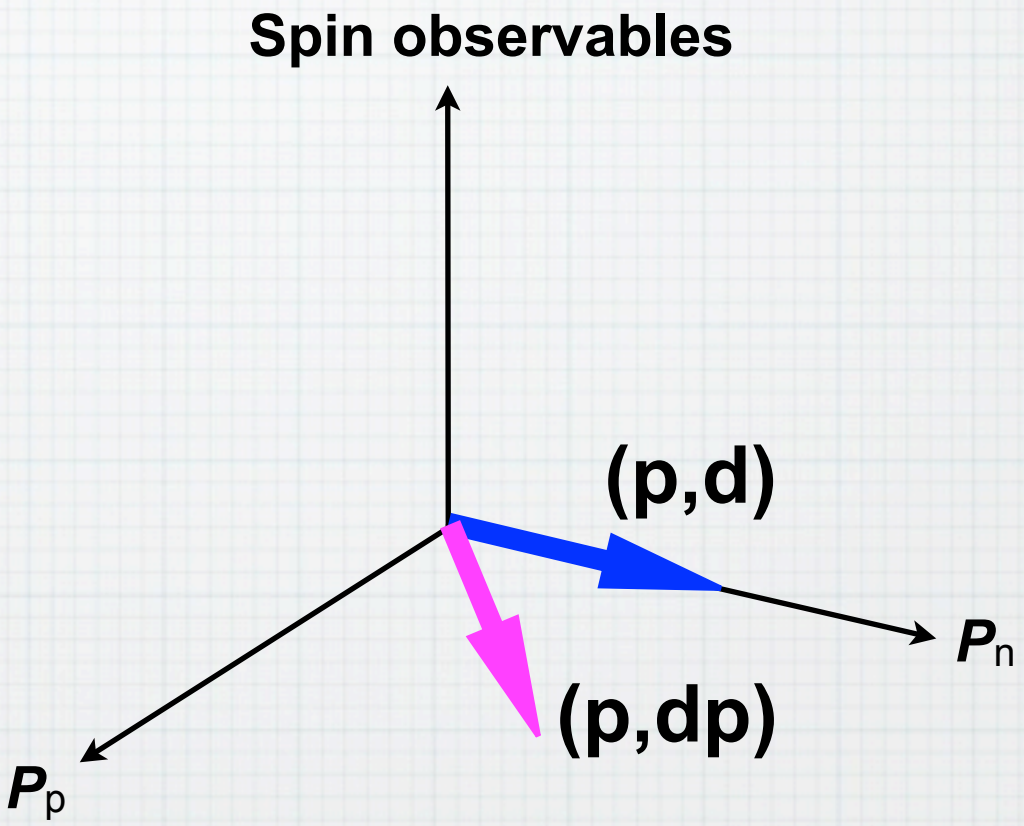

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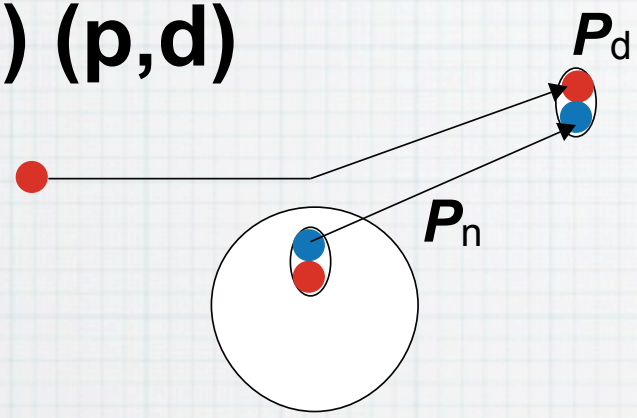

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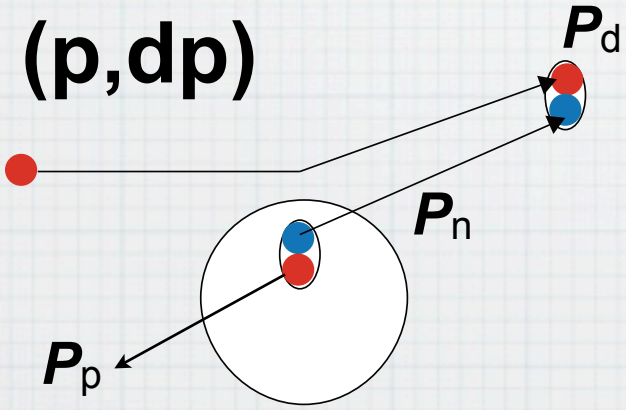

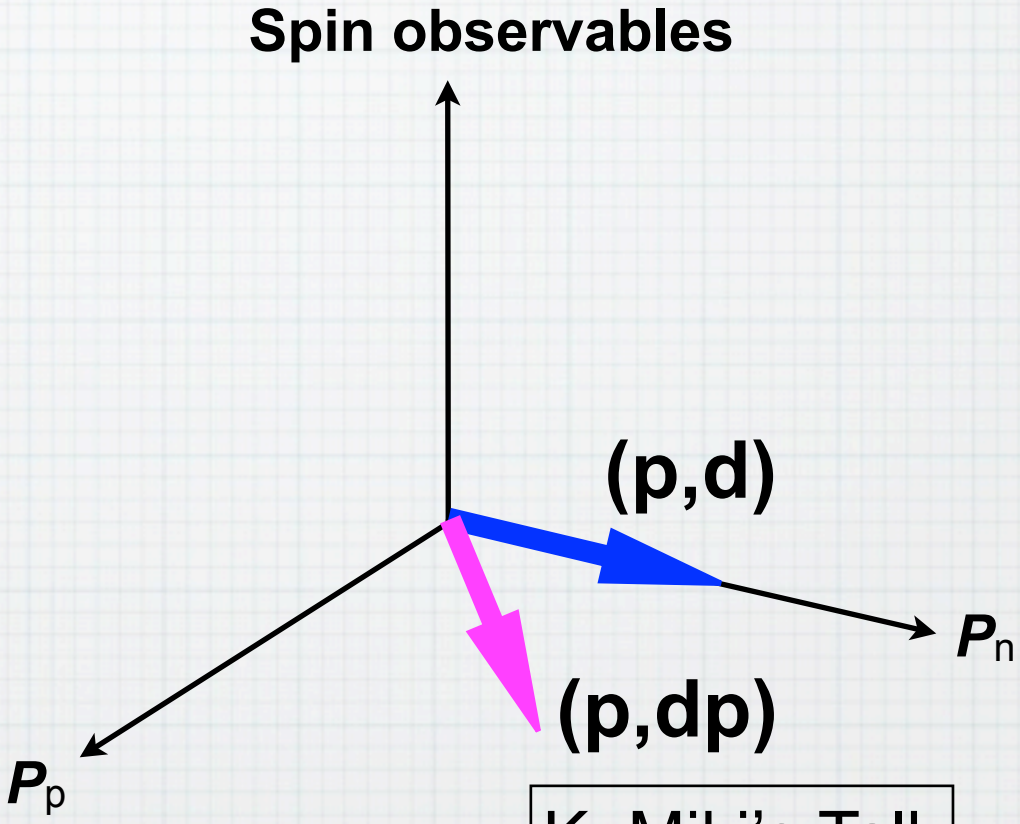

See also

K. Miki's Talk

T.Suda's Talk

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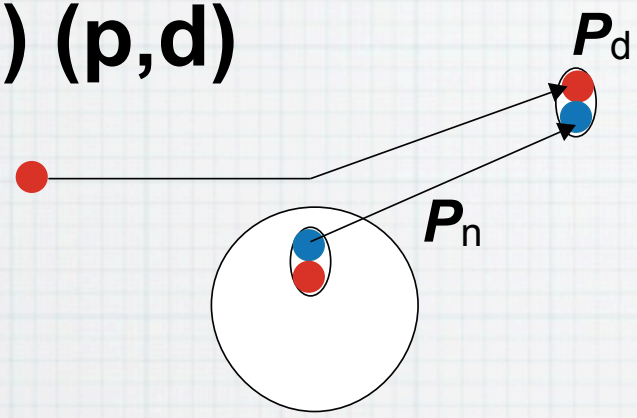

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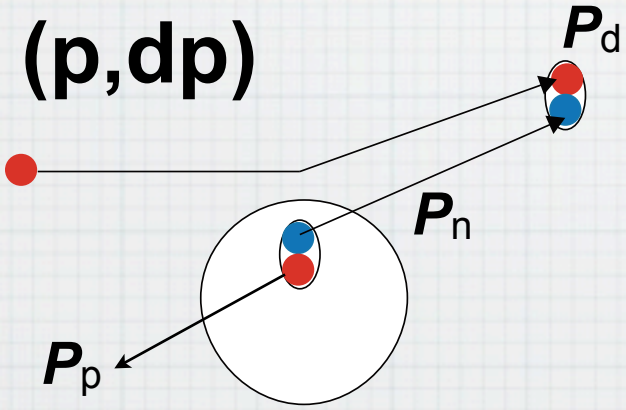
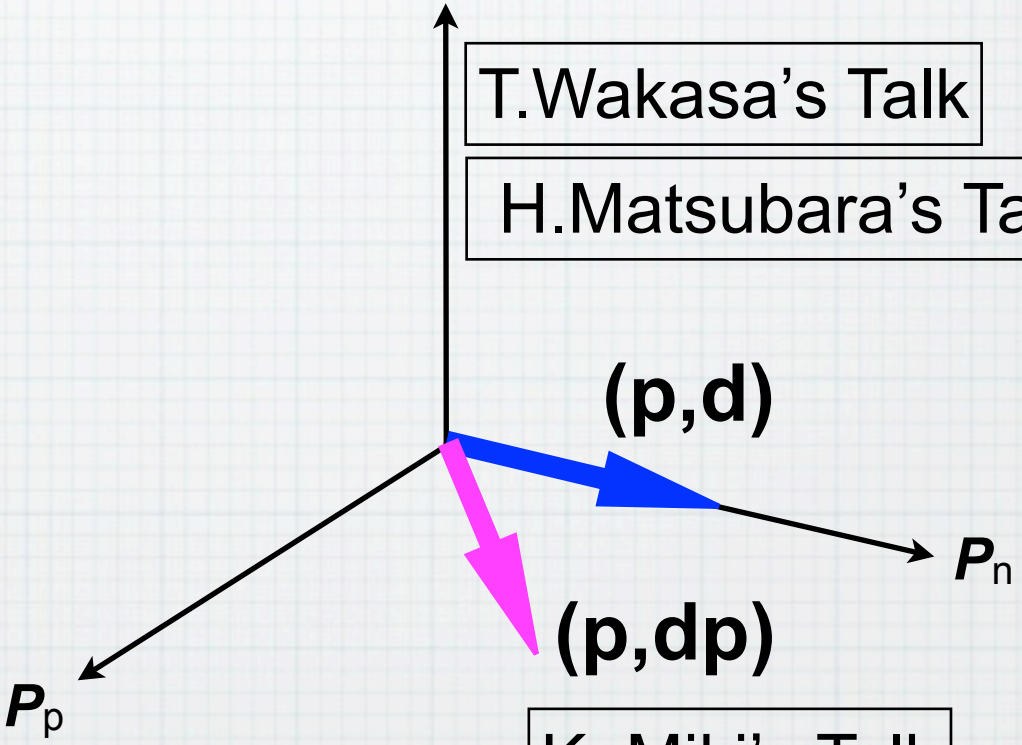


Spin observables



T.Wakasa's Talk

H.Matsubara's Talk

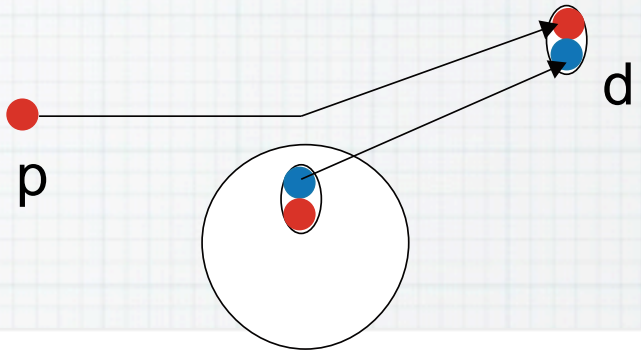
See also

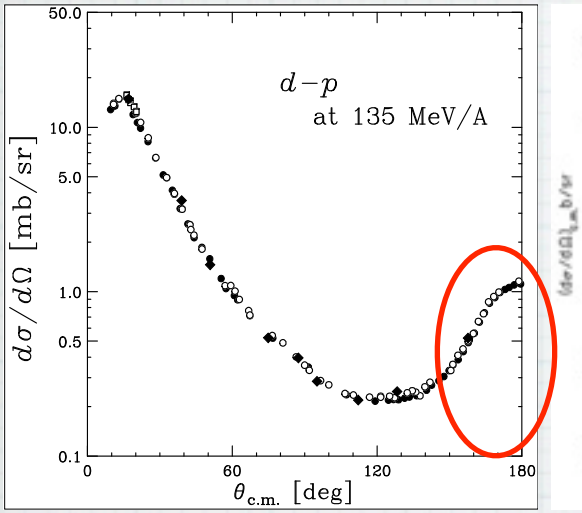
K. Miki's Talk

T.Suda's Talk

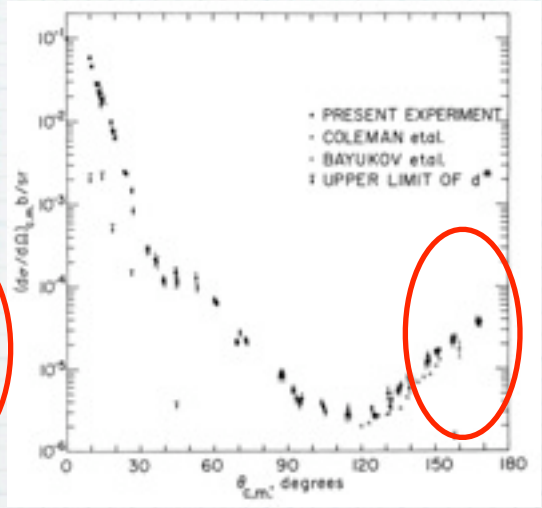
Probe internal momentum of nucleon by (p,d) reaction

- taking advantage of the momentum selectivity

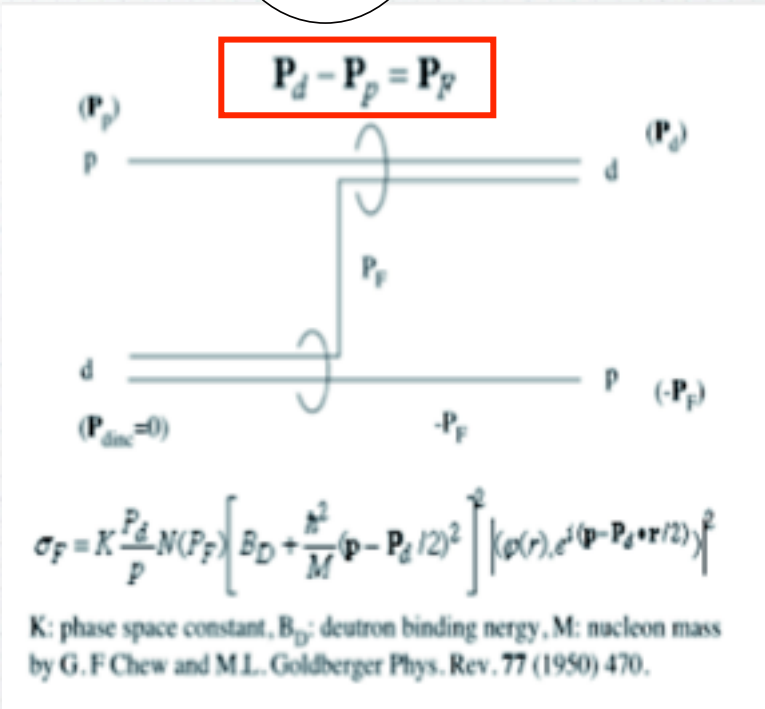




K. Sekiguchi *et al.*, PRL95, 162301(2004)



G. W. Bennett *et al.*, PRL19, 387(1967)



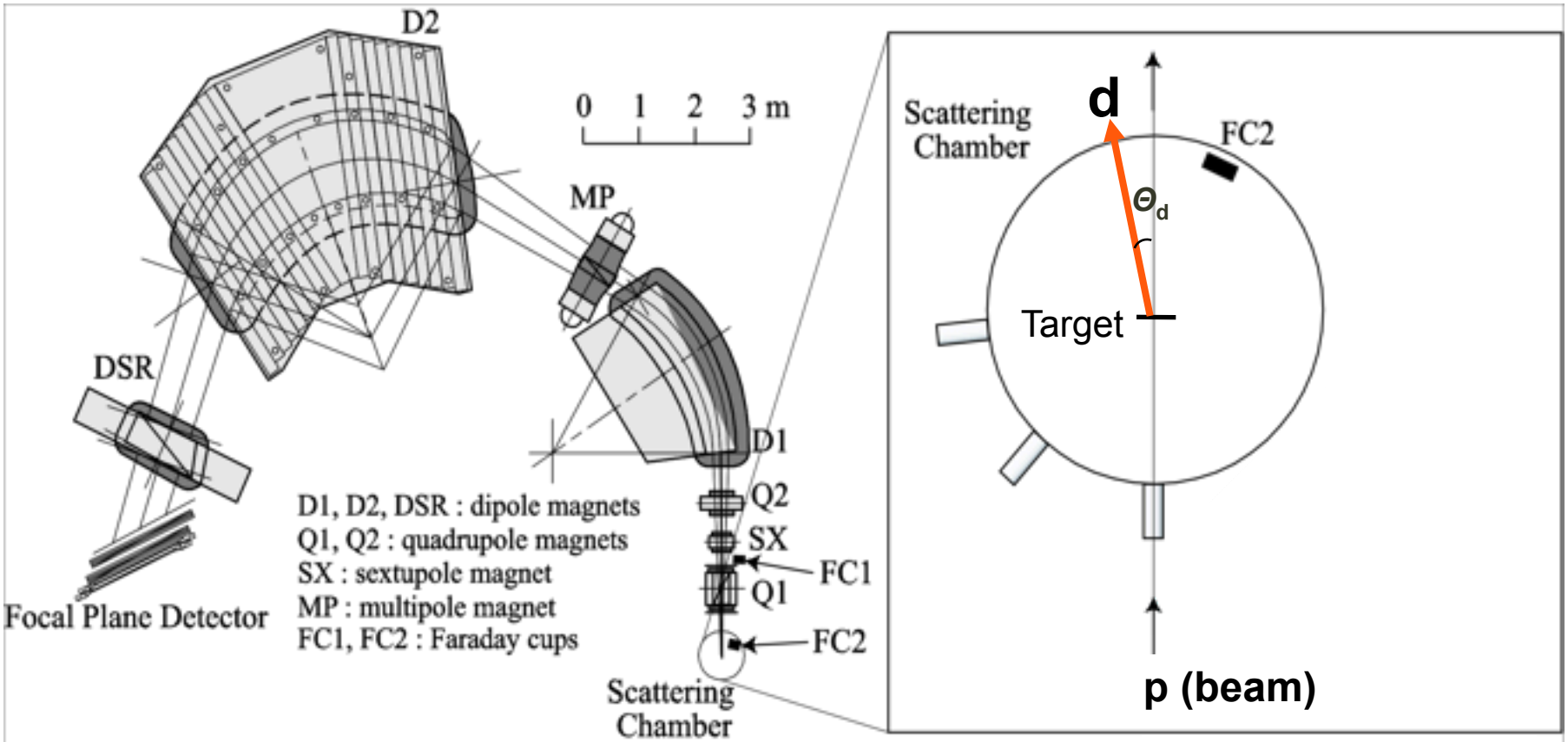
RCNP-E314 collaboration

RCNP	**H.J. Ong**, **I. Tanihata**, A. Tamii, T. Myo, K. Ogata, K. Hirota, D. Ishikawa, H. Matsubara, T. Naito, Y. Ogawa, H. Sakaguchi, T. Suzuki, M. Takashina, H. Toki, Y. Yasuda, M. Yosoi, J. Zenihiro
Dep. of Phys., Osaka Univ.	M. Fukuda, K. Matsuta, M. Mihara, D.Nishimura
Kyoto Univ.	T. Kawabata
Tsukuba Univ.	A. Ozawa
RIKEN Nishina Center	K. Sekiguchi, K. Ikeda
Nara Women's Univ.	M. Taniguchi
Beihang Univ.	S. Terashima, D.Y. Pang

[RCNP-E314] Experiment

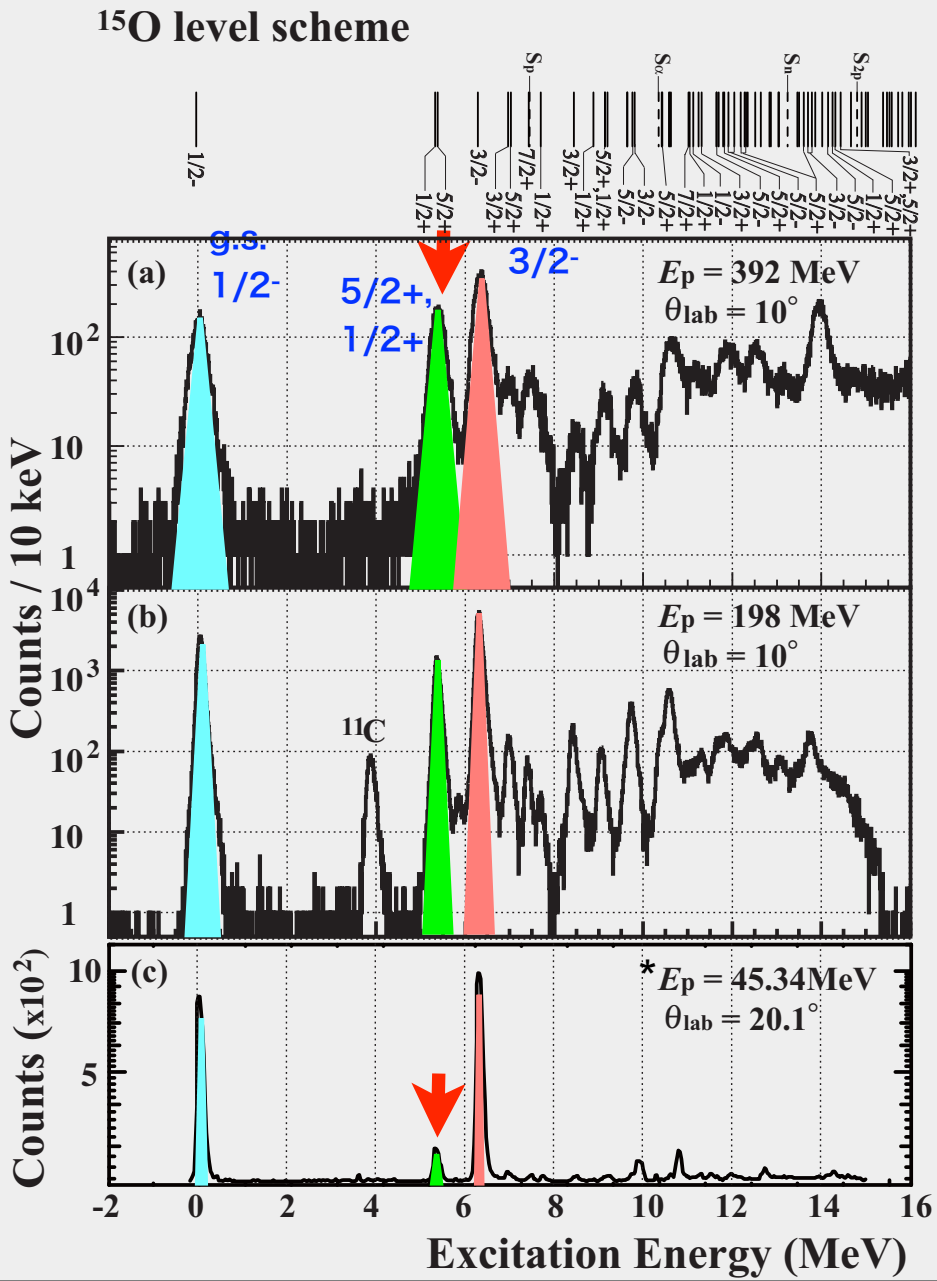
RCNP Grand RAIDEN
($p/\Delta p$ ~ 37000)

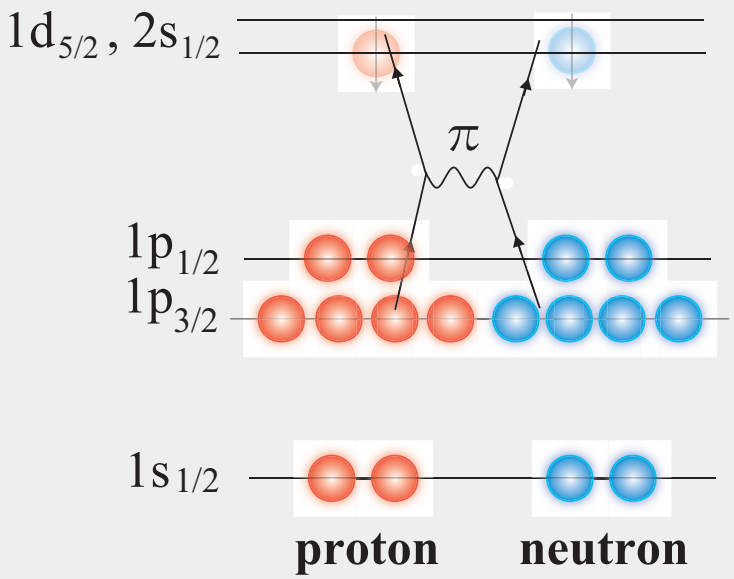
M. Fujiwara et al., NIMA422, 484(1999)



- 198, 295, 392 MeV
- ~2 nA

[RCNP-E314] Missing mass spectra





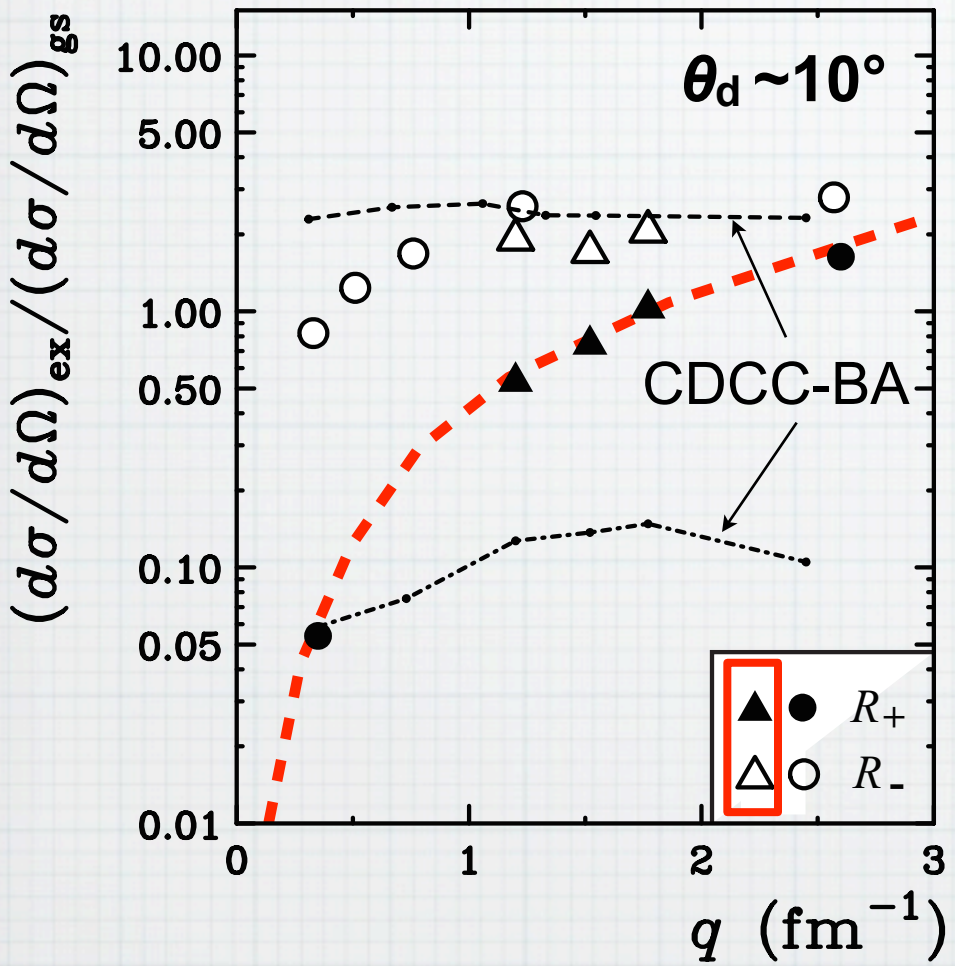
Ground-state of ^{16}O:
mixing of 2p-2h configuration **

Selection Rule: $\Delta J=0$, $\Delta L=\Delta S=2$

* J.L. Snelgrove *et al.*, PR 187 (1969) 1246

** T. Myo, private communication

Possible Signature of Tensor Interactions

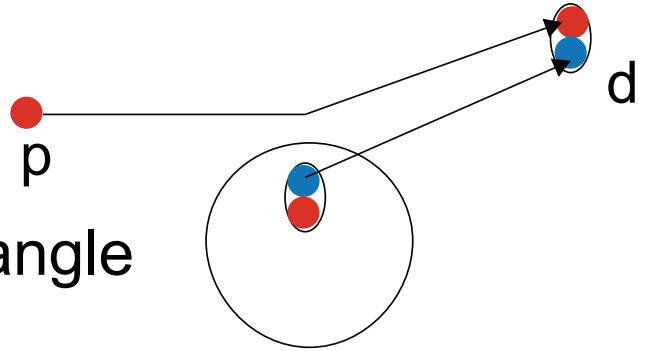


HJO, IT *et al.*, PLB 725, 277(2013)

- **CDCC-BA calculation with known spectroscopic factors:**
  - ✓ qualitatively agree with ratios for the neutron-hole states (3/2- to 1/2-)
  - ✓ cannot explain the ratios for the positive-parity state (1/2+ or 5/2+ to 1/2-)
- **Two(Multi)-step process does not help**
- **TOSM-type momentum wave functions** that include high-momentum components "fit" the data well.

T. Myo, PTP 117 (2007) 257.

Issues to be addressed...



(p,d) at finite (≥10 deg) scattering angle

reaction mechanism effect at finite angle

ambiguity of contributions from p-n and/or n-n pairs

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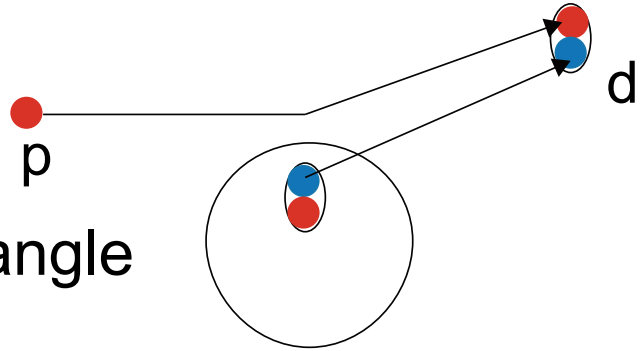

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⇒ **0 degree measurement**

- (p,d) at 0 deg with 400-MeV proton
  -> RCNP-E396 (Nov. 2013)

- (p,d) at 0 deg with 400～1200-MeV proton to cover 2 fm^{-1}
  -> **GSI-S436/S437** (July, 2014)

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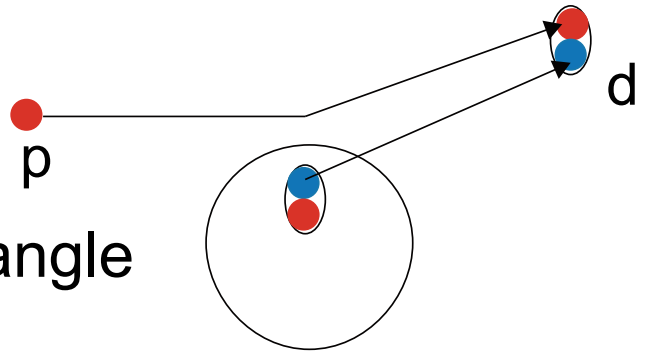

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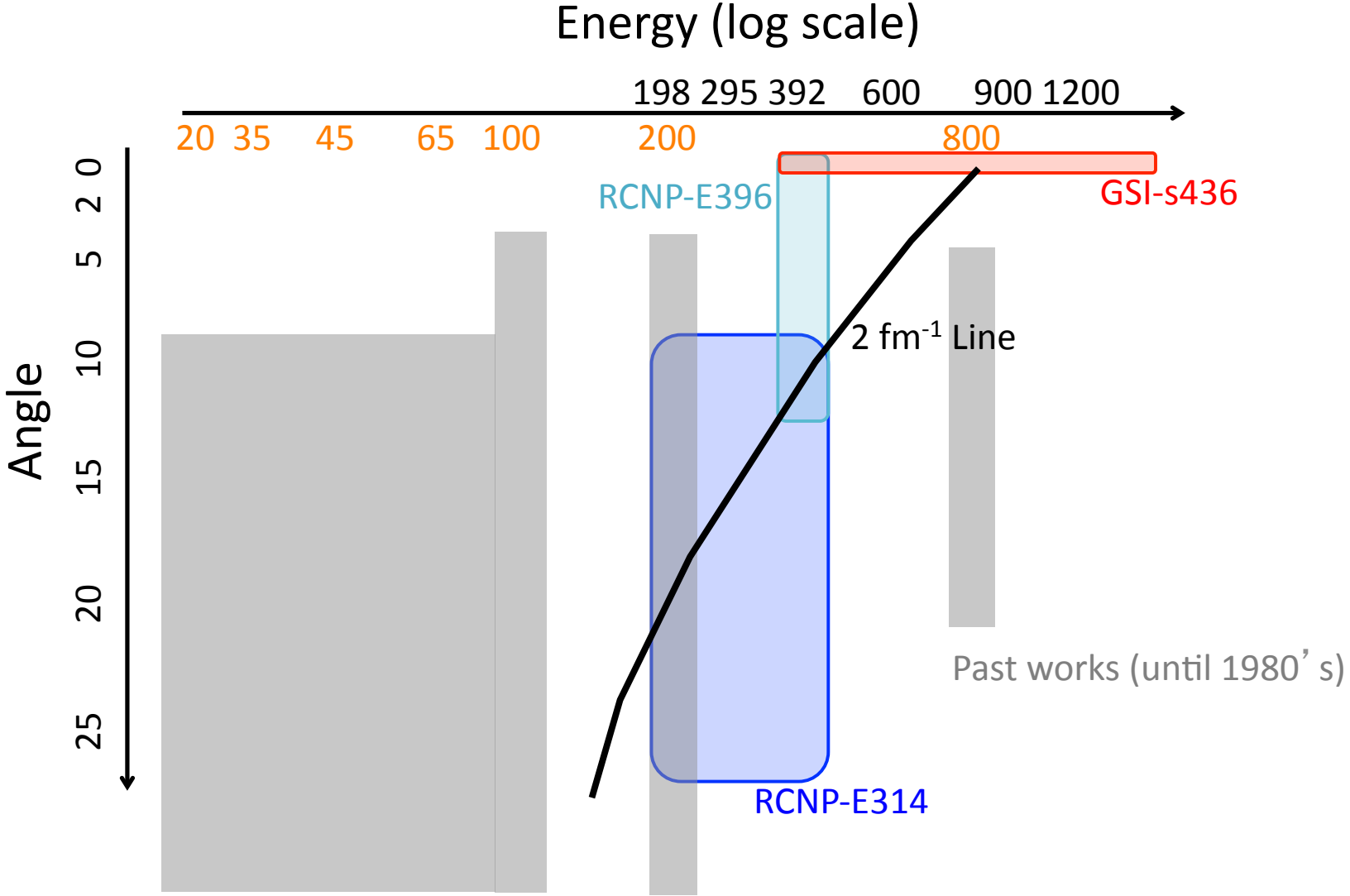
⇒ (p,dp) and (p,dn) measurements

- (p,dp), (p,dn) at finite angles with 400-MeV proton to study p-n and n-n correlations
  -> RCNP-E443 (Autumn 2015)
- (p,dp), (p,dn) at higher energy to cover 2 fm^{-1} is being planned at the future SuperFRS at FAIR/GSI, Germany.

Tensor-effect studies via (p,d) reactions: Past works and our strategy



We also probe mass(^{16}O,^{12}C) and J^{π} dependence

RCNP-E396 Collaboration

RCNP **H. J. Ong**, **I. Tanihata**, N. Aoi, Y. Ayyad, T. Hashimoto, A. Inoue, T. Ito, C. Iwamoto, K. Miki, M. Miura, K. Ogata, Y. Ogawa, A. Tamii, D.T. Tran, H. Toki, T. Yamamoto

Beihang Univ. **S. Terashima**, **C.L. Guo***, X.Y. Le, W.W. Qu, B.H. Sun, T.F. Wang, L. Yu, G.L. Zhang

Osaka Inst. of Tech. T. Myo

Dep. of Phys.,

Osaka Univ. M. Fukuda, K. Matsuta, M. Mihara

Tsukuba Univ. A. Ozawa

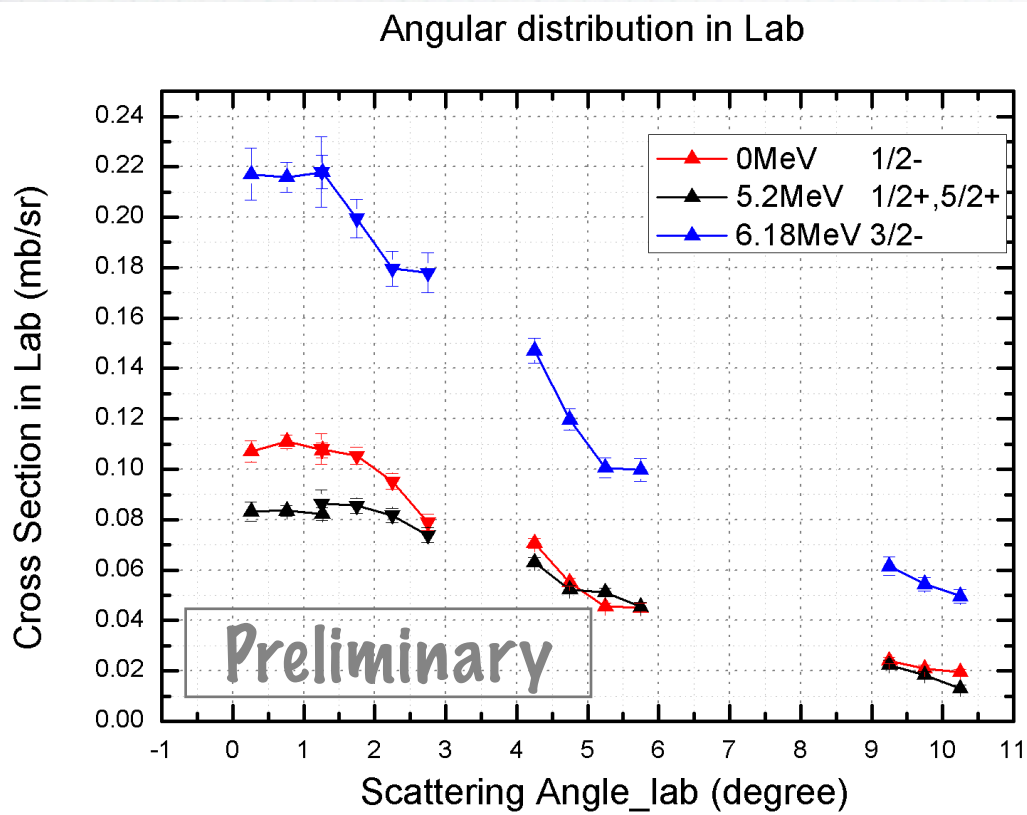
RIKEN

Nishina Center J. Zenihiro

Kyoto Univ. T. Kawabata, Y. Matsuda

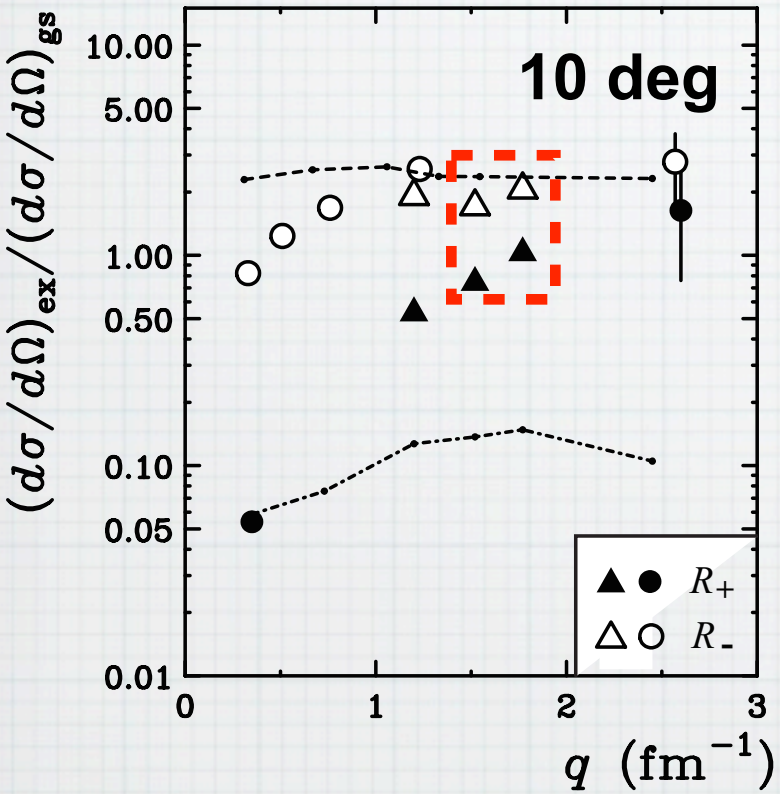
[RCNP-E396]

$^{16}O(p,d),^{12}C(p,d)$ reactions at forward angles with 392 MeV proton beam



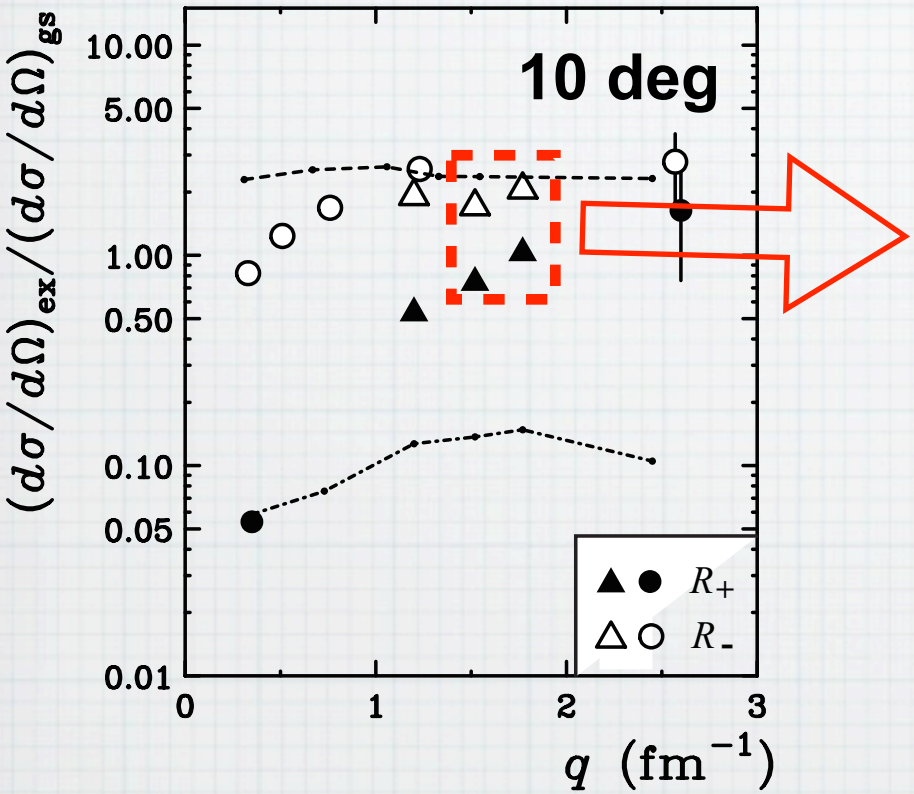
[RCNP-E396]

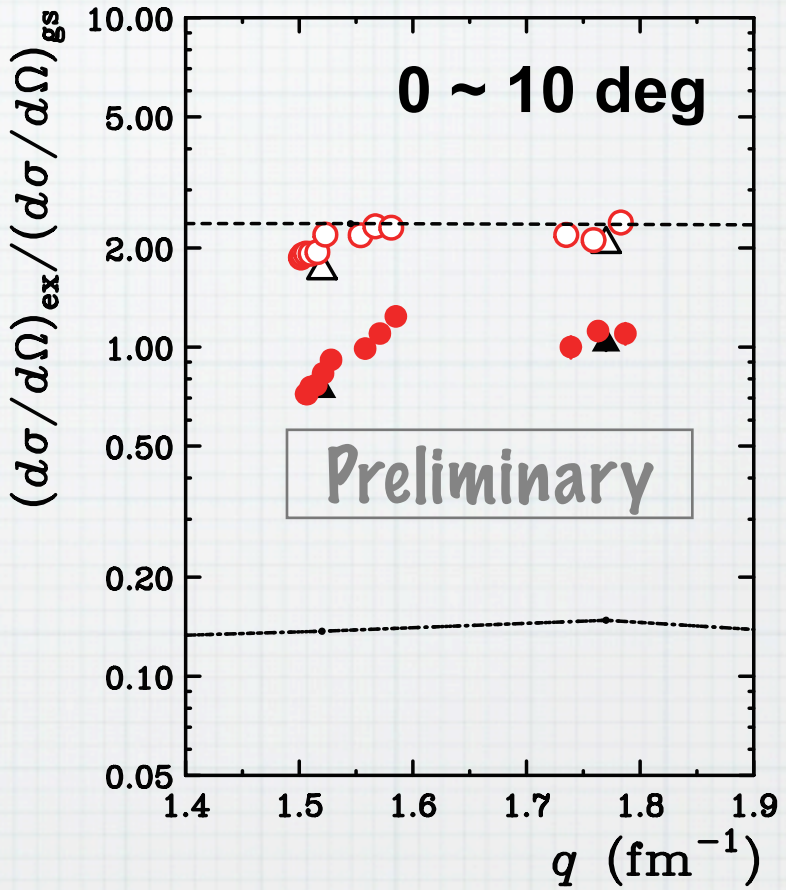
^{16}O(p,d),^{12}C(p,d) reactions at forward angles with 392 MeV proton beam



[RCNP-E396]

^{16}O(p,d),^{12}C(p,d) reactions at forward angles with 392 MeV proton beam





See Chenlei Guo's Talk

Effect of reaction mechanism is negligible

GSI-S436/S437 collaboration

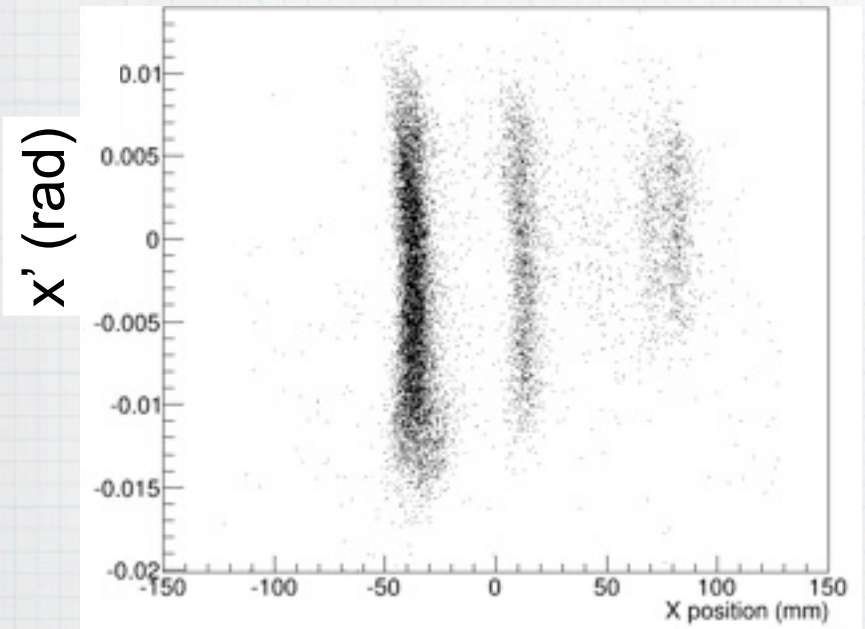
Y. Ayyad, J. Benlliure, K.-T. Brinkmann, S. Friedrich, H. Fujioka,
H. Geissel, J. Gellanki, C.L. Guo, E. Haettner, R. S. Hayano,
Y. Higashi, S. Hirenzaki, Y. Igarashi, N. Ikeno, K. Itahashi, M. Iwasaki,
D. Jido, N. Kalantar, R. Knoebel, N. Kurz, V. Metag, K. Miki, I. Mukha,
M. Harakeh, T. Myo, T. Nagae, H. Nagahiro, M. Nanova, C. Nociforo,
T. Nishi, H.J. Ong, S. Pietri, A. Prochazka, S. Purushothaman,
C. Rappold, M.P. Reiter, K. Rituparna, J.L.R. Sanchez,
C. Scheidenberger, H. Simon, B.H. Sun, K. Suzuki, M. Takechi,
Y.K. Tanaka, I. Tanihata, S. Terashima, H. Toki, Y.N. Watanabe,
H. Weick, E. Widmann, J. Winfield, X. Xu, H. Yamakami, J.W. Zhao

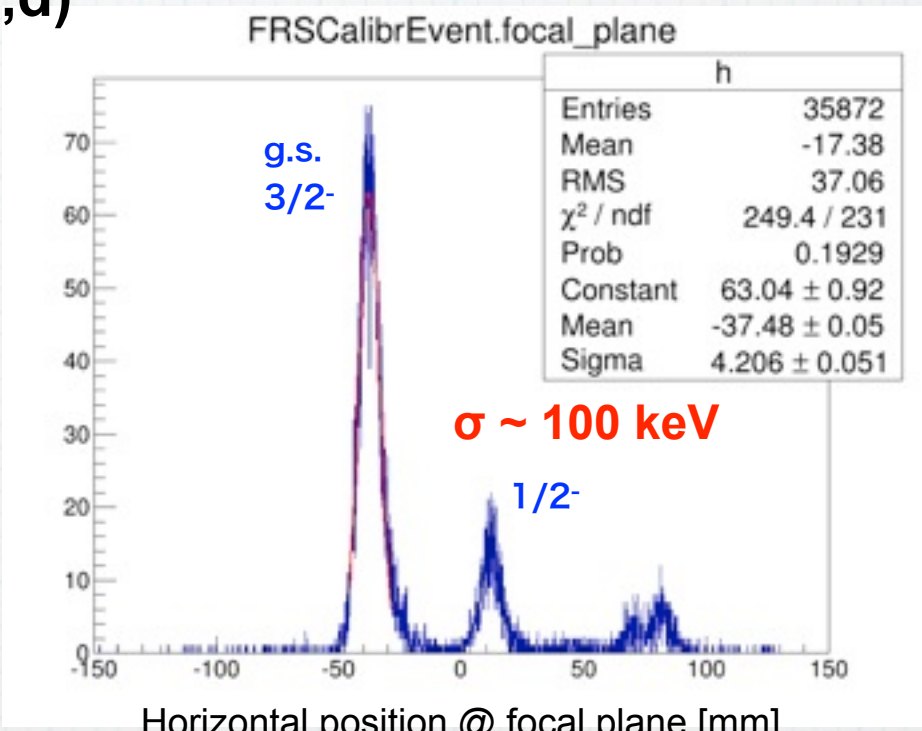
Osaka University, Universidade de Santiago de Compostela,
Universitaet Giessen, Kyoto University, GSI, University of Groningen,
Beihang University, The University of Tokyo, Nara Women's University, KEK,
RIKEN, Tokyo Metropolitan University, Technische Universitaet Darmstadt,
TRIUMF and Saint Mary’s University, Stefan Meyer Institut, Niigata University

[GSI-S436]
^{16}O(p,d),^{12}C(p,d) reactions at forward angles with 400 - 1200 MeV/u proton beams

Proton beam @400 MeV/u, with 107 mg/cm^2 ^{nat}C target

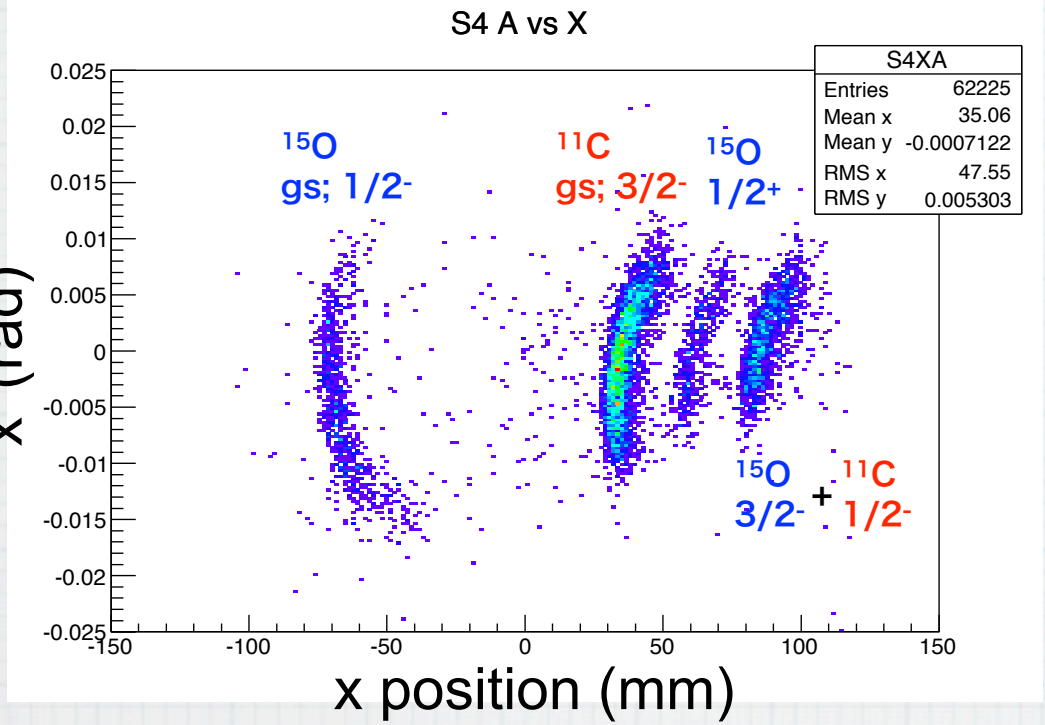
^{12}C(p,d)

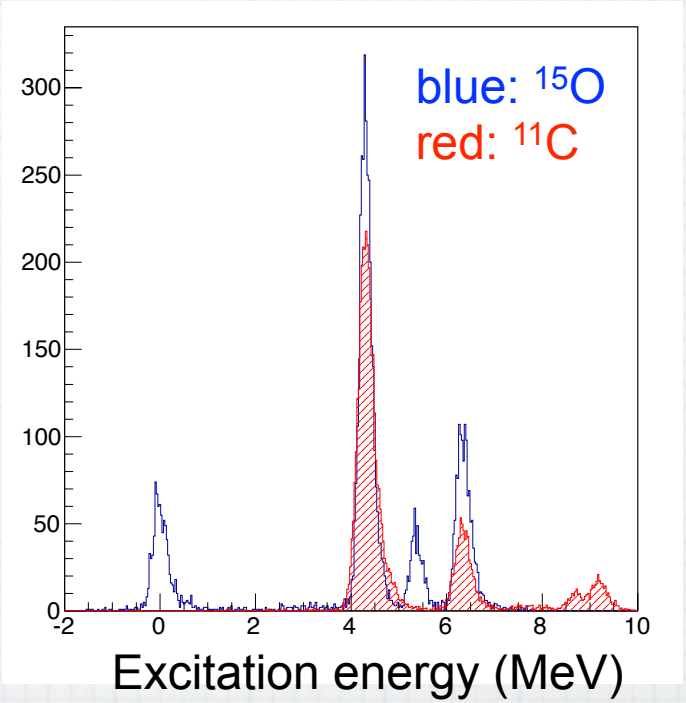




Sufficient resolution achieved

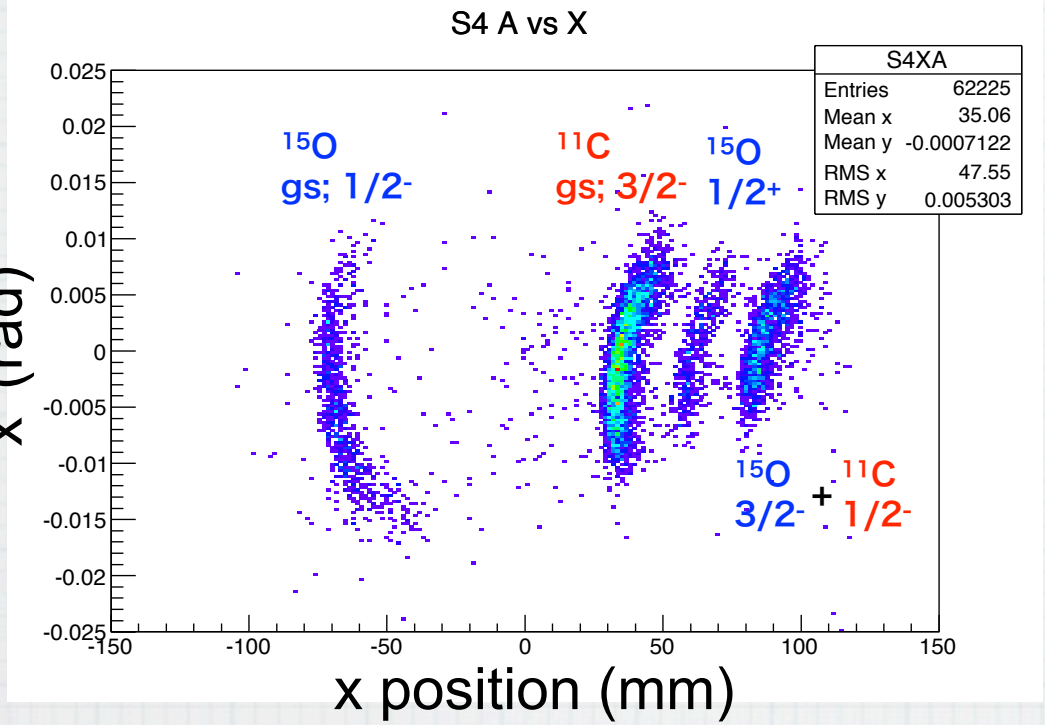
[GSI-S436]
Preliminary Results for ^{16}O(p,d)@400 MeV/u

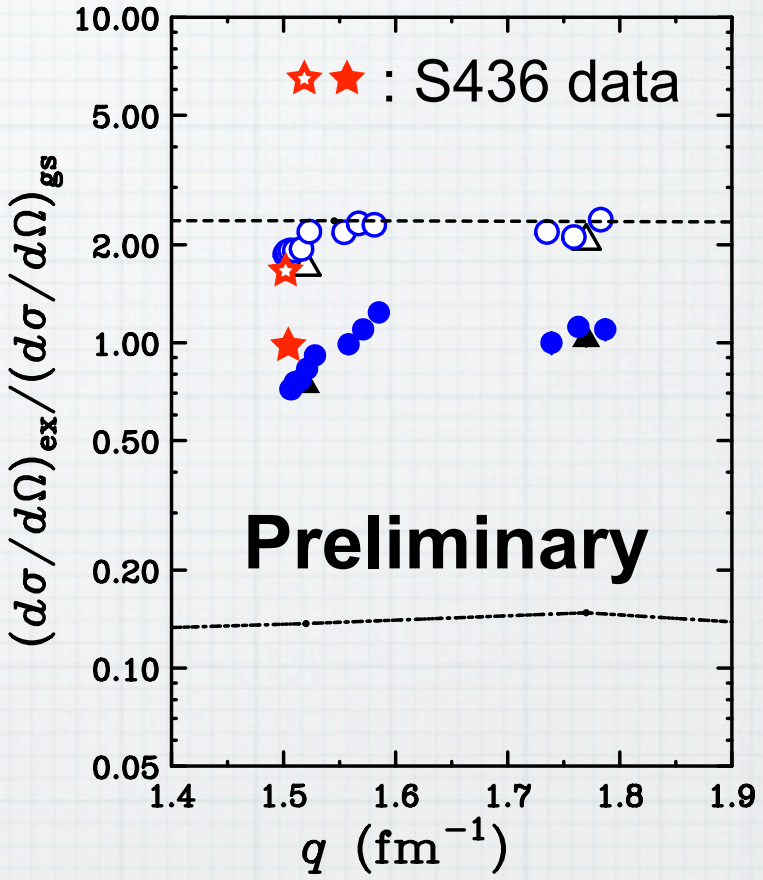




[GSI-S436]

Preliminary Results for ^{16}O(p,d)@400 MeV/u





Ratios consistent with RCNP data

2015年11月18日水曜日

Hot News!

[RCNP-E443]
Understanding the effect of tensor interactions in light nuclei
- Studies of proton-neutron and neutron-neutron correlations -

TERASHIMA Satoru (Beihang University)

ONG Hooi Jin (RCNP, Osaka University)

--Collaborators--

Lei Yu, **P.Y. Chan**, X.Y. Le, L.H. Zhu, G.L. Zhang, B.H. Sun, T.F. Wang, I. Tanihata, N. Aoi, A. Tamii, Y. Ayyad, J. Tanaka, D.T. Tran, H. Sakaguchi, M. Fukuda, K. Matsuta, M. Mihara, T. Kawabata, Y. Matsuda, J. Zenihiro, K. Miki, C. Schiedenberger, H. Geissel, H. Weick, E. Haettner

--Theoretical support--

H. Toki, K. Ogata, T. Myo, Y. Ogawa, D.Y. Pang

Performed!
Oct.31-Nov.4, 2015

[RCNP-E443]
Understanding the effect of tensor interactions in light nuclei
- Studies of proton-neutron and neutron-neutron correlations -

TERASHIMA Satoru (Beihang University)

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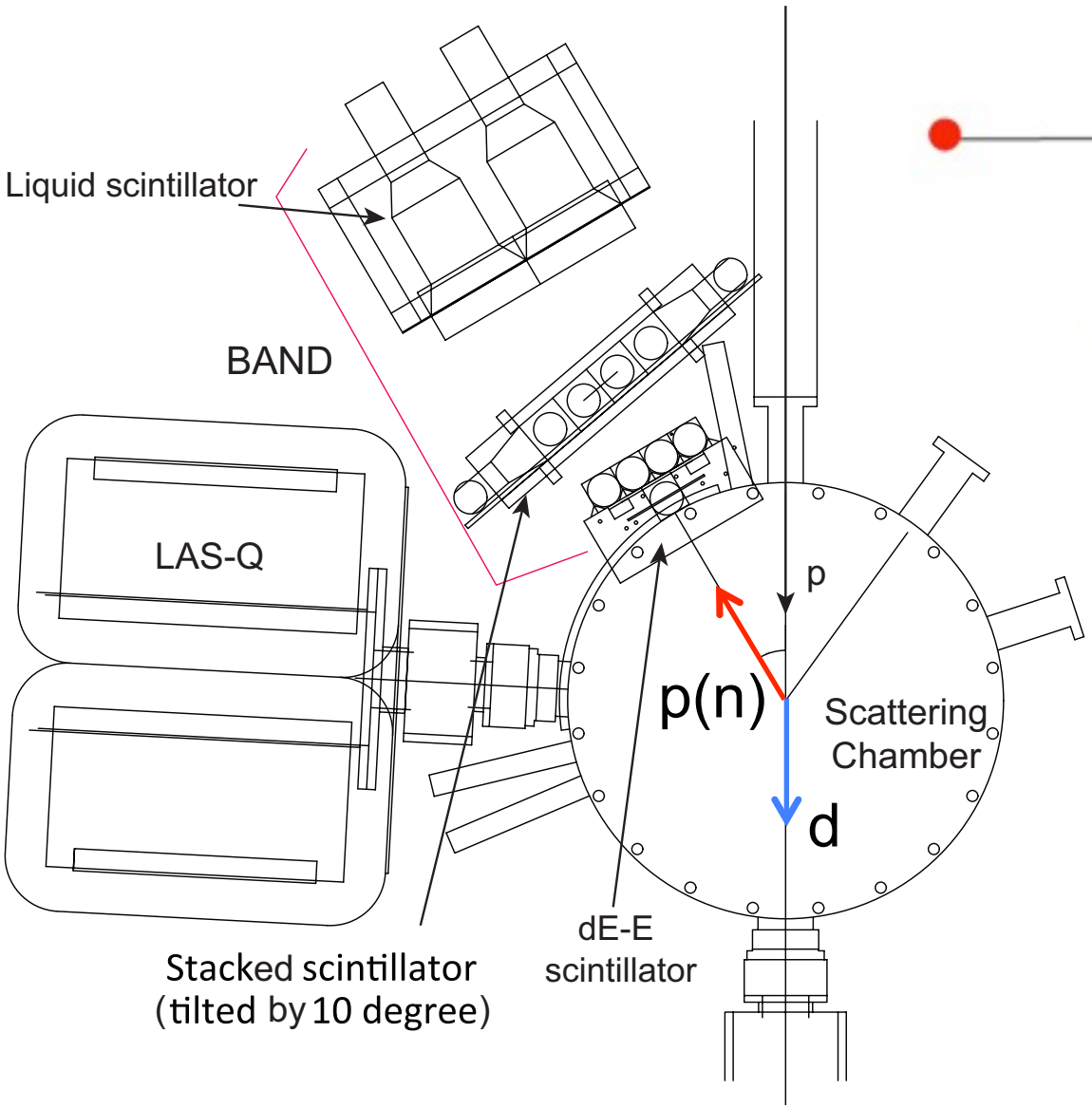
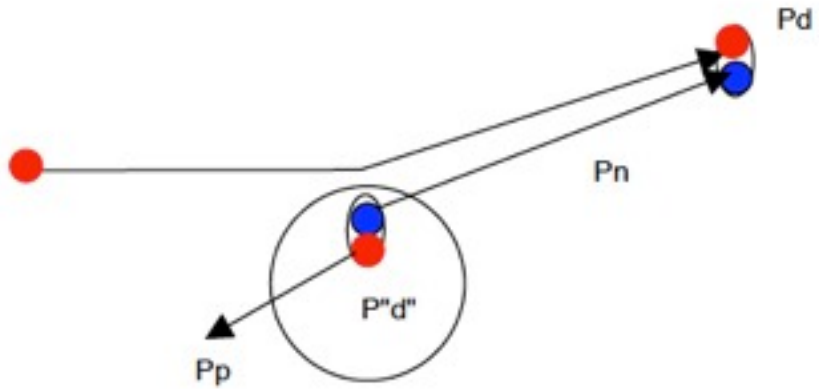
Lei Yu, **P.Y. Chan**, X.Y. Le, L.H. Zhu, G.L. Zhang, B.H. Sun, T.F. Wang, I. Tanihata, N. Aoi, A. Tamii, Y. Ayyad, J. Tanaka, D.T. Tran, H. Sakaguchi, M. Fukuda, K. Matsuta, M. Mihara, T. Kawabata, Y. Matsuda, J. Zenihiro, K. Miki, C. Schiedenberger, H. Geissel, H. Weick, E. Haettner

--Theoretical support--

H. Toki, K. Ogata, T. Myo, Y. Ogawa, D.Y. Pang

[RCNP-E443] (p,dp), (p,dn) measurements





Proton beam:
400 MeV; 20 pnA
Target: 60 mg/cm^2

θ_{GR}=8.7^o, 15.0^o
θ_{BAND}=112^o ,135^o

Past experiments with triple coincidence

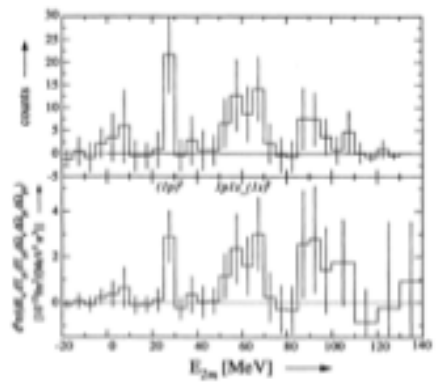


FIG. 1. In the upper panel the total number of triple coincidences, measured for $\theta_{p_1} = 53°$ ($\gamma_{p_1 p_2} = 35°$) and $\theta_{p_2} = -90°$, $-104°$, and $-118°$, is displayed as a function of the double missing energy E_{2m}. The data have been corrected for inefficiencies and accidental coincidences. In the lower panel the cross sections obtained from these data are presented. They are corrected for radiative effects.

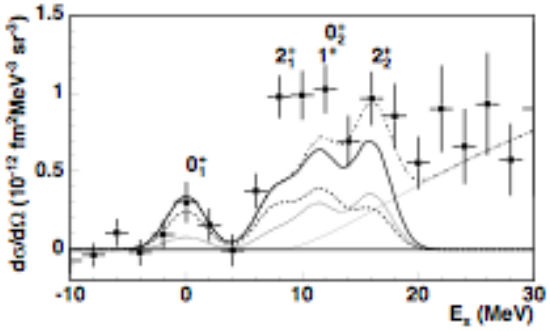


FIG. 1. The ninefold-differential cross section as a function of the excitation energy, averaged over missing momenta between 50 and 350 MeV/c and over γ_1 between 10° and 40° ($d\sigma/d\Omega = d^9\sigma/dE_e d\Omega_e dE_1 d\Omega_1 dE_2 d\Omega_2$). The measured cross sections are indicated with the solid circles. The error bars represent the statistical uncertainty. The curves correspond to results of a microscopic calculation (see text).

^{12}C(p,ppn) at BNL
PRL90(03),042301

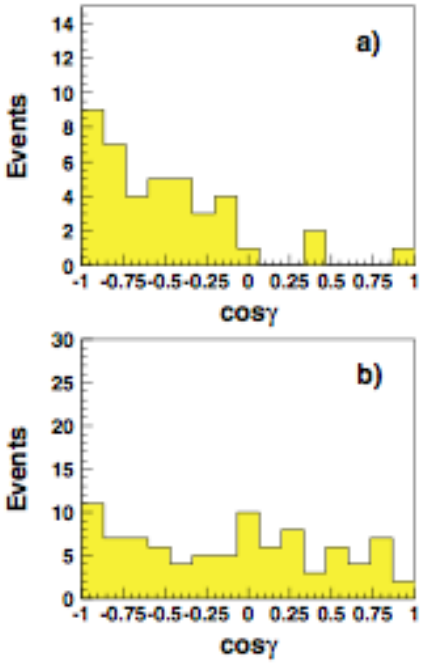


FIG. 2 (color online). Plots of cosγ, where γ is the angle between $\mathbf{p}_n$ and $\mathbf{p}_f$, for ^{12}C($p, 2p + n$) events. Panel (a) is for events with $p_n > 0.22$ GeV/c, and panel (b) is for events with $p_n < 0.22$ GeV/c; 0.22 GeV/$c = k_F$, the Fermi momentum for ^{12}C.

^{12}C,^{16}O(e,e'pp) at NIKEFF PRL74(95), 1712, PRL81(98), 2213

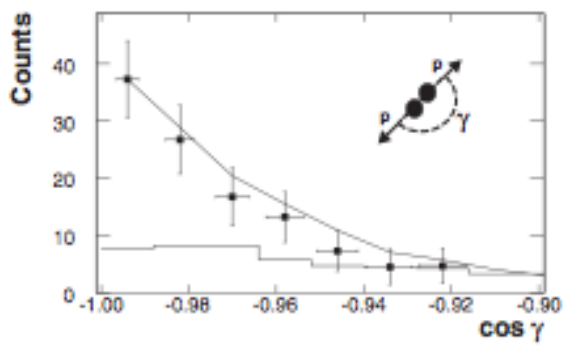


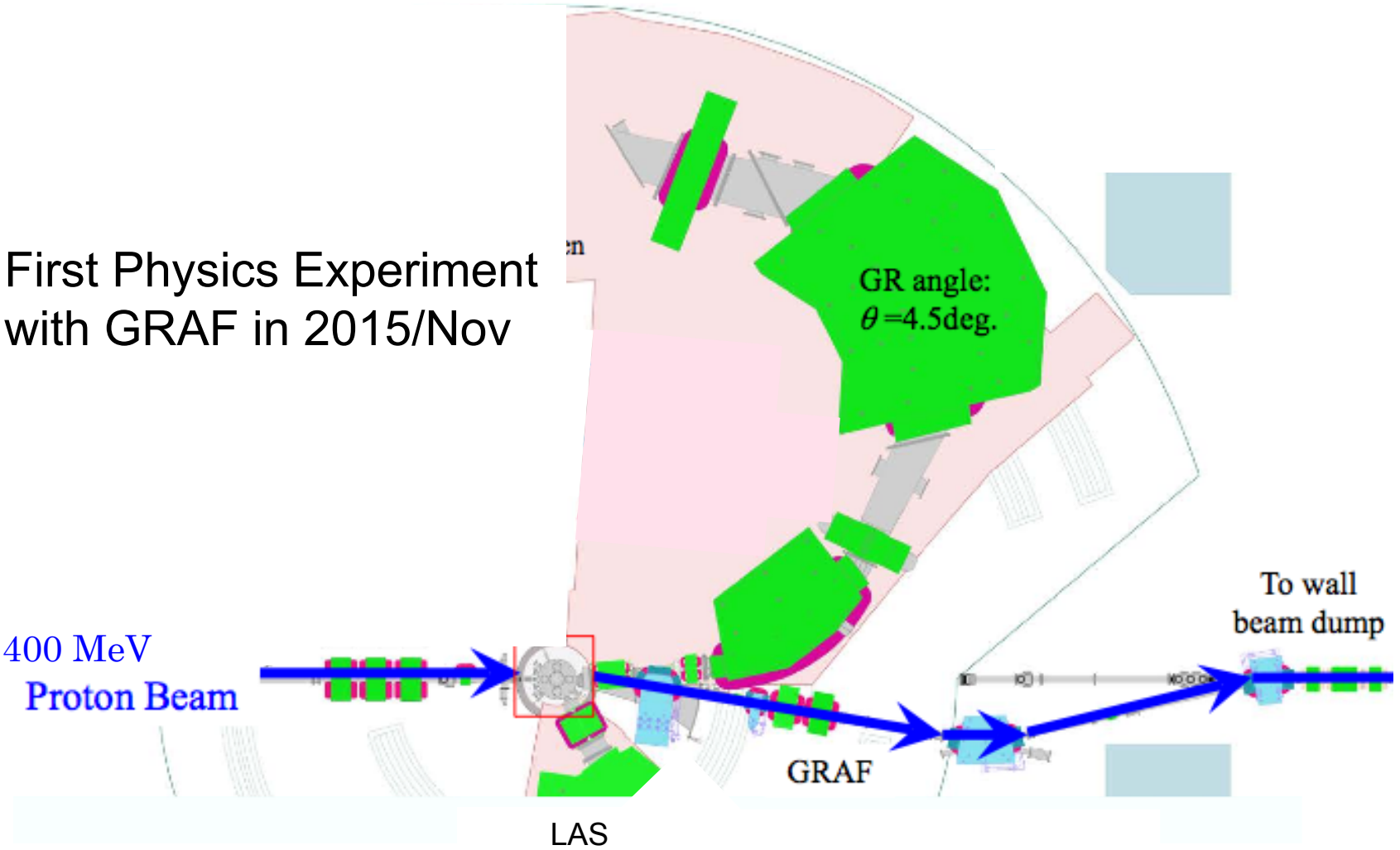
FIG. 3. The distribution of the cosine of the opening angle between the $\vec{p}_{miss}$ and $\vec{p}_{rec}$ for the $p_{miss} = 0.55$ GeV/c kinematics. The histogram shows the distribution of random events. The curve is a simulation of the scattering off a moving pair with a width of 0.136 GeV/c for the pair c.m. momentum.

^{12}C(e,e'pp[or n]) at JLab
PRL99(07)072501

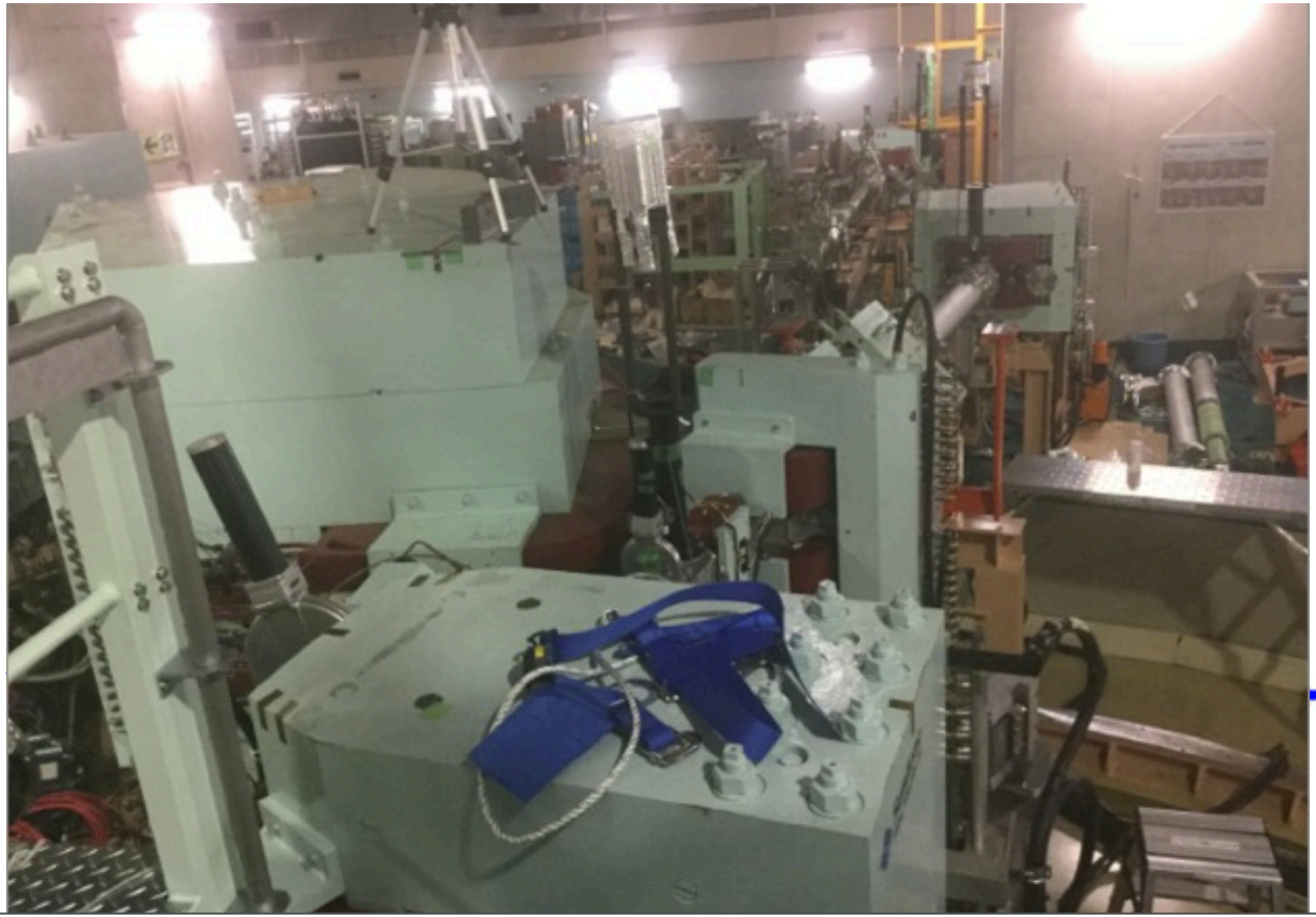
High statistics measurement is needed
=> (p,dN) reaction

WSF/GRAF(WS/Grand-RAiden Forward mode)
- New beam line for low-background coincidence measurement

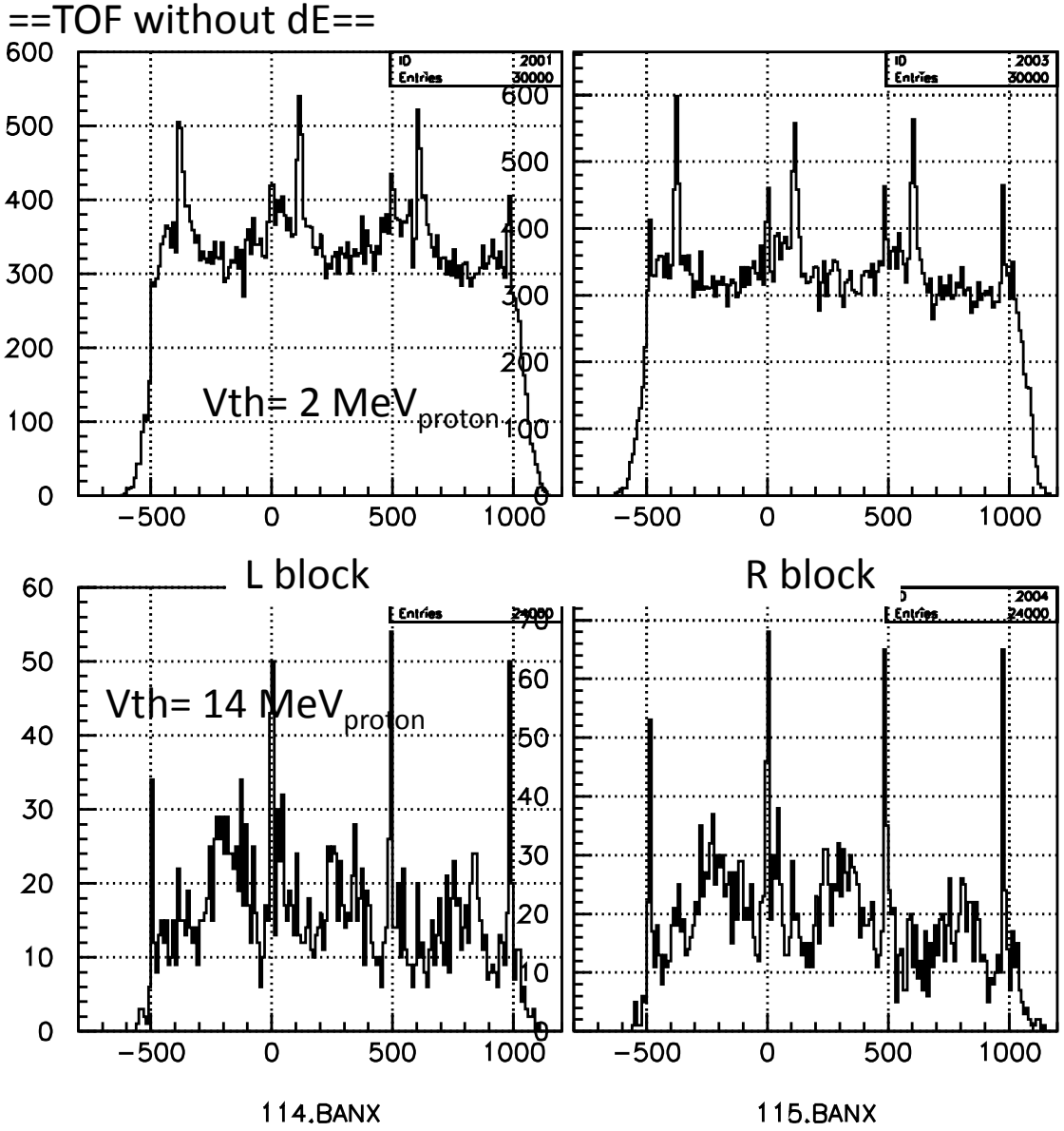
First Physics Experiment
with GRAF in 2015/Nov



WSF/GRAF(WS/Grand-RAiden Forward mode)
- New beam line for low-background coincidence measurement



Before GRAF



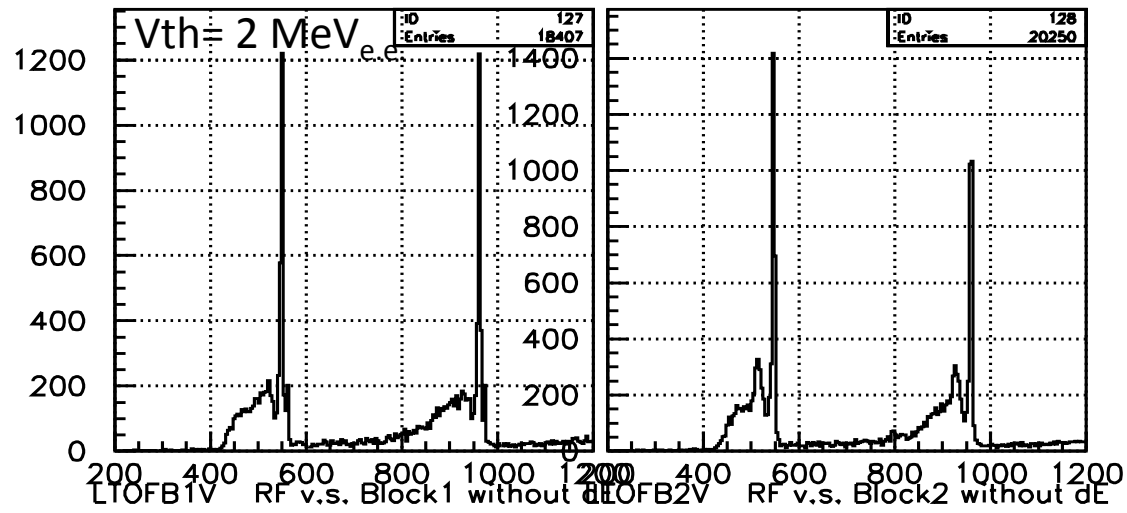
[RCNP-E396:2013/Nov]

θ_{GR}=5.0°, Q1FC, 8 nA

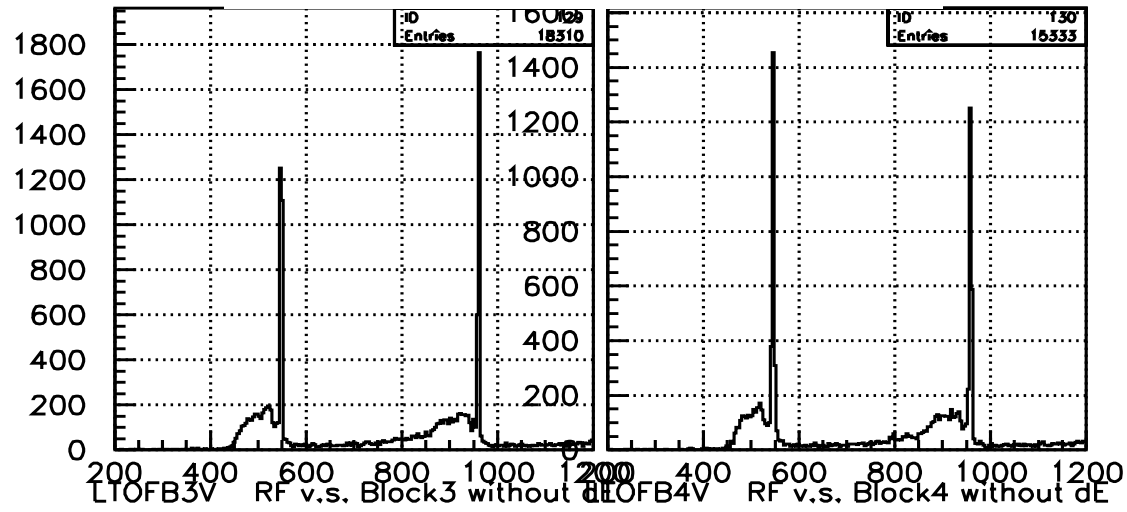
Continuum background from beam stopper[FC]

With GRAF

==TOF without dE==



block 1(LL) block 2(L)



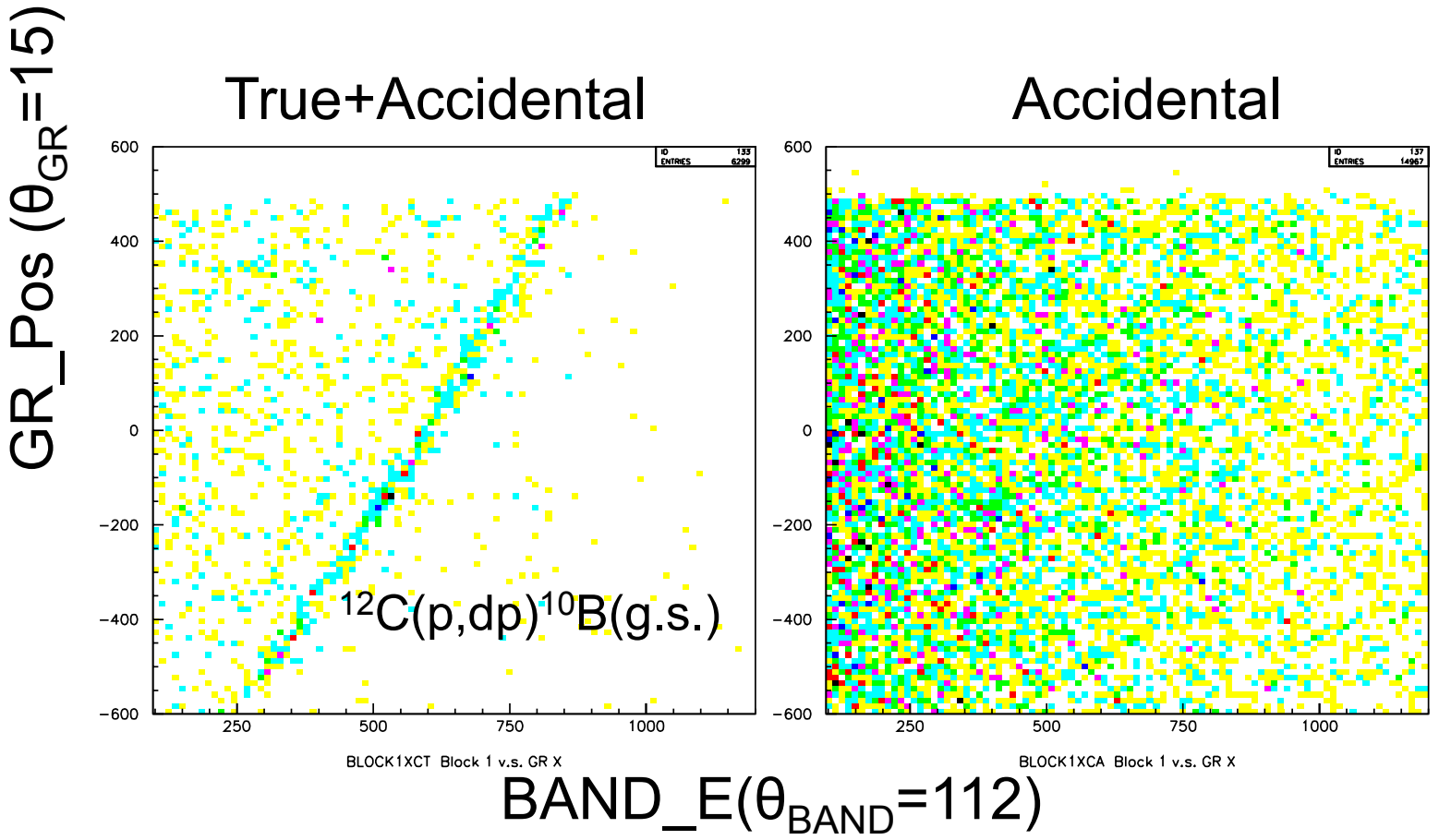
block 3(R) block 4(RR)

[RCNP-E443:2015/Nov]

θ_{GR}=8.7°, WallFC, 20 nA

Now ready for neutron coincidence measurement at finite angle

[RCNP-E443] Snapshots of online data



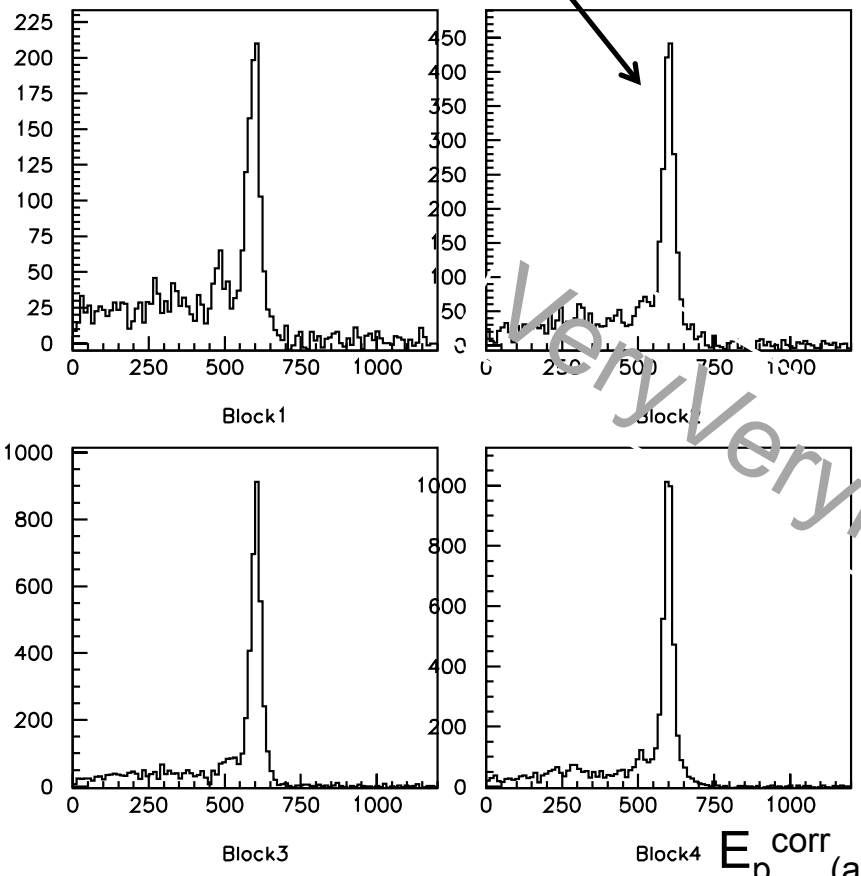
3% in σ for Pla-QDC
150 psec in σ for RF-Pla-TDC

1-2% of total data set

Cont.

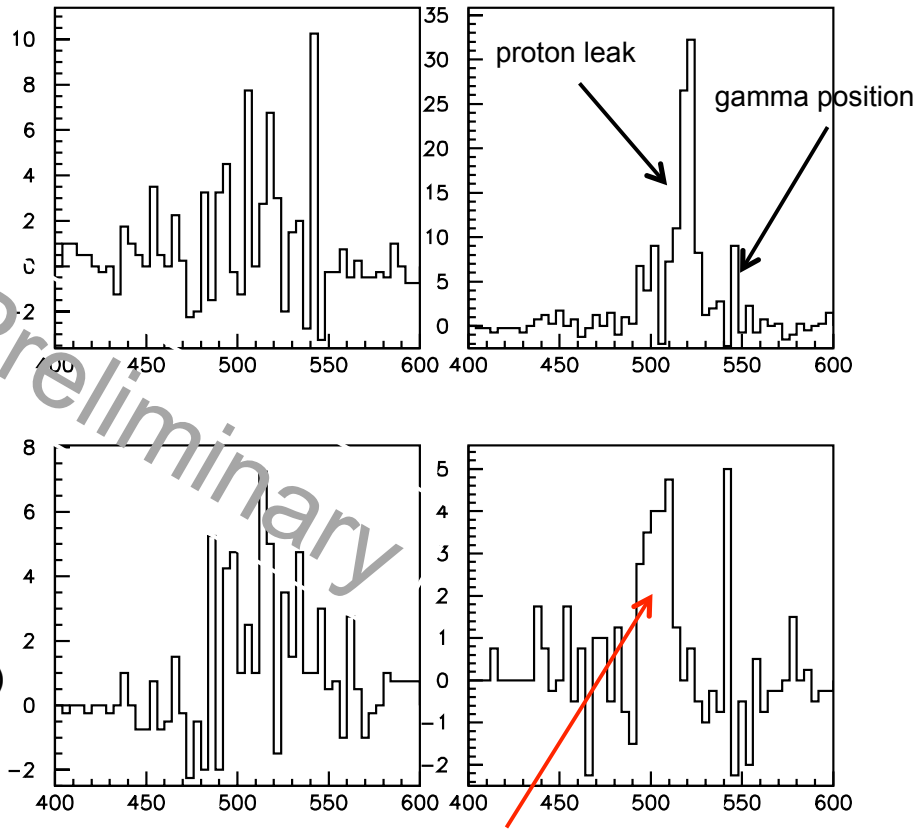
$^{12}C(p,dp)^{10}B(g.s.)$

Ex



$^{nat}C(p,dn)$ in 30 min

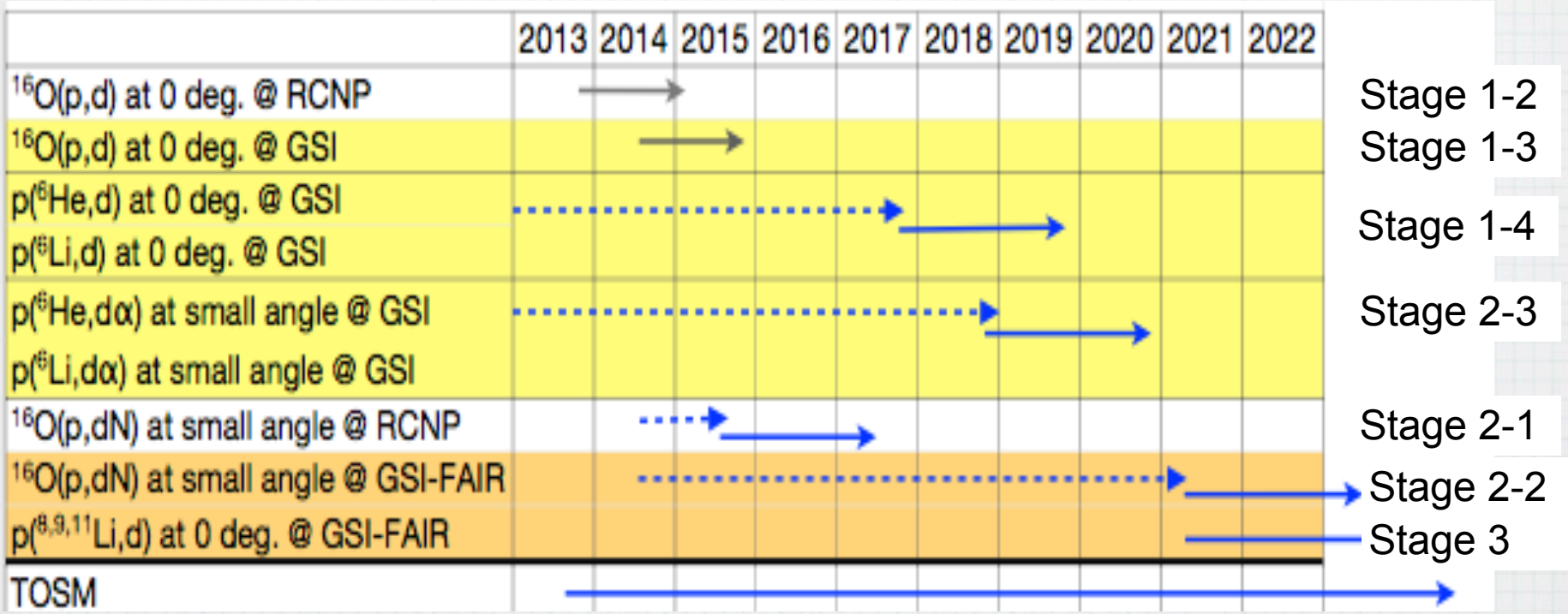
Estimated resolution ~ 4 MeV[σ]



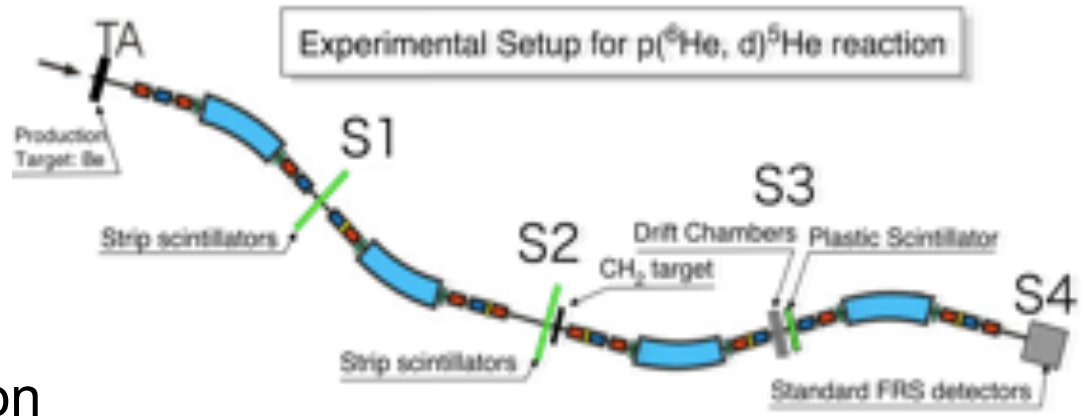
$^{nat}C(p,dp)$ in 30 min

Estimated resolution ~ 2 MeV[σ]

Roadmap of Experiments at RCNP & GSI-FAIR, ...



Stage 1-4: p(^{6}He/^{6}Li,d) experiment @ FRS



Exp. Requirements:

High energy HI acceleration
➔high momentum transfer
Fragment Separator
➔unstable ^{6}He beam
Moderate Resolution Spectrometer (~ a few 1000) at 0 degree
➔ to separate excited states of ^{5}He, ^{5}Li
High rate tracker [or good quality RI beam at the high energy]
➔ scintillation fiber array + multi-hit TDC

Stage 1-4: p(^{6}He/^{6}Li,d) experiment @ FRS

Exp. Requirements:

High energy HI acceleration
➔high momentum transfer
Fragment Separator
➔unstable ^{6}He beam
Moderate Resolution Spectror
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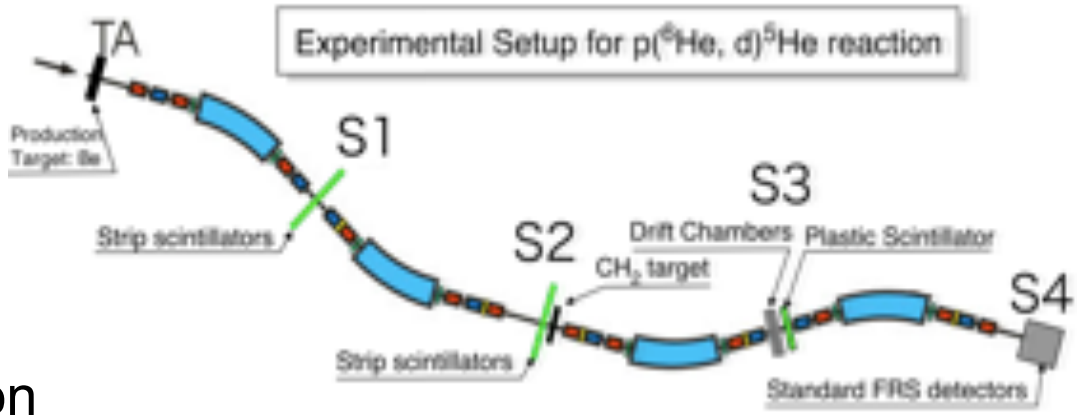
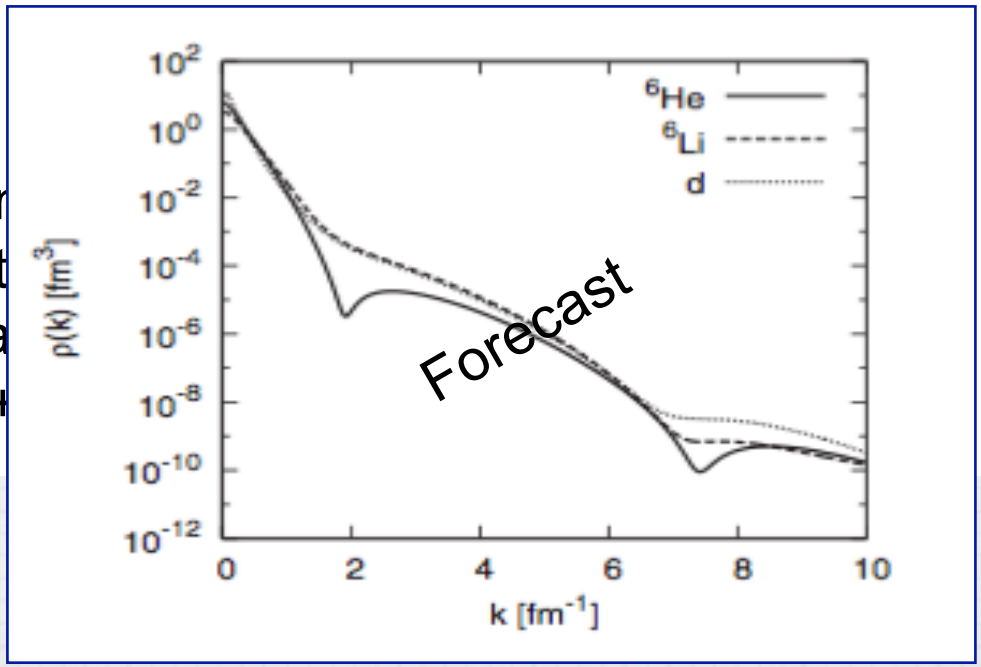
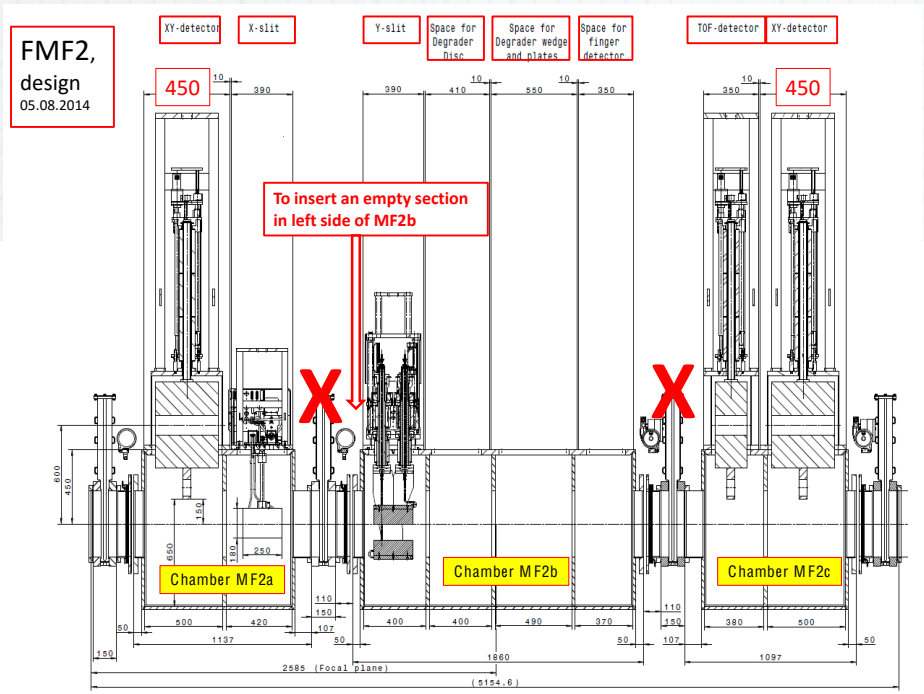




Stage 2-2: (p,dN) experiment @ Super-FRS



Summary

- We have observed large components of high-momentum neutrons in the ^{16}O ground state via (p,d) reaction.
- The results indicate possible evidence on the effect of tensor interactions in ^{16}O.
- Further ^{16}O(p,d) experiments at RCNP, GSI-(FAIR) using proton beams at 400-1200 MeV were performed to confirm the results, and to provide more experimental information.
- $^{12}C/^{16}O$(p,dN) experiment was (successfully) performed at RCNP using newly constructed WSF (GRAF).
- Further experiments to study the effect of tensor interactions in $^{6}He/^{6}Li$, and $^{12}C/^{16}O$(p,dN) at GSI-FAIR are planned/proposed.

Thank you very much for your attention!