Parity-transfer (^{16}O,$^{16}F(0^-)$) reaction for study of spin-dipole 0^- mode

Masanori Dozono
Center for Nuclear Study, the University of Tokyo

The 9th international conference on Direct Reactions with Exotic Beams (DREB) 2016

July 11-15, 2016, Halifax, Canada

Please keep in your minds !!

- ~~Exotic~~ beam ⇒ Primary beam
  (Outgoing particle is exotic)
- ~~Inverse~~-kinematics ⇒ Normal-kinematics

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Direct Reactions with Exotic ~~Beams (DREB)~~ 2016
Particle (DREP)
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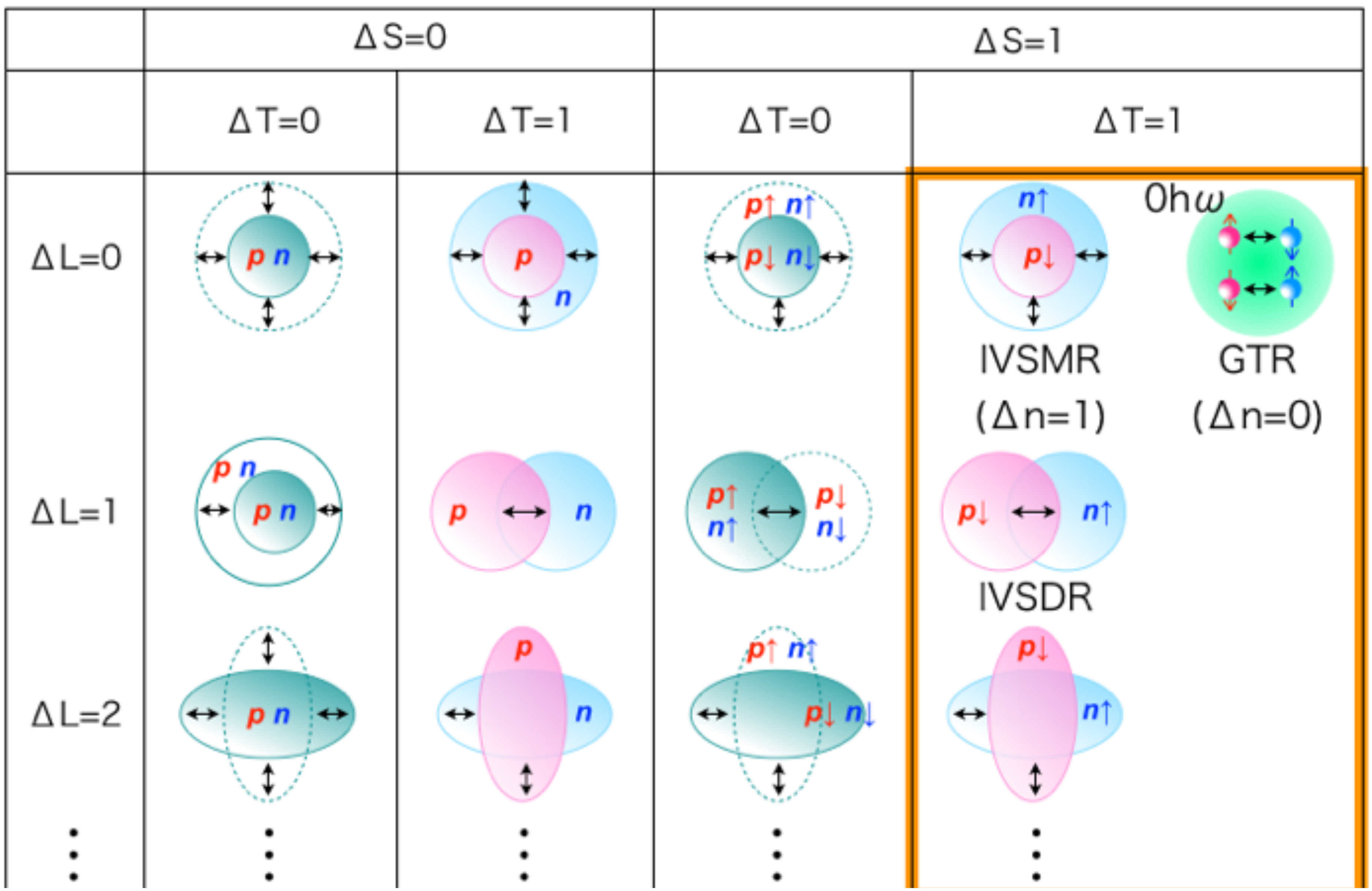
Giant resonances and collective modes

- Related to bulk properties of nuclei
- We can lean about nuclear interaction (correlation)



Spin-isospin mode
(ΔS=1,ΔT=1)

π field in nuclei
(ΔS=1,ΔT=1)

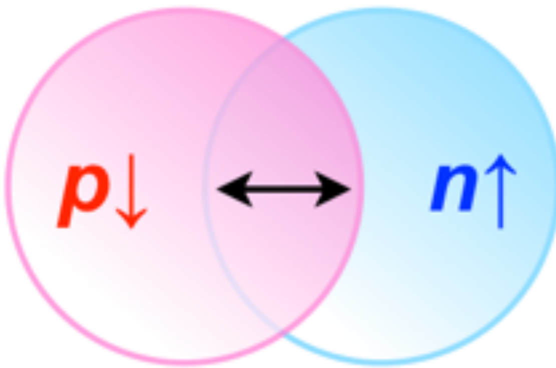
$\propto (\sigma_1 \cdot q)(\sigma_2 \cdot q)(\tau_1 \cdot \tau_2)$

Giant resonances and collective modes

uclei

raction (correlation)

Spin-Dipole (SD) mode



$$\hat{O}^{\lambda,\mu}_{\pm} = \sum_i \tau^i_{\pm} r_i [Y_1(\hat{r}_i) \times \sigma_i]^{\lambda}_{\mu}$$

- ΔL=1, ΔS=1, ΔT=1
- ΔJ^{π}=0⁻, 1⁻, 2⁻

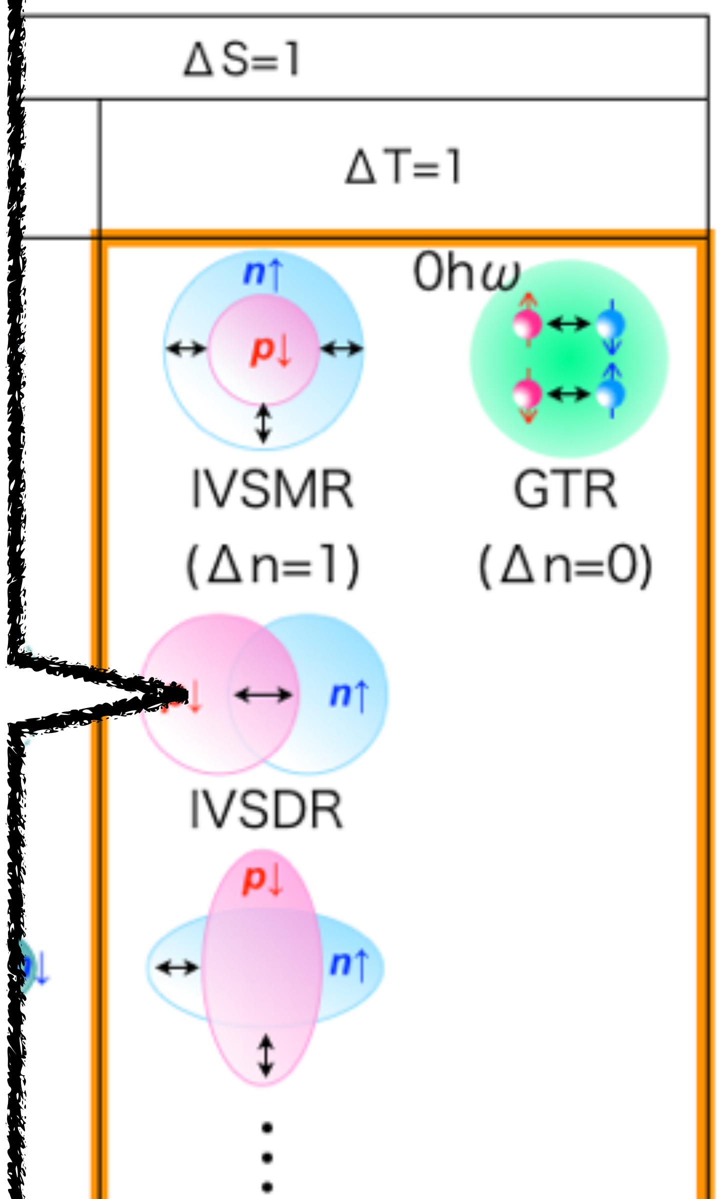
SD(0⁻) mode :

Purely sensitive to σ・q

(No σxq contribution)

⇒ Directly probe

π-field (tensor) effects



Spin-isospin mode

(ΔS=1,ΔT=1)

π field in nuclei

(ΔS=1,ΔT=1)

$$\propto (\sigma_1 \cdot q)(\sigma_2 \cdot q)(\tau_1 \cdot \tau_2)$$

Tensor effects on 0⁻ strengths

C. L. Bai, H. Sagawa et al., PRC 83, 054316 (2011); Private communication

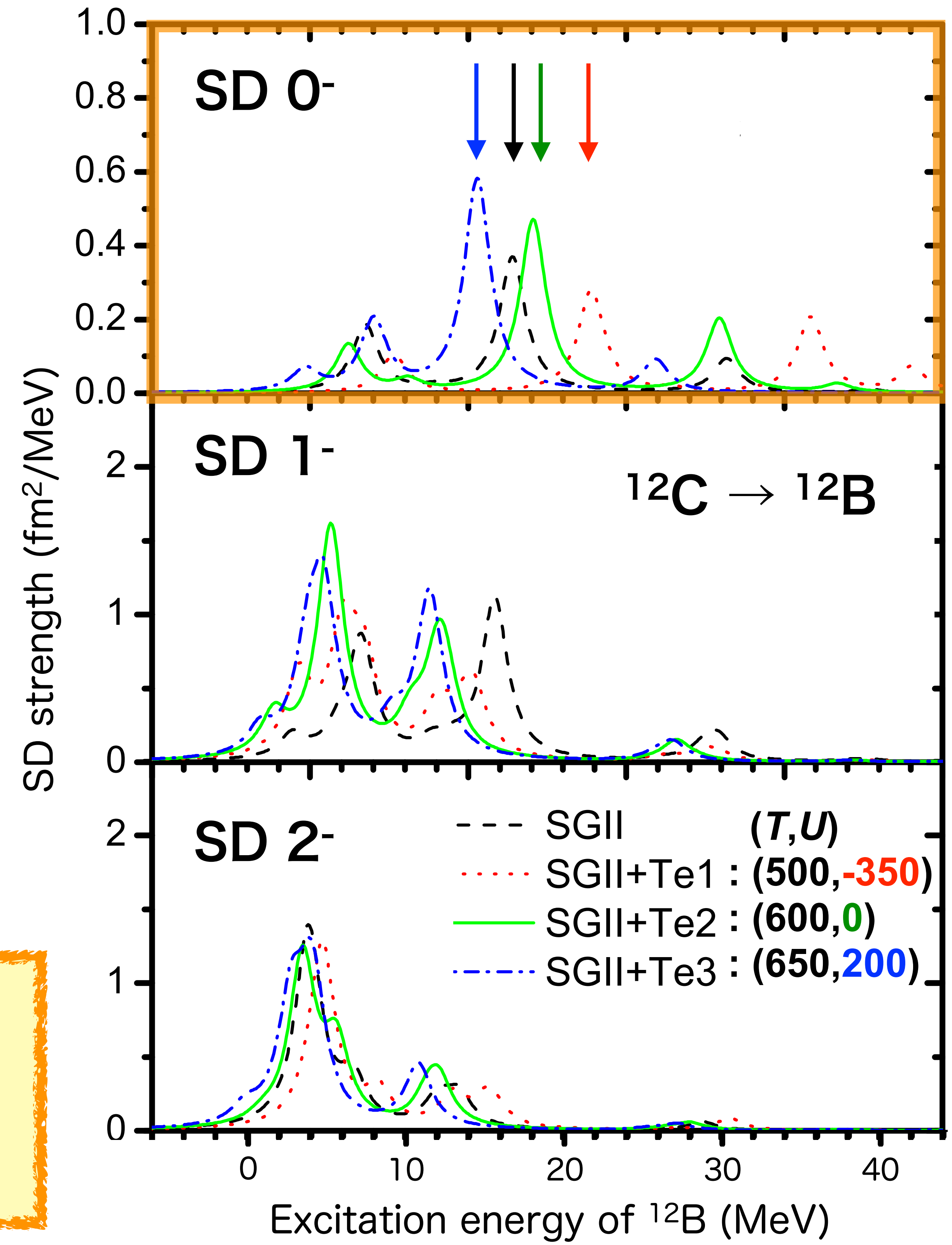
- Results of HF+RPA calc.
  - Tensor effects
    - 0⁻ peak shifts by several MeV
  - Skyrme-type tensor int.
    - Triplet-Even
      : Constrained by GT data
    - Triplet-Odd : NOT well constrained

$$V^T = \frac{T}{2}\left\{\left[(\sigma_1\cdot\mathbf{k}')(\sigma_2\cdot\mathbf{k}') - \frac{1}{3}(\sigma_1\cdot\sigma_2)\mathbf{k}'^2\right]\delta(r) + \delta(\mathbf{r})\left[(\sigma_1\cdot\mathbf{k})(\sigma_2\cdot\mathbf{k}) - \frac{1}{3}(\sigma_1\cdot\sigma_2)\mathbf{k}^2\right]\right\}$$

Triplet-Even (T)

$$+\frac{U}{2}\left\{(\sigma_1\cdot\mathbf{k}')\delta(\mathbf{r})(\sigma_2\cdot\mathbf{k}) + (\sigma_2\cdot\mathbf{k}')\delta(\mathbf{r})(\sigma_1\cdot k) - \frac{2}{3}[(\sigma_1\cdot\sigma_2)\mathbf{k}'\cdot\delta(\mathbf{r})\mathbf{k}]\right\}.$$

Triplet-Odd (U)

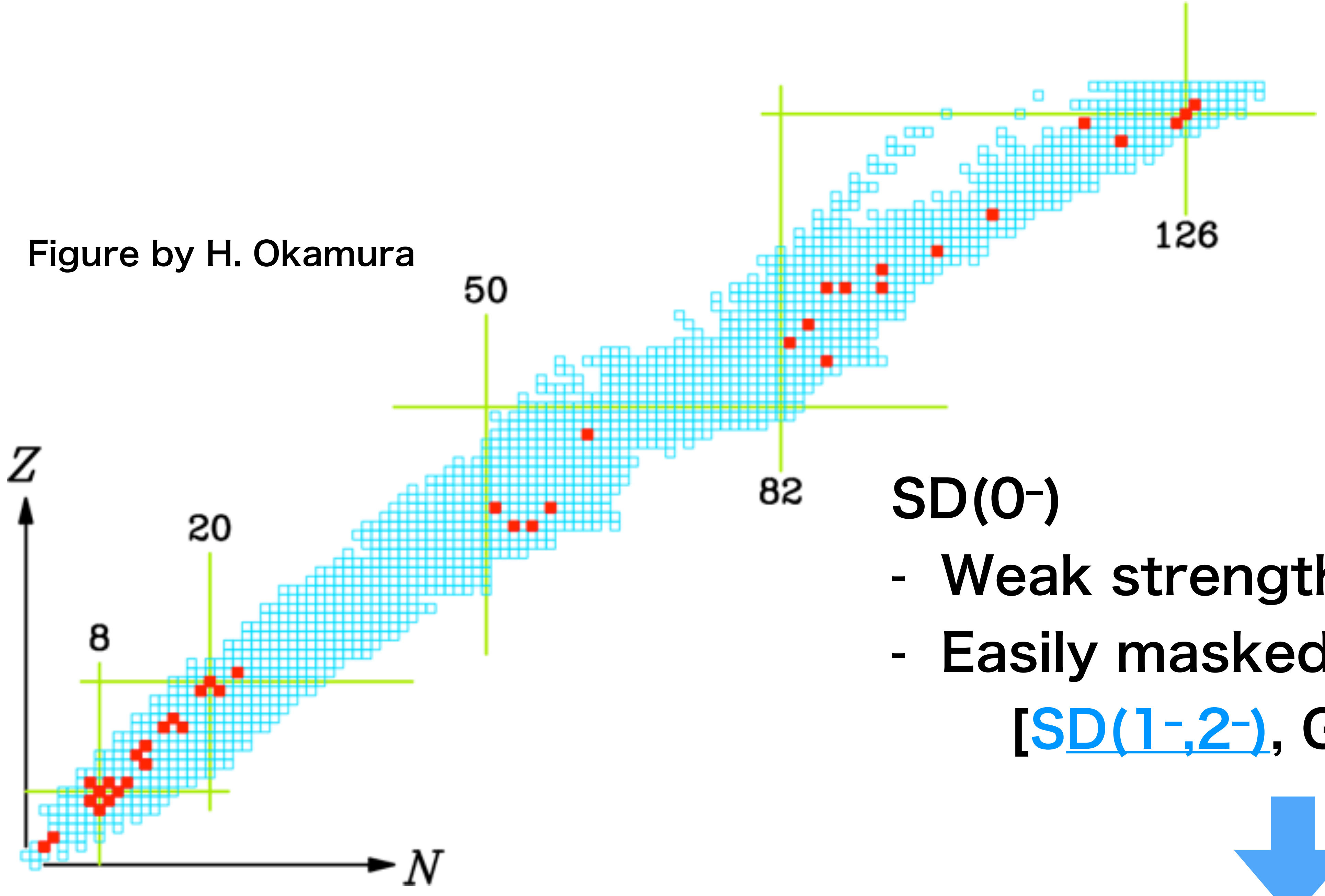


0⁻ distribution is sensitive to tensor
⇒ Exp. data of 0⁻ are important
to pin down tensor force effects

Experimental studies of 0⁻ states

Exp. information on 0⁻ states is very limited

Figure by H. Okamura



SD(0⁻)

- Weak strength
- Easily masked by other J^π
  [SD(1⁻,2⁻), GT(1⁺), . . .]

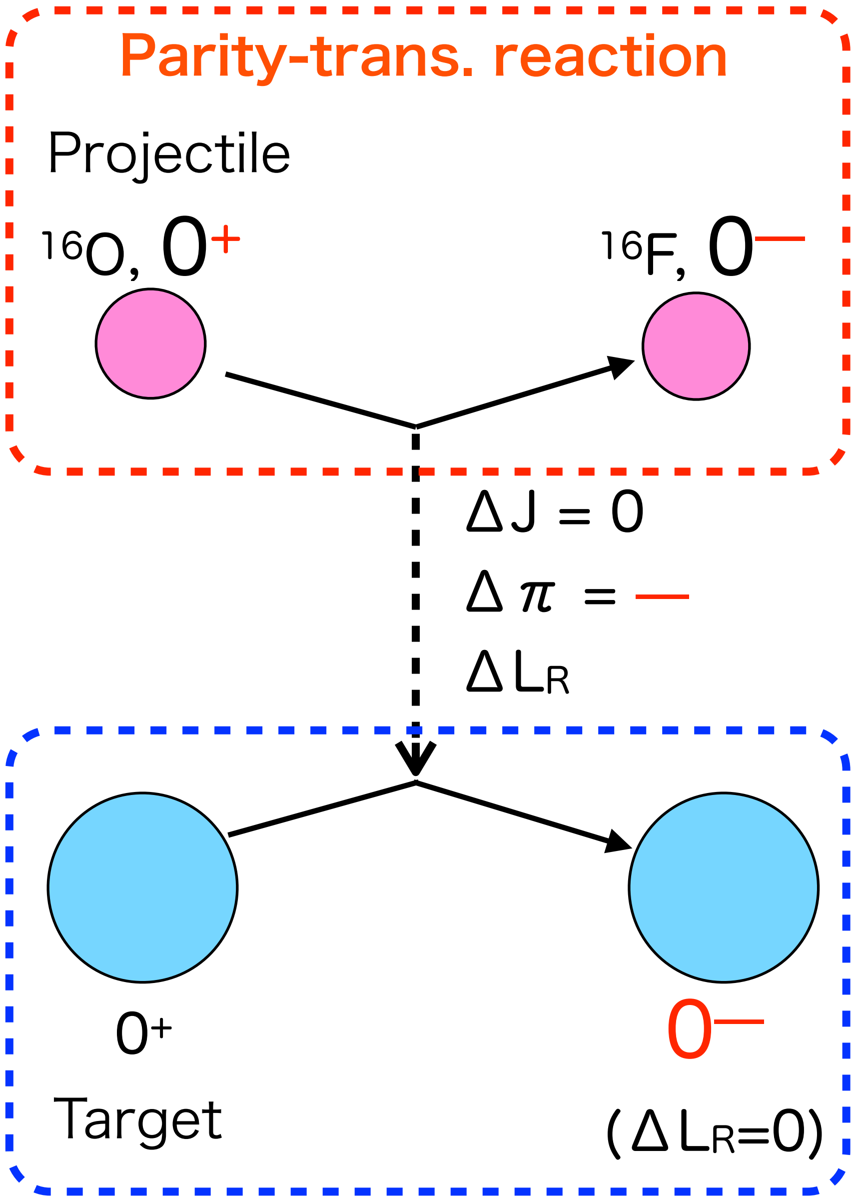
Selective tool for SD(0⁻) !

Parity-transfer (^{16}O,$^{16}F(0^-)$) reaction

Parity-transfer reaction is selective tool for 0^- !

- Parity-trans. (^{16}O,$^{16}F(0^-)$)
  - ^{16}O (g.s., 0^+) → ^{16}F (g.s.,0^-)
- Advantages
  - Selectively excite unnatural-parity states
    - No SD(1^-) contribution
  - Single J^π for each ΔL_R
    - J^π (0^-, 1^+, 2^-,...) can be assigned by the angular distribution

	$\Delta L_R=0$	$\Delta L_R=1$	$\Delta L_R=2$	···
Parity-trans.	0^-	1^+	2^-	···
(p,n),(d,^{2}He) etc.	0^+,1^+	0^-, 1^-, 2^-	1^+, 2^+, 3^+	···



Clean probe for SD(0^-) search

First parity-transfer measurement : $^{12}C(^{16}O,^{16}F(0^-))^{12}B$ at 250 MeV/u

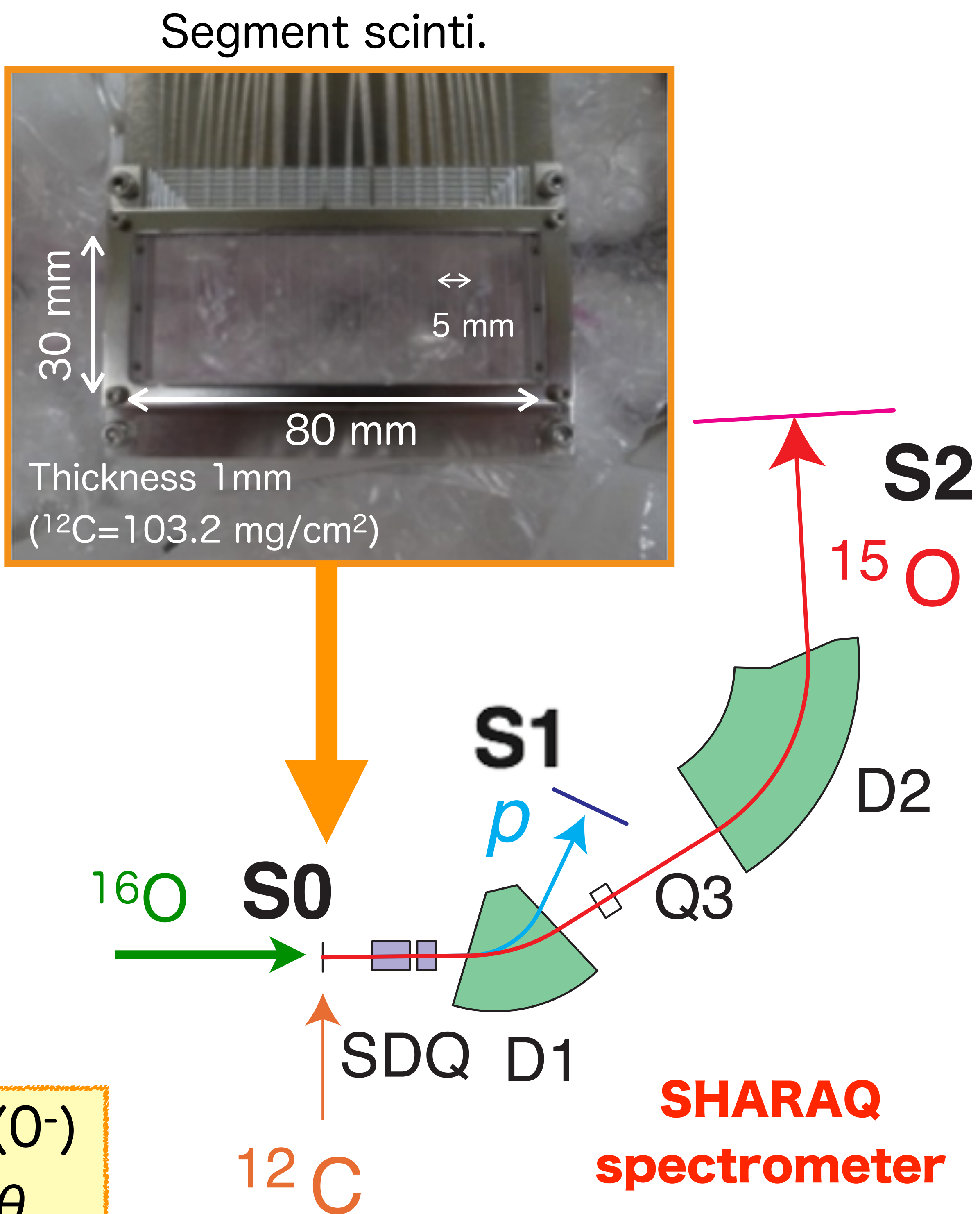
We apply parity-trans. reaction to ^{12}C target

- Why ^{12}C ?
  - Known 0^- at E_x = 9.3 MeV in ^{12}B
    ⇒ Confirm effectiveness of parity-trans. reaction
  - Experimentally more feasible
    - High luminosity,
    - Low B.G. compared with heavier nuclei

GOAL
Establish ($^{16}O,^{16}F(0^-)$)reaction
as a new tool for 0^- study

$^{12}C(^{16}O,^{16}F(0^-))^{12}B$ exp. @ RIBF & SHARAQ

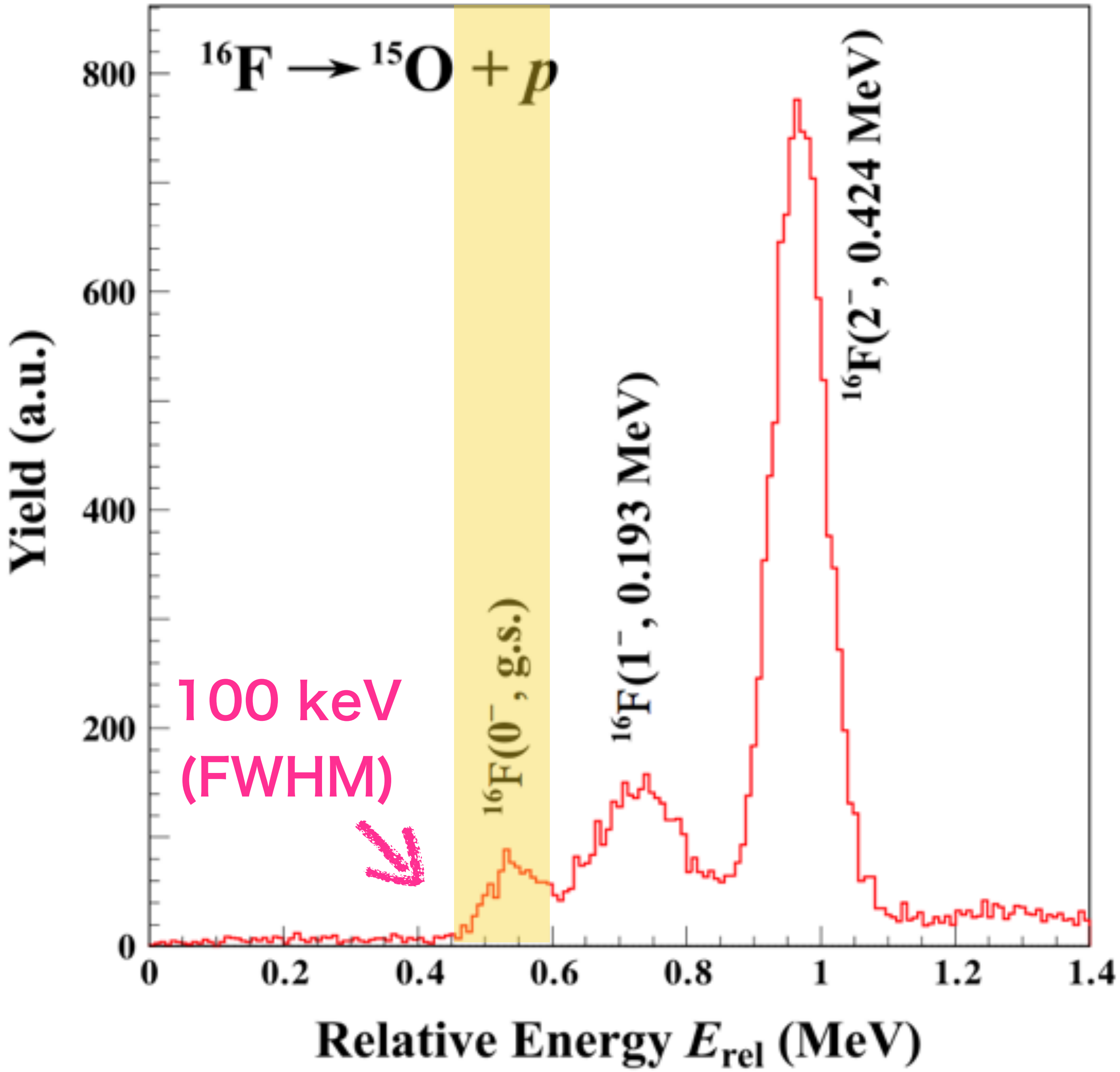
- Beam : Primary ^{16}O
  - 250MeV/u, 10^7 pps (radiation limit)
  - Dispersive matched beam
- Target : ^{12}C
  - Segmented plastic scinti. (active C target, ~100 mg/cm^2)
  - Determine beam x-position @ S0 (NOT used in present analysis)
- Coincidence measurement of $^{16}F \rightarrow {}^{15}O + p$
  - ^{15}O : 2 LP-MWDCs @ S2
  - p : 2 MWDCs @ S1



- Invariant-mass of ^{15}O+p ⇒ Identify $^{16}F(0^-)$
- Missing-mass ⇒ Deduce E_x in ^{12}B and θ

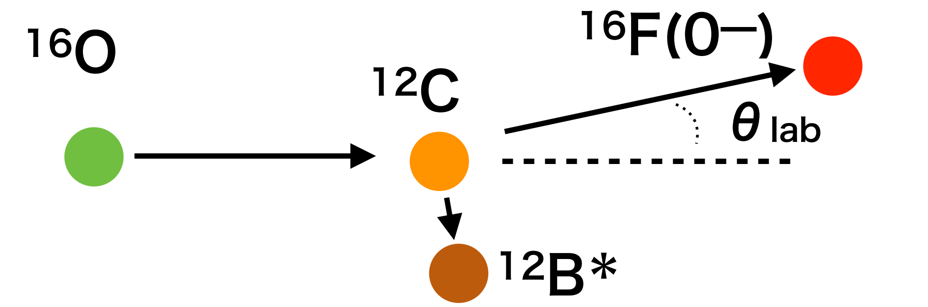
Identification of $^{16}F(0^-)$

- Relative energy E_{rel} between $^{15}O + p$

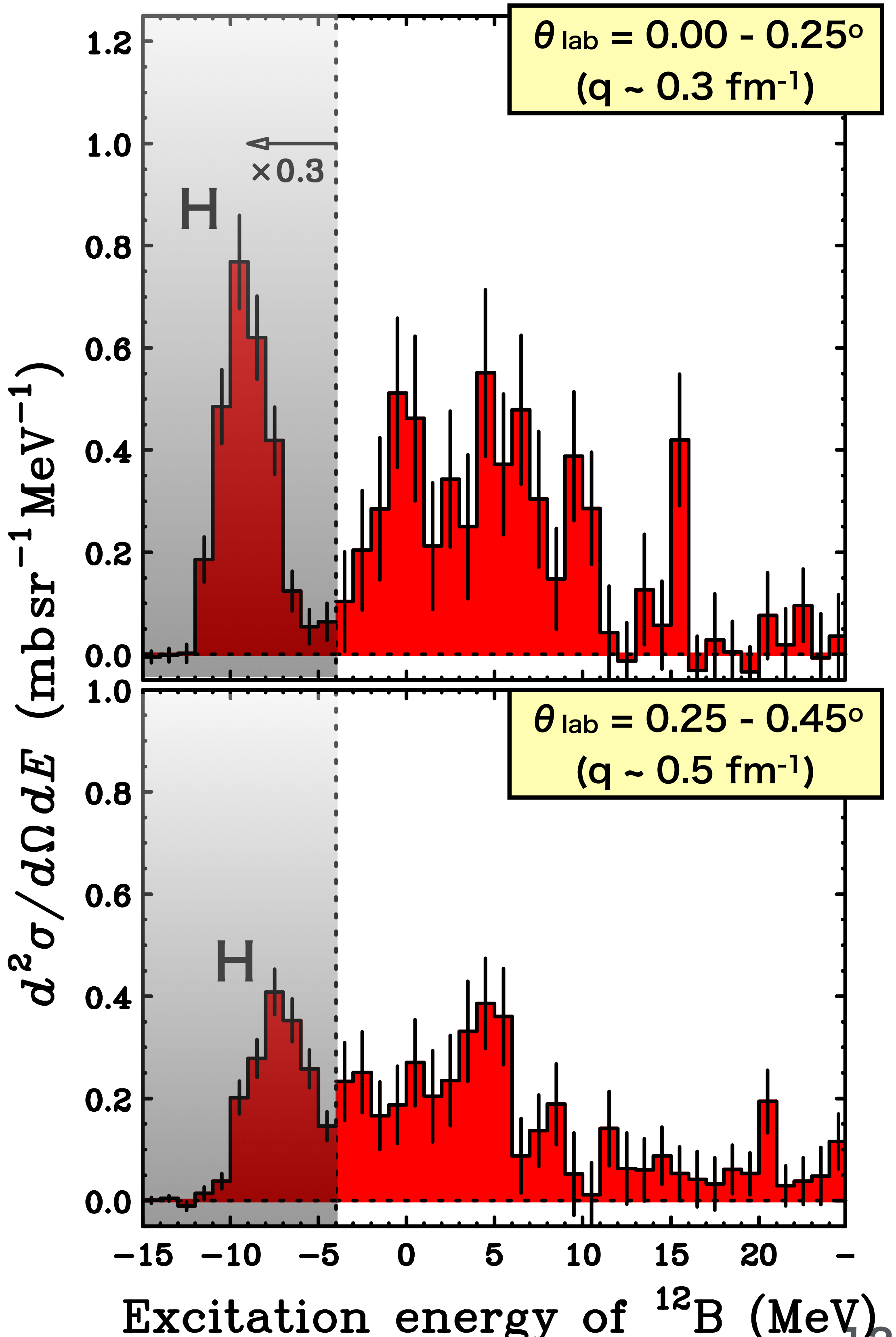


δE_{rel} = 100 keV (FWHM) ⇒ Successfully identify $^{16}F(0^-)$!

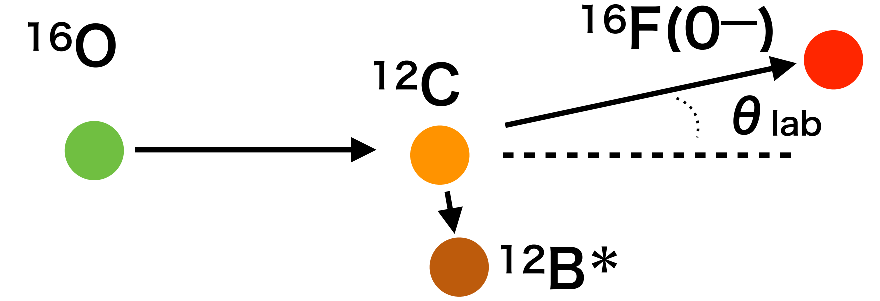
$^{12}C(^{16}O,^{16}F(0^-))^{12}B$ spectra



- ($^{16}O,^{16}F(0^-)$) data
- δE_x = 2.6 MeV (FWHM)



$^{12}C(^{16}O,^{16}F(0^-))^{12}B$ spectra



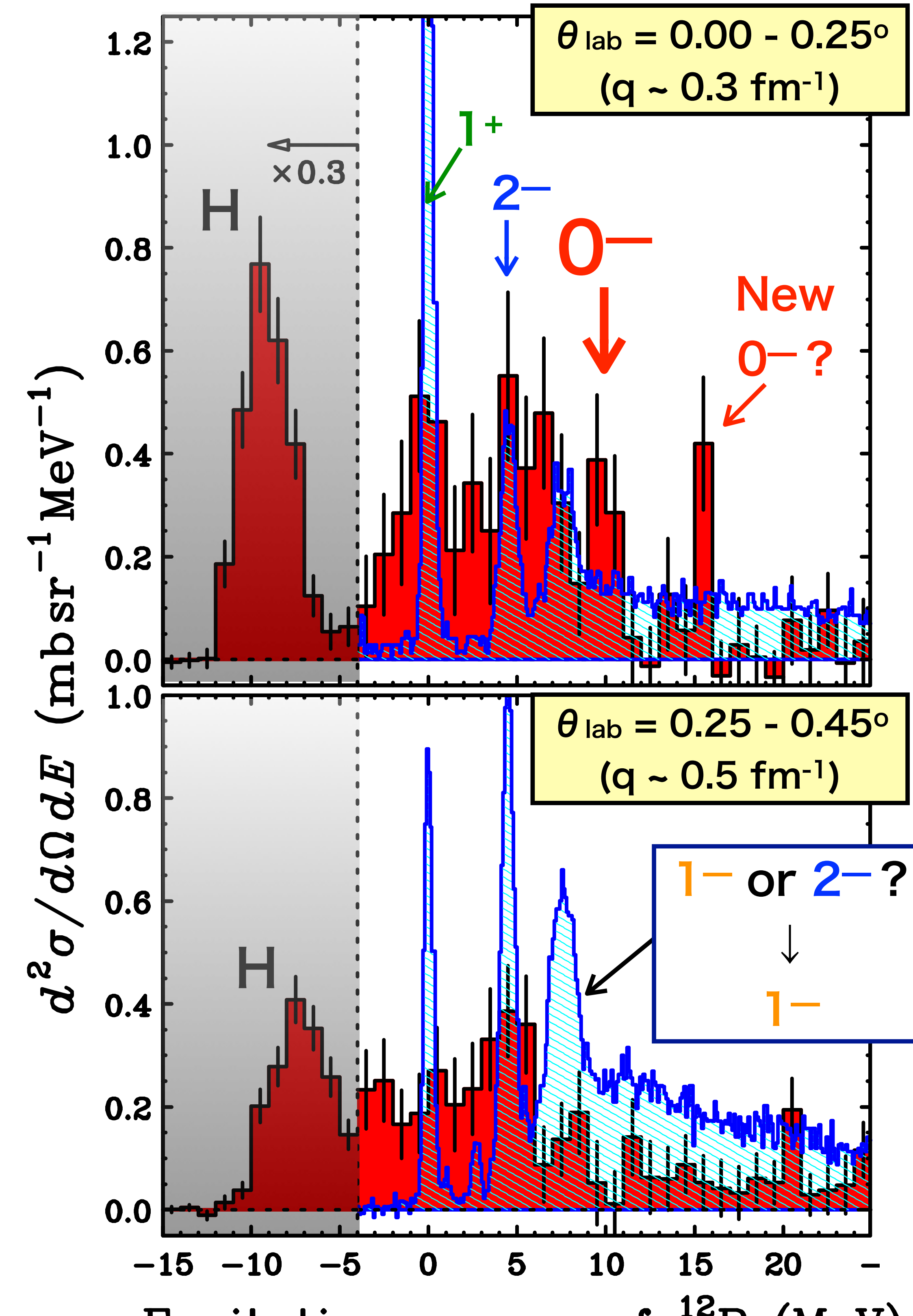
- $(^{16}O,^{16}F(0^-))$ data
  - δE_x = 2.6 MeV (FWHM)
- $(d,^2He)$ data [Normalized to 1^+ g.s.]

  H. Okamura *et al*. PLB 345 (1995) 1.

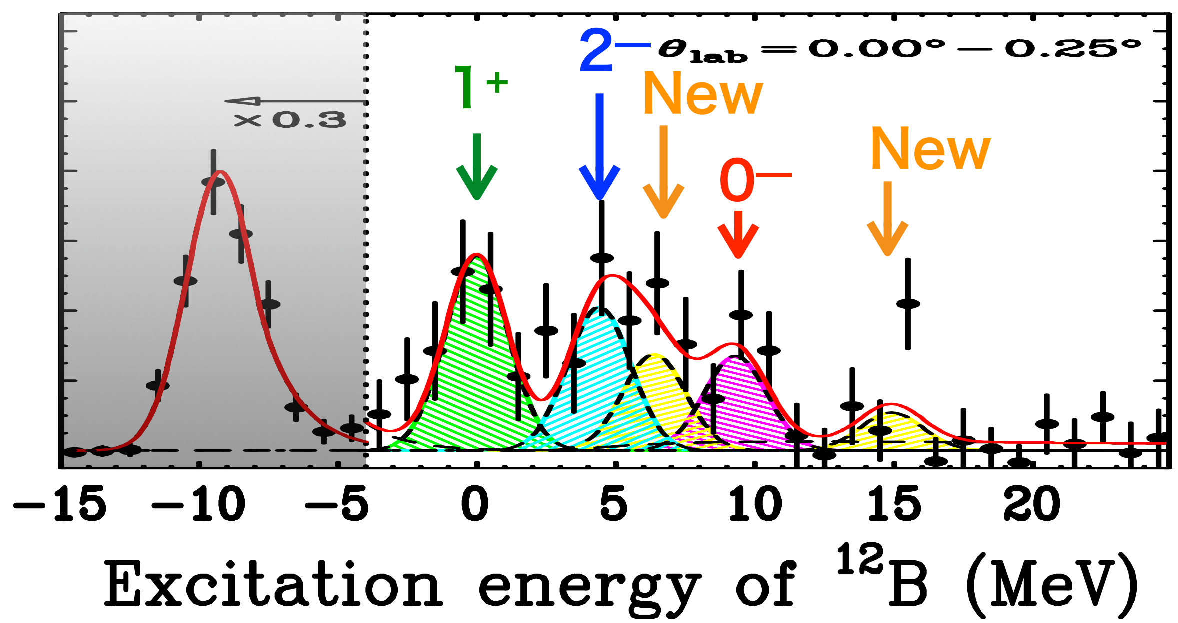
- 0 MeV : GT(1^+)
- 4.4 MeV : SD(2^-)
- 7.5 MeV : SD(1^-) or SD(2^-) ?
  - No peak in $(^{16}O,^{16}F(0^-))$ data ⇒ SD(1^-)
  - $(^{16}O,^{16}F(0^-))$ excites only $(-)^{J+1}$ states
- 9.3 MeV : SD(0^-)
  - Selectively excited with good S/N ratio

$(^{16}O,^{16}F(0^-))$ is clean probe for SD(0^-) !

- Enhancement at ~15 MeV ⇒ New SD(0^-) ?

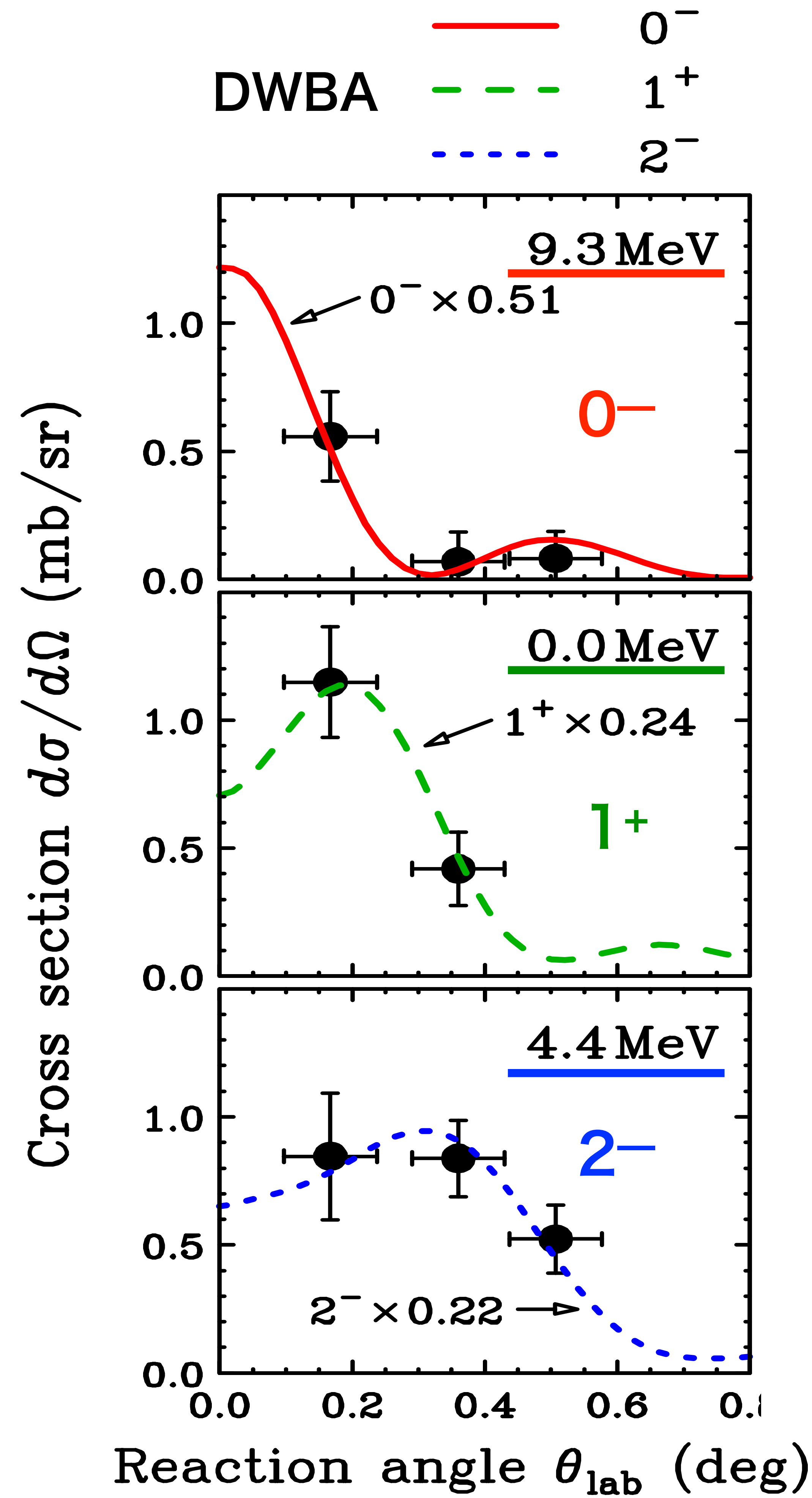


Angular distributions
~ Known states ~

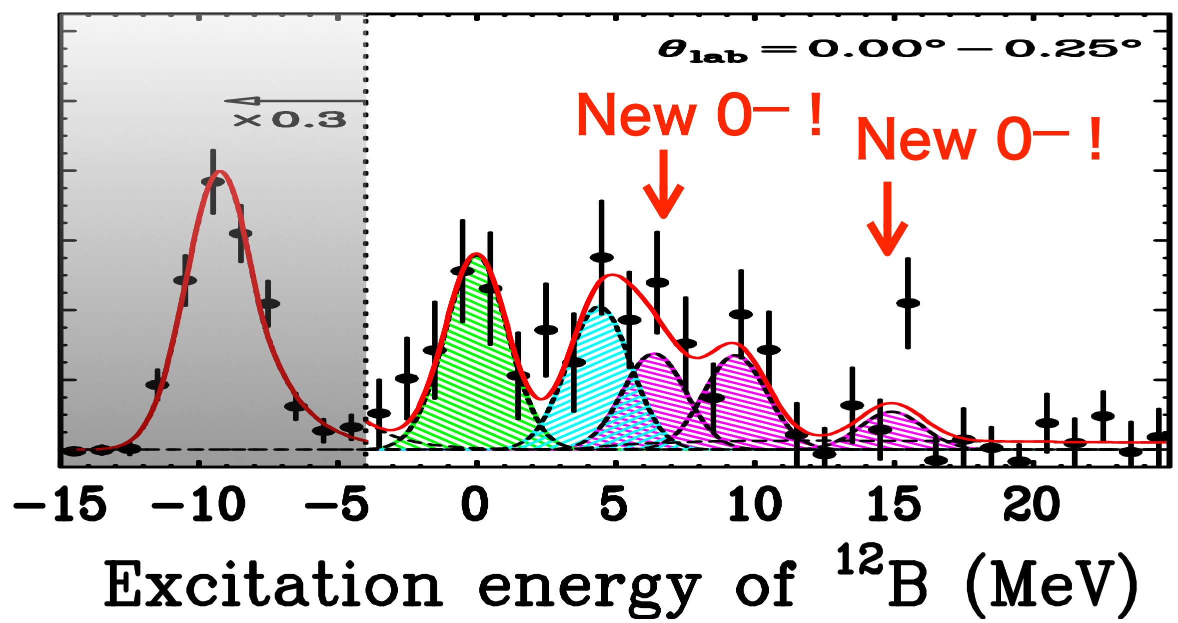


- DWBA
  - Predict different patterns depending on J^π
    - 0− has strong forward-peaking
  - Reproduce exp. data well

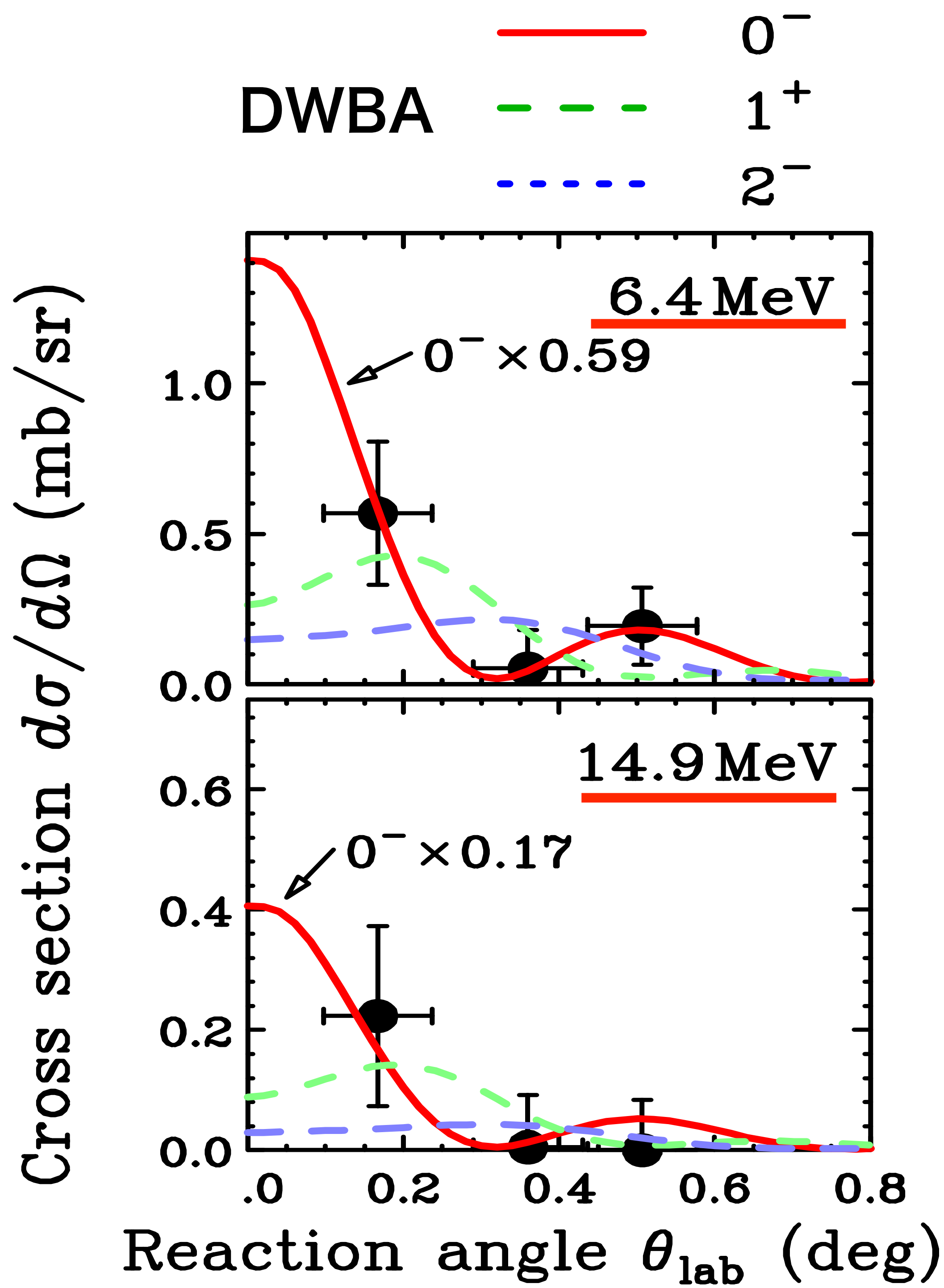
Angular distribution allows clear J^π determination !



Angular distributions
~ New states ~



- Exp. data are well reproduced by DWBA calc. for SD(0−)



Possible evidence for NEW SD(0−) states !

Summary

- We propose parity-transfer reaction (^{16}O,$^{16}F(0^-)$) for SD(0^-) study
- To confirm its effectiveness, we applied this reaction to ^{12}C.
  ⇒ ^{12}C(^{16}O,$^{16}F(0^-)$) at 250A MeV @ RIBF & SHARAQ
- Results
  - (^{16}O,$^{16}F(0^-)$) is clean probe for SD(0^-)
    - Selective excitation of ^{12}B(9.3 MeV, 0^-)
    - Angular distribution allows clear J^π determination
  - Possible evidence for NEW SD(0^-) at 6.4 & 14.9 MeV

This is FIRST-STEP study to apply parity-trans. reaction to Collective 0^- strengths in heavier nuclei (^{40}Ca, ^{90}Zr,…)
⇒ Systematic 0^- study

Collaborators

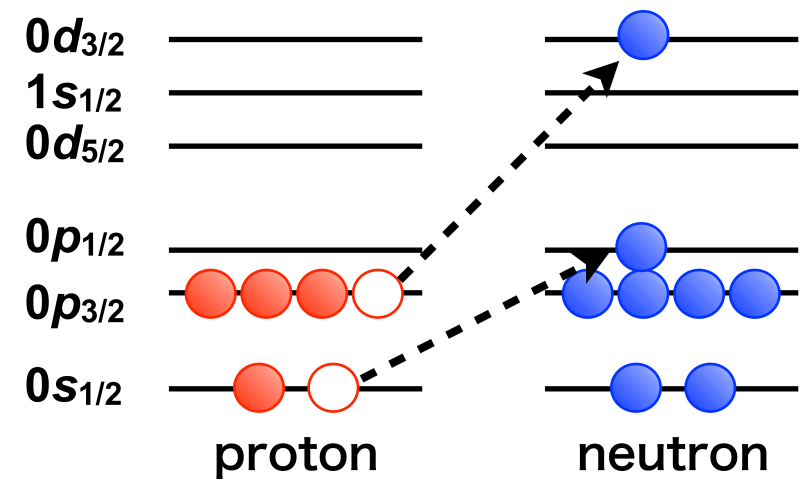
- CNS, University of Tokyo
  - S. Shimoura, K. Yako, S. Michimasa, S. Ota, M. Matsushita, H. Tokieda, H. Miya, S. Kawase, K. Kisamori, M. Takaki, Y. Kubota, C. S. Lee, R. Yokoyama, M. Kobayashi, K. Kobayashi
- RIKEN Nishina Center
  - T. Uesaka, M. Sasano, J. Zenihiro, H. Sakai, T. Kubo, K. Yoshida, Y. Yanagisawa, N. Fukuda, H. Takeda, N. Inabe, M. Ichimura
- Kyushu University
  - T. Wakasa, K. Fujita, S. Sakaguchi, J. Yasuda, A. Ohkura, S. Shindo, K. Tabata
- Aizu University
  - H. Sagawa, M. Yamagami

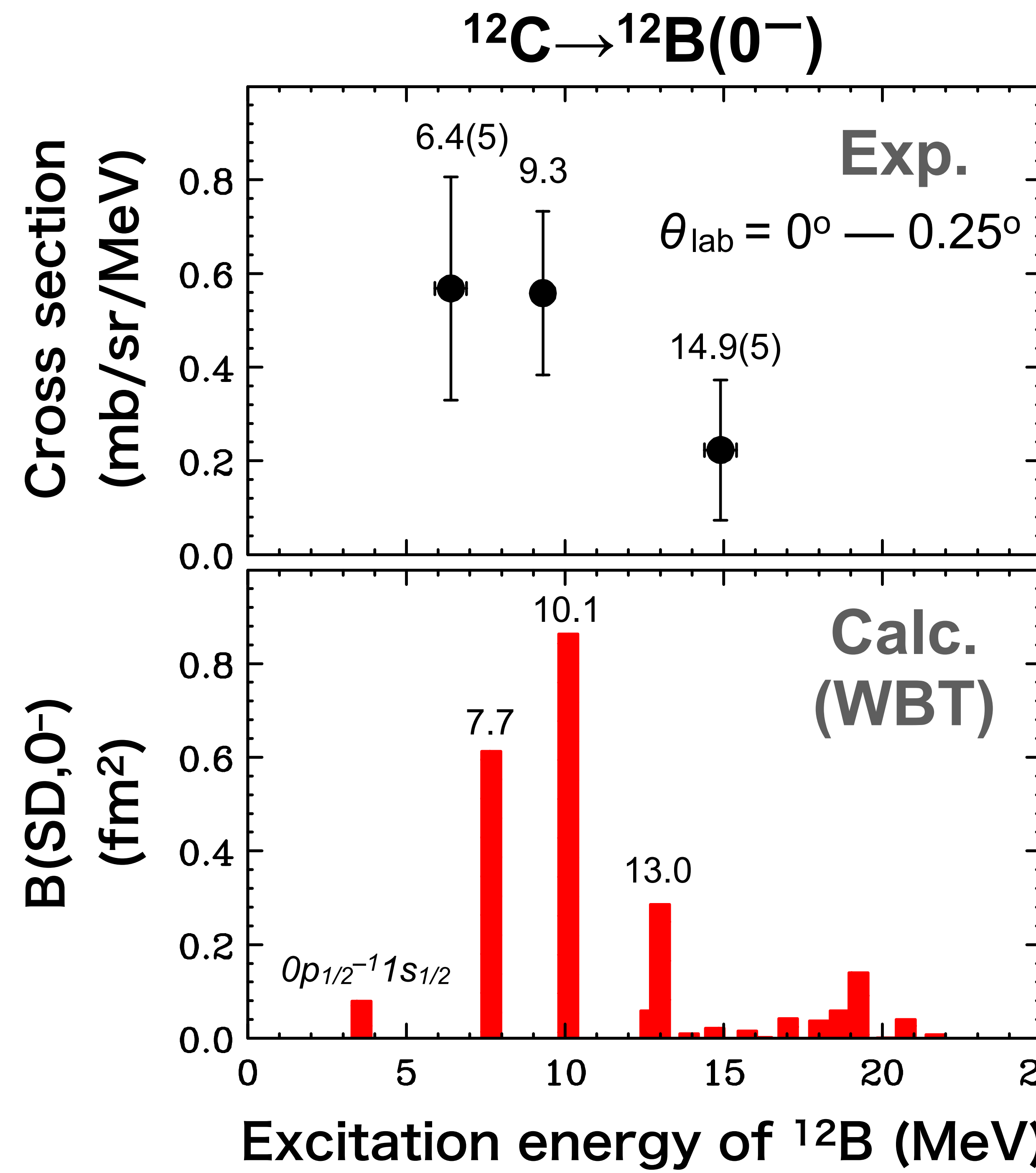
Backup

Comparison with SM calculation (I)

- SM model
  - WBT interaction
  - spsd model space
  - $1\hbar\omega$ excitation
- As a result of configuration mixing between $(0p_{3/2}^{-1}0d_{3/2})$ and $(0s_{1/2}^{-1}0p_{1/2})$, B(SD,0−) is split into 3 states (7.7, 10.1, 13.0 MeV)
  - Deformation effects ?
  - Tensor effects ?

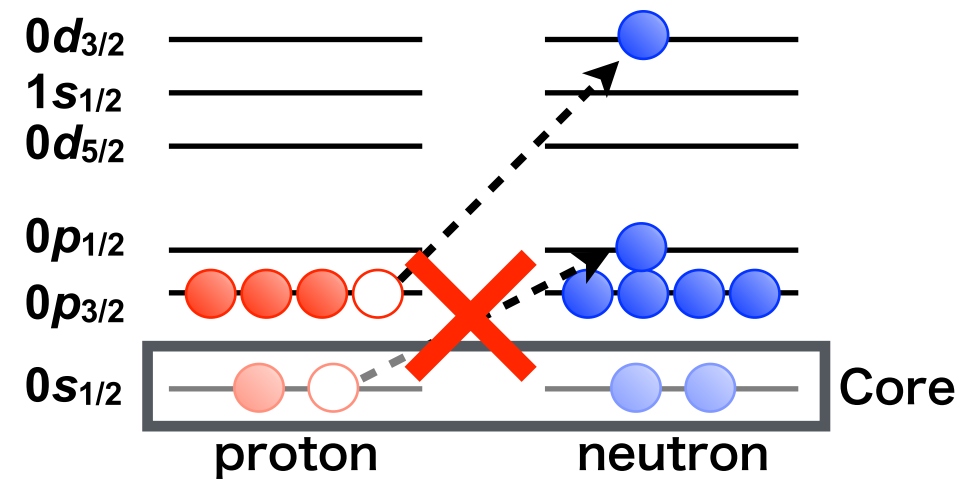
<u>Our data is roughly consistent with WBT result</u>

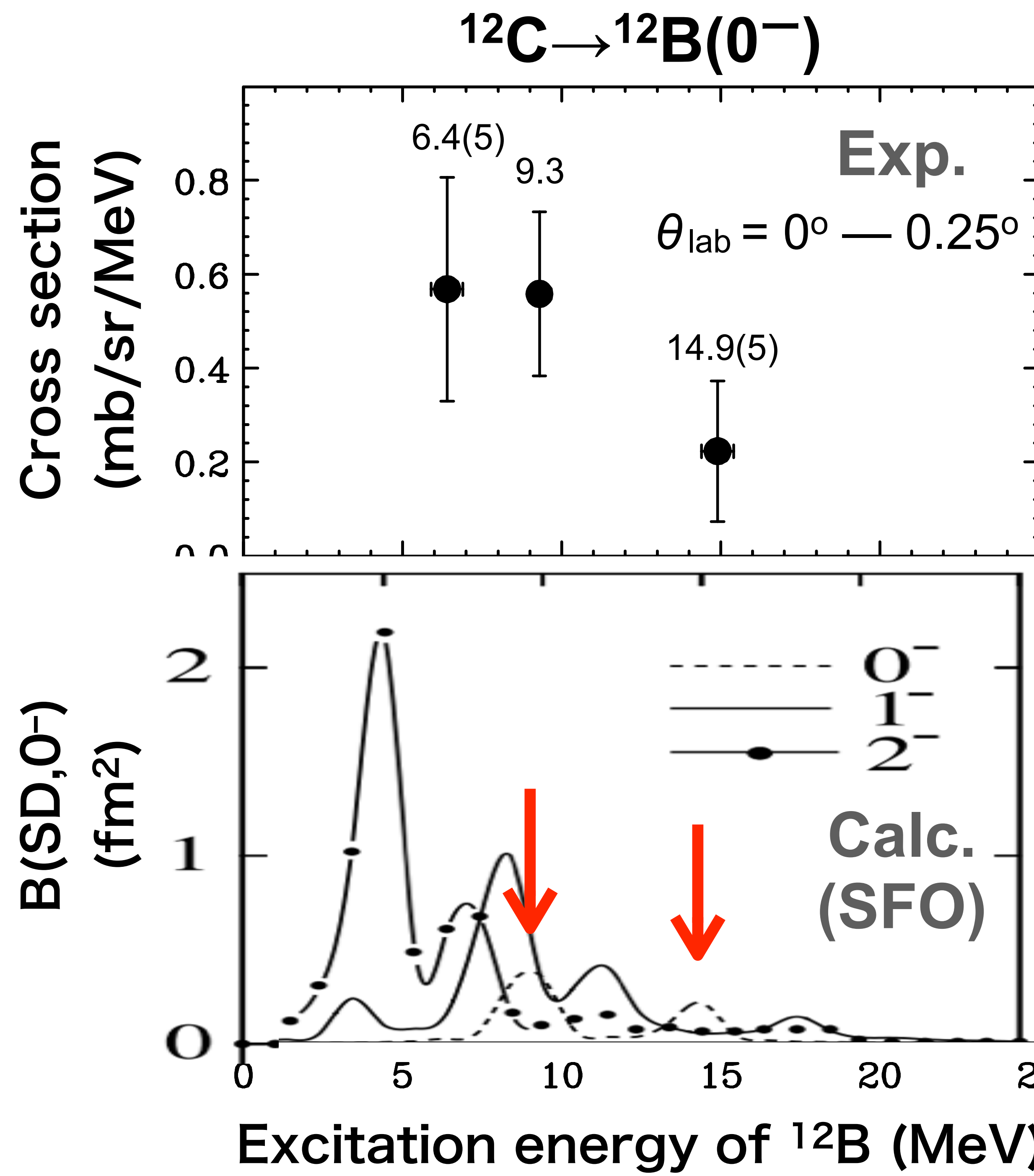




Comparison with SM calculation (II)

- SM model T. Suzuki *et al*. PRC 74 (2006) 034307
  - SFO interaction
  - psd model space
  - 3hω excitation
- Only 2 states



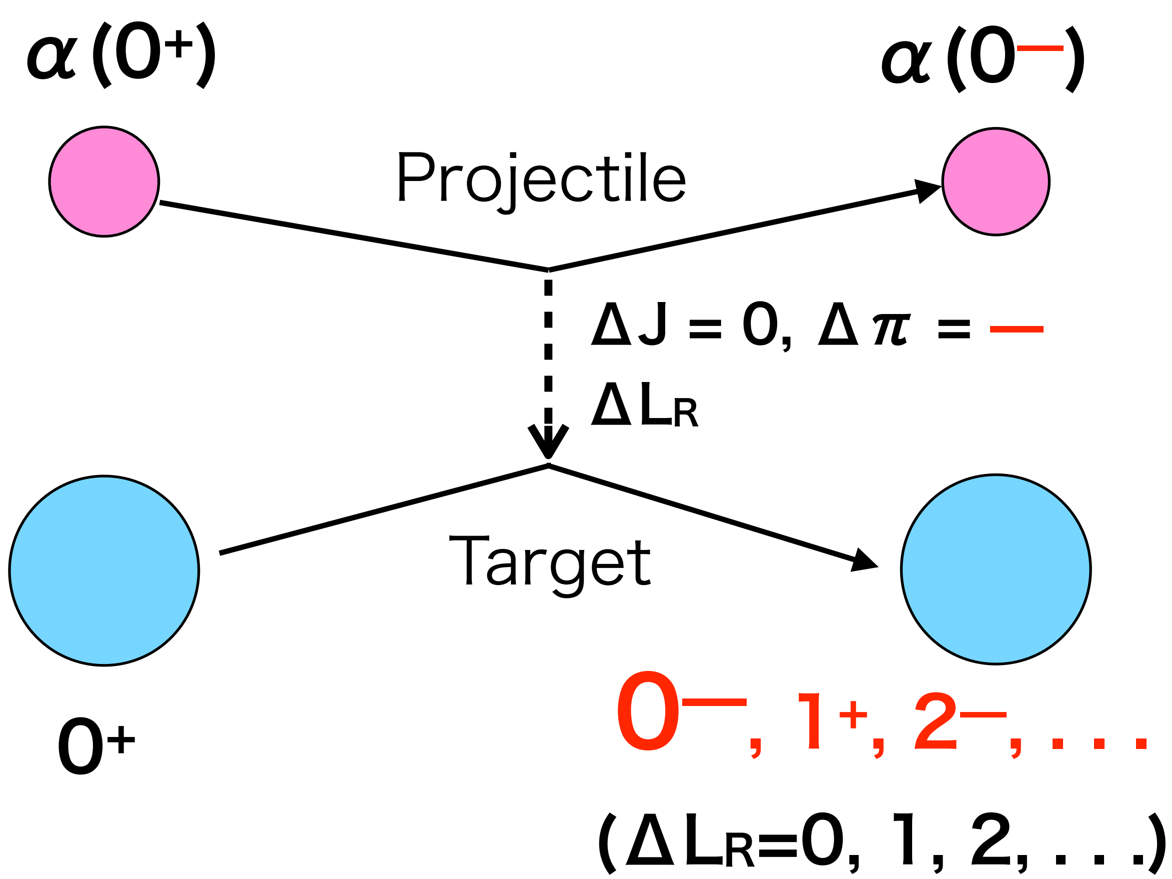


<u>To reproduce our data, ($0S_{1/2}^{-1}0p_{1/2}$) is important</u>

Parity-transfer (^{16}O,$^{16}F(0^-)$) reaction

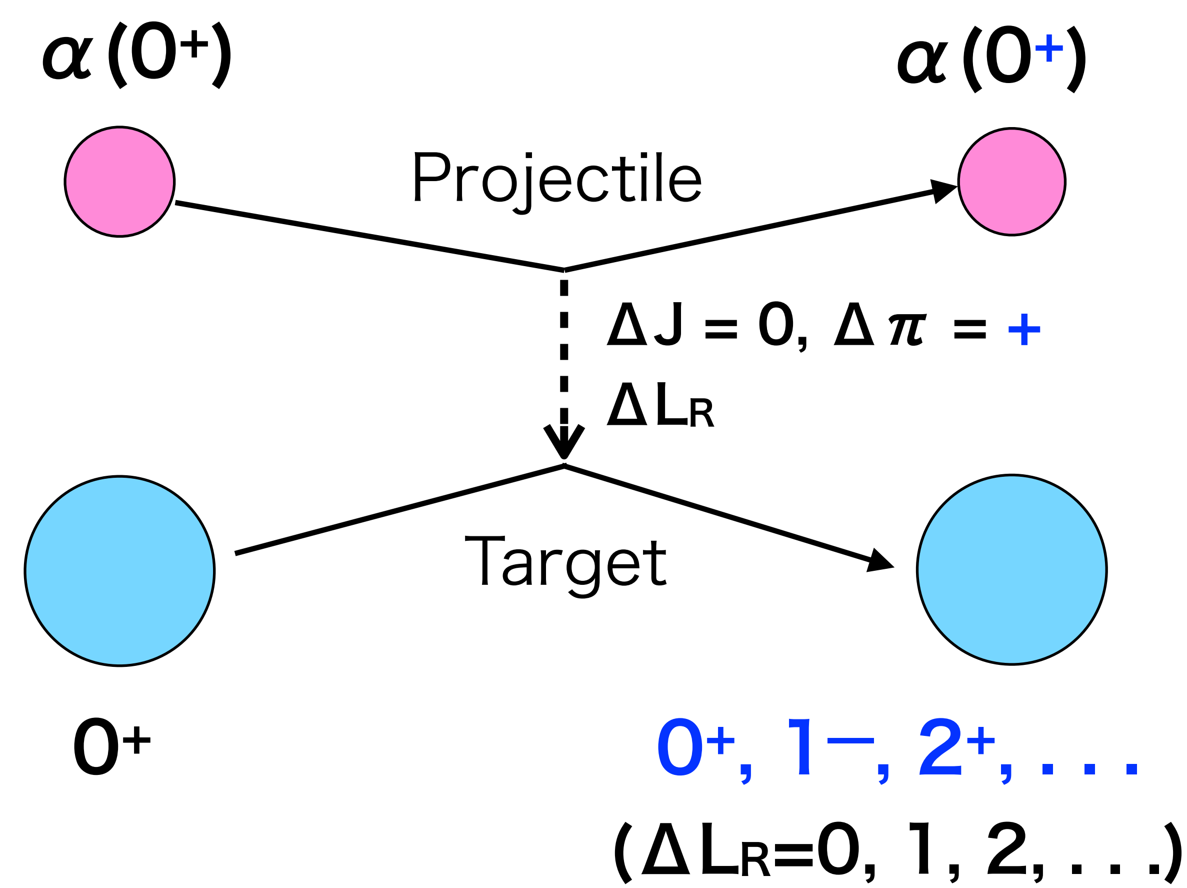
Parity-transfer reaction is selective tool for SD(0^-) !

(^{16}O,^{16}F) : $0^+ \rightarrow 0^-$



- Selectively excite $(-)^{J+1}$ states
  ⇒ No SD(1^-) contribution
- J^π can be assigned
  by angular distribution

(α,α') : $0^+ \rightarrow 0^+$



- Selectively excite $(-)^{J}$ states
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Parity-transfer (^{16}O,^{16}F(0^-)) reaction

Parity-transfer reaction is selective tool for 0^- !

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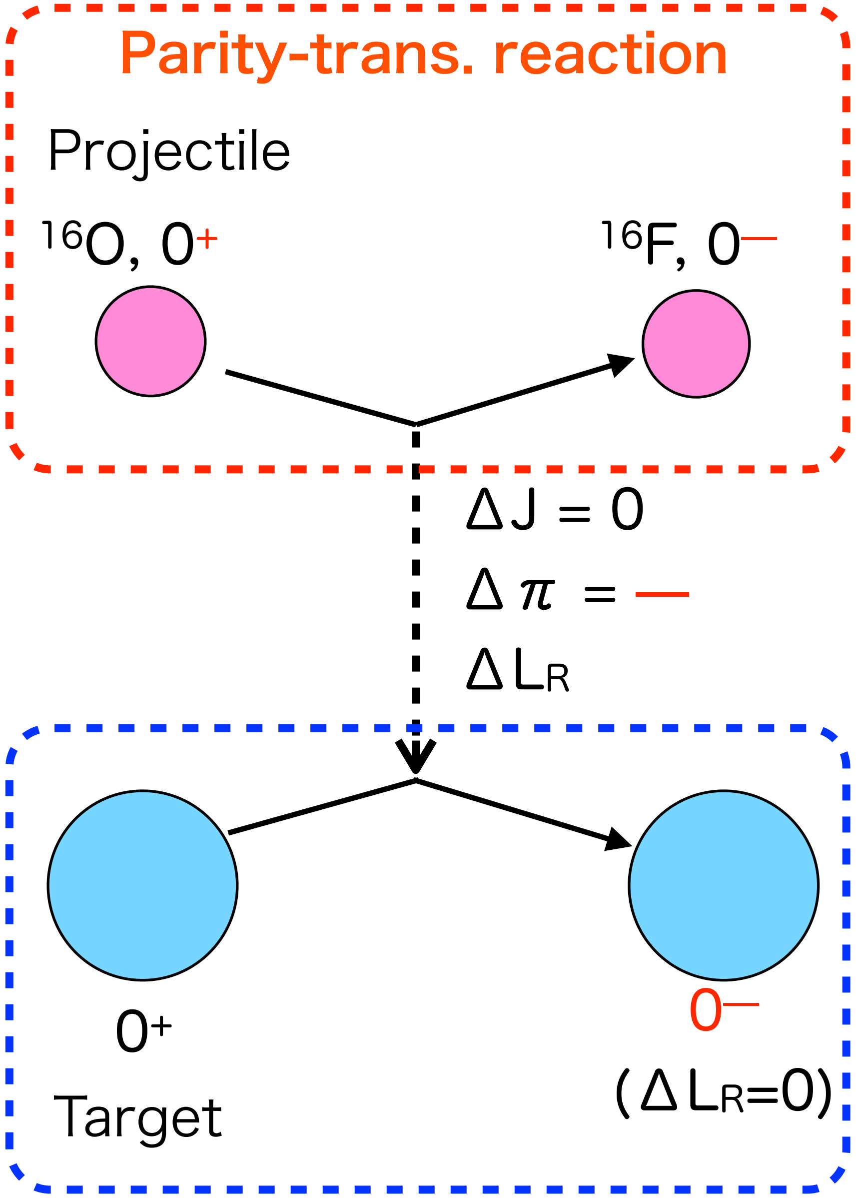
  - ^{16}O (g.s., 0^+) → ^{16}F (g.s.,0^-)
- Advantages
  - Selectively excite unnatural-parity states
    - No 1^- contribution
  - Single J^π for each ΔL_R
    - J^π (0^-, 1^+, 2^-,...) can be assigned only by the angular distribution (⇔ ΔL_R)

	ΔL_R=0	ΔL_R=1	ΔL_R=2	…
Parity-trans.	0^-	1^+	2^-	…
(p,n),(d,^{2}He) etc.	0^+,1^+	0^-, 1^-, 2^-	1^+, 2^+, 3^+	…



Clean probe for SD 0^- search

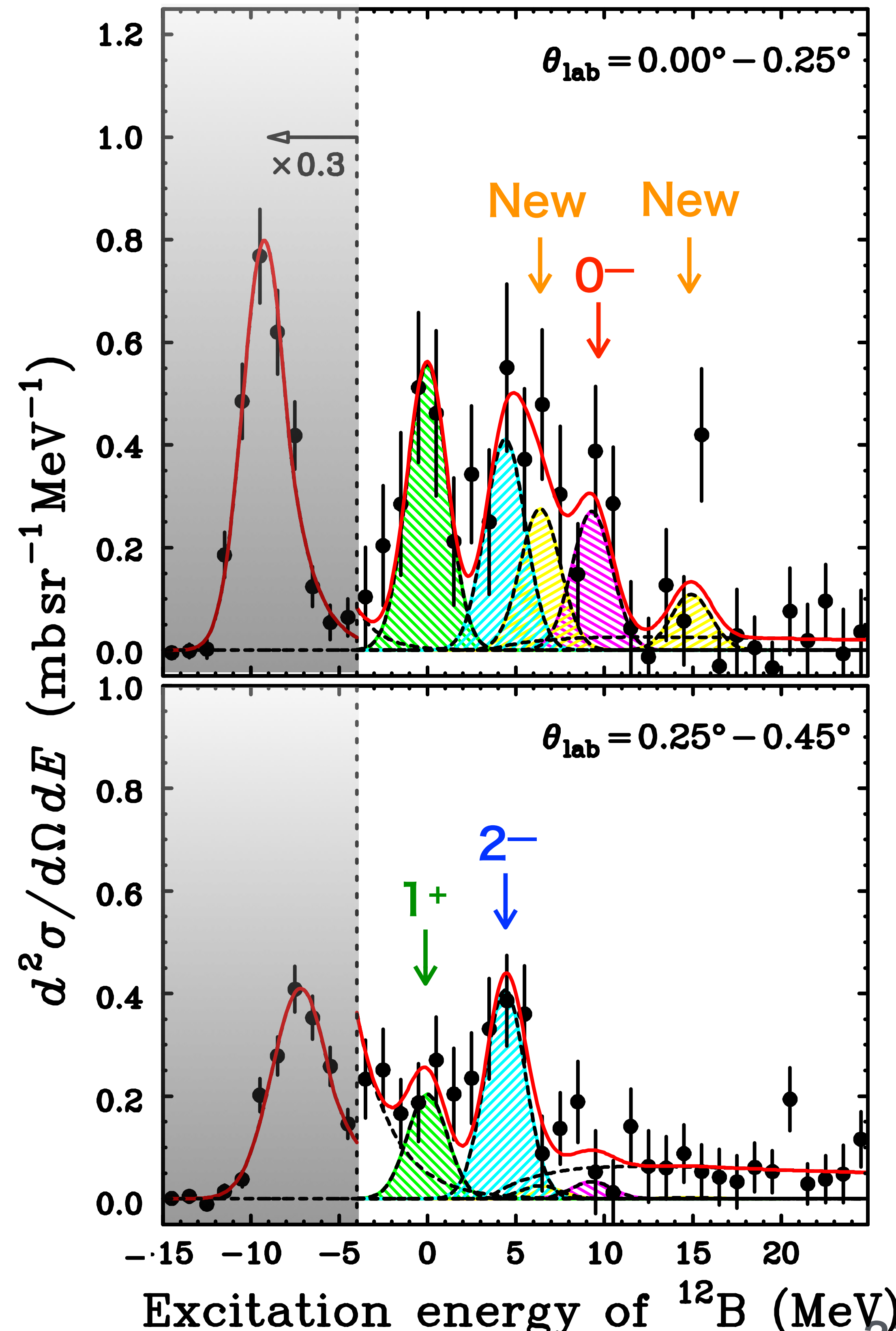
Peak fitting

- H peak : Gaussian with exp. tail
- Quasi-free continuum :

$$\frac{d^2\sigma}{d\Omega\, dE} = N \frac{1 - \exp[-(E_x - E_0)/T]}{1 + [(E_x - E_{QF})/W_L]^2}, \quad E_x > E_0,$$

A. Erell *et al*. PRC 34 (1986) 1822.

- ^{12}B states : Gaussian
  - 0.0 MeV, GT(1^+)
  - 4.4 MeV, SD(2^-)
  - 9.3 MeV, SD(0^-)
  - 6.4 MeV, New
  - 14.9 MeV, New



Parity-transfer (^{16}O,$^{16}F(0^-)$) reaction

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- Advantages
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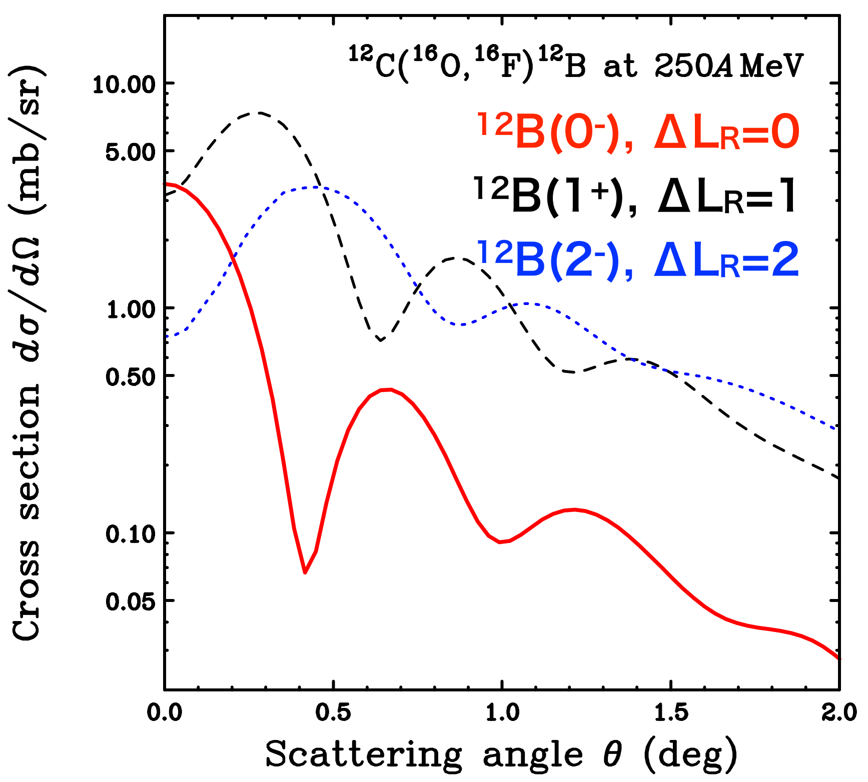
    - No 1^- contribution
  - Single J^π for each ΔL_R
    - J^π (0^-, 1^+, 2^-,...) can be assigned only by the angular distribution (⇔ ΔL_R)

DWBA calculations with FOLD/DWHI



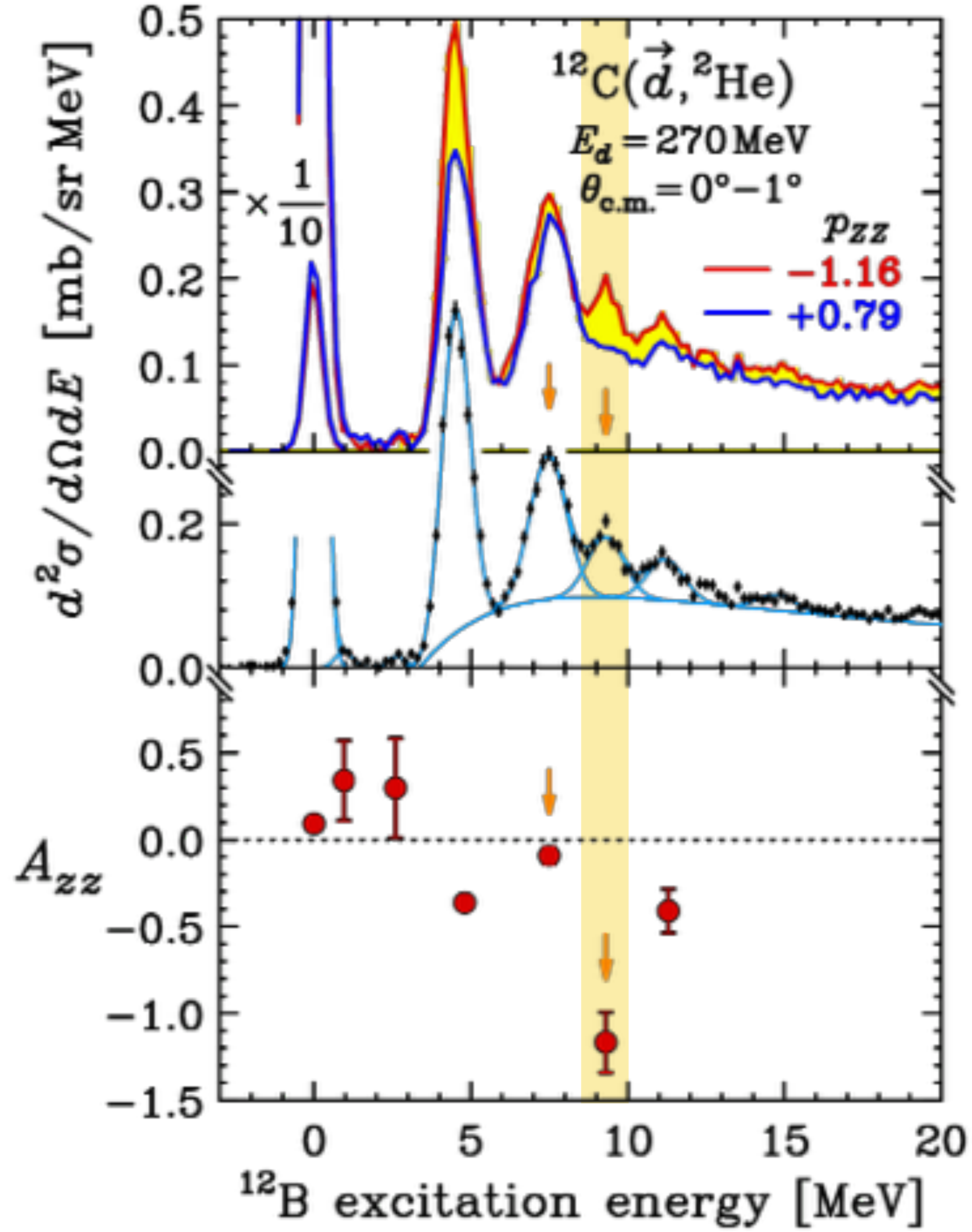
	$\Delta L_R=0$	$\Delta L_R=1$	$\Delta L_R=2$	…
Parity-trans.	0^-	1^+	2^-	…
(p,n),(d,^{2}He) etc.	0^+,1^+	0^-, 1^-, 2^-	1^+, 2^+, 3^+	…

Clean probe for SD 0^- search

First parity-transfer measurement : $^{12}C(^{16}O,^{16}F(0^-))^{12}B$ at 250 MeV/u

We apply parity-trans. reaction to ^{12}C target

H. Okamura *et al*. PRC 66 (2002) 054602



- Why ^{12}C ?
  - <u>Known</u> 0^- at E_x = 9.3 MeV in ^{12}B
    ⇒ Confirm effectiveness of parity-trans. reaction
  - Experimentally more feasible
    - High luminosity,
    - Low B.G. compared with heavier nuclei

GOAL
Establish $(^{16}O,^{16}F(0^-))$reaction as a new tool for 0^- study

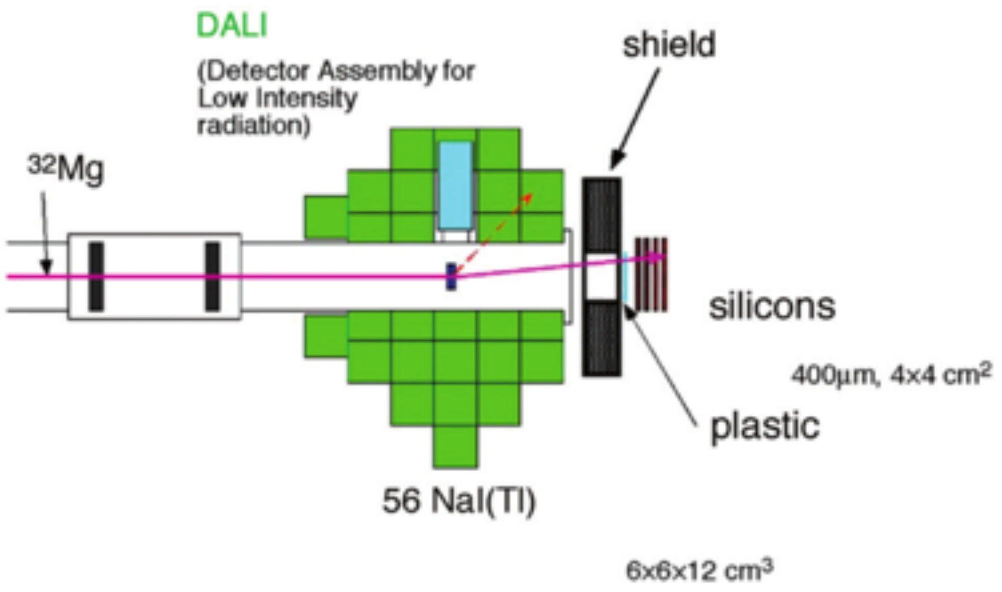
Introduction

- Availability of RI beams has made it possible
  - to study the exotic properties of nuclei far from the β-stability line
  - to investigate key nuclear reactions relevant to important astrophysical phenomena

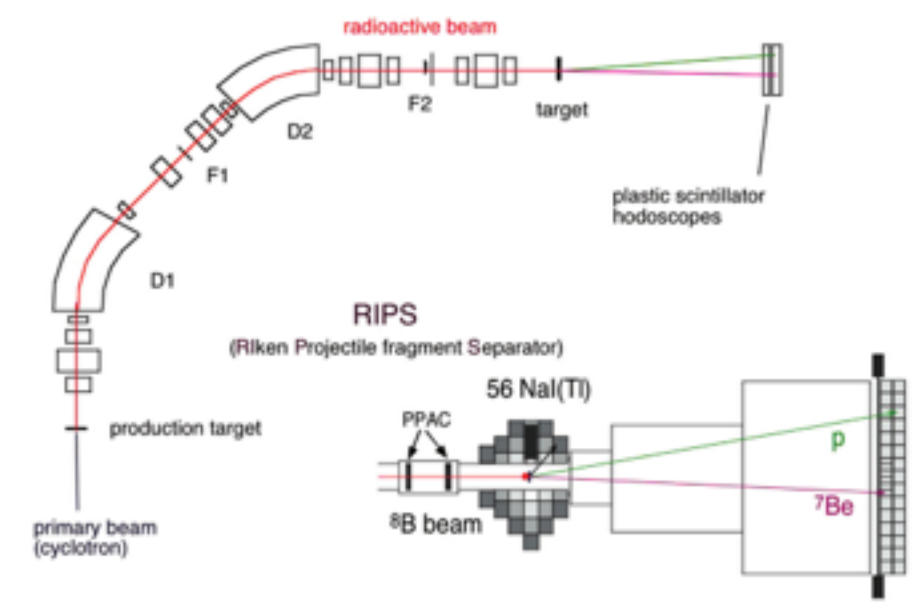
- Experimental methods with RI beams

T. Motobayashi and H. Sakurai, PTEP 2012 (2012) 03C001.

In-beam gamma spectroscopy (for bound states)



Invariant-mass spectroscopy (for unbound states)

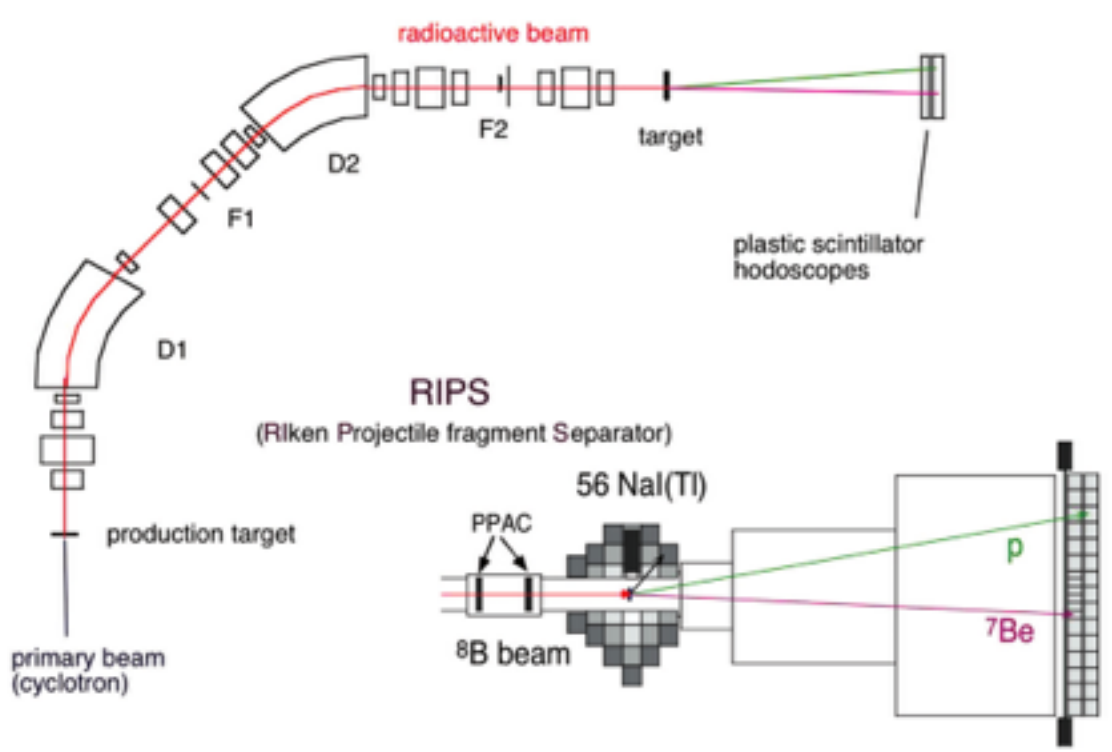


Invariant-mass measurements at RIKEN/RIPS

- **We need nucleon - HI coincidence detection**

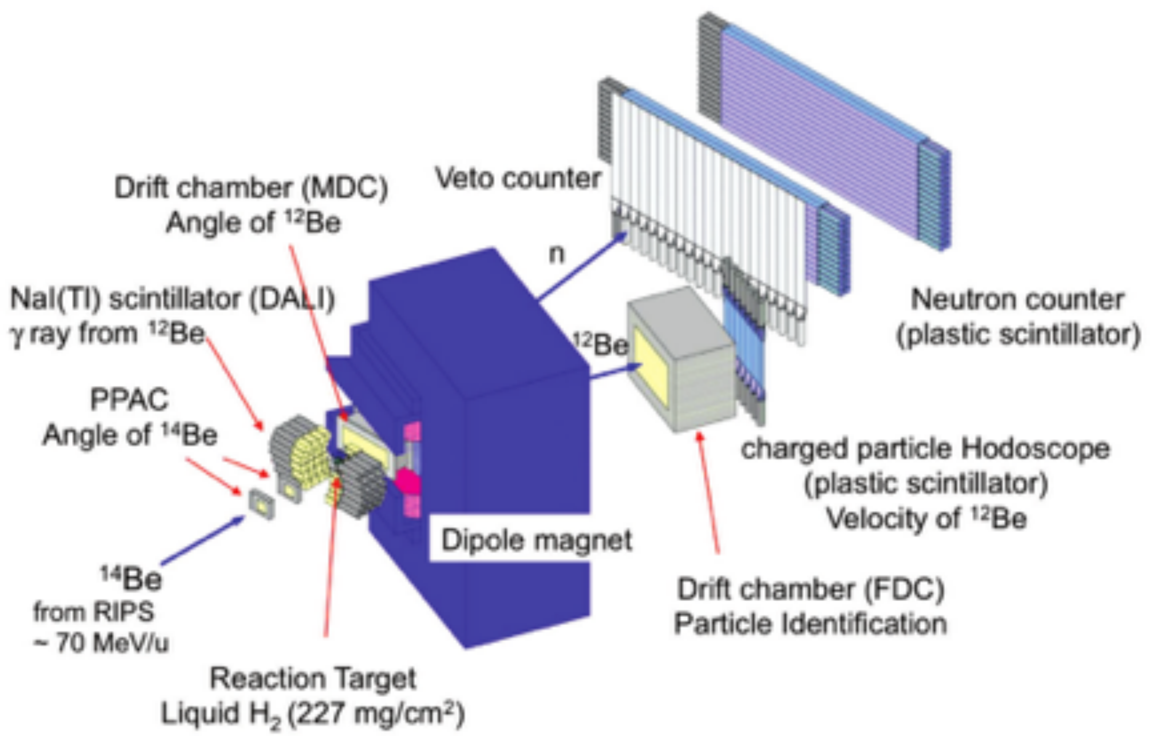
^{8}B coulomb dissociation experiment
(proton-rich side)

T. Motobayashi, NPA 693 (2001) 258.



^{13}Be experiment
(neutron-rich side)

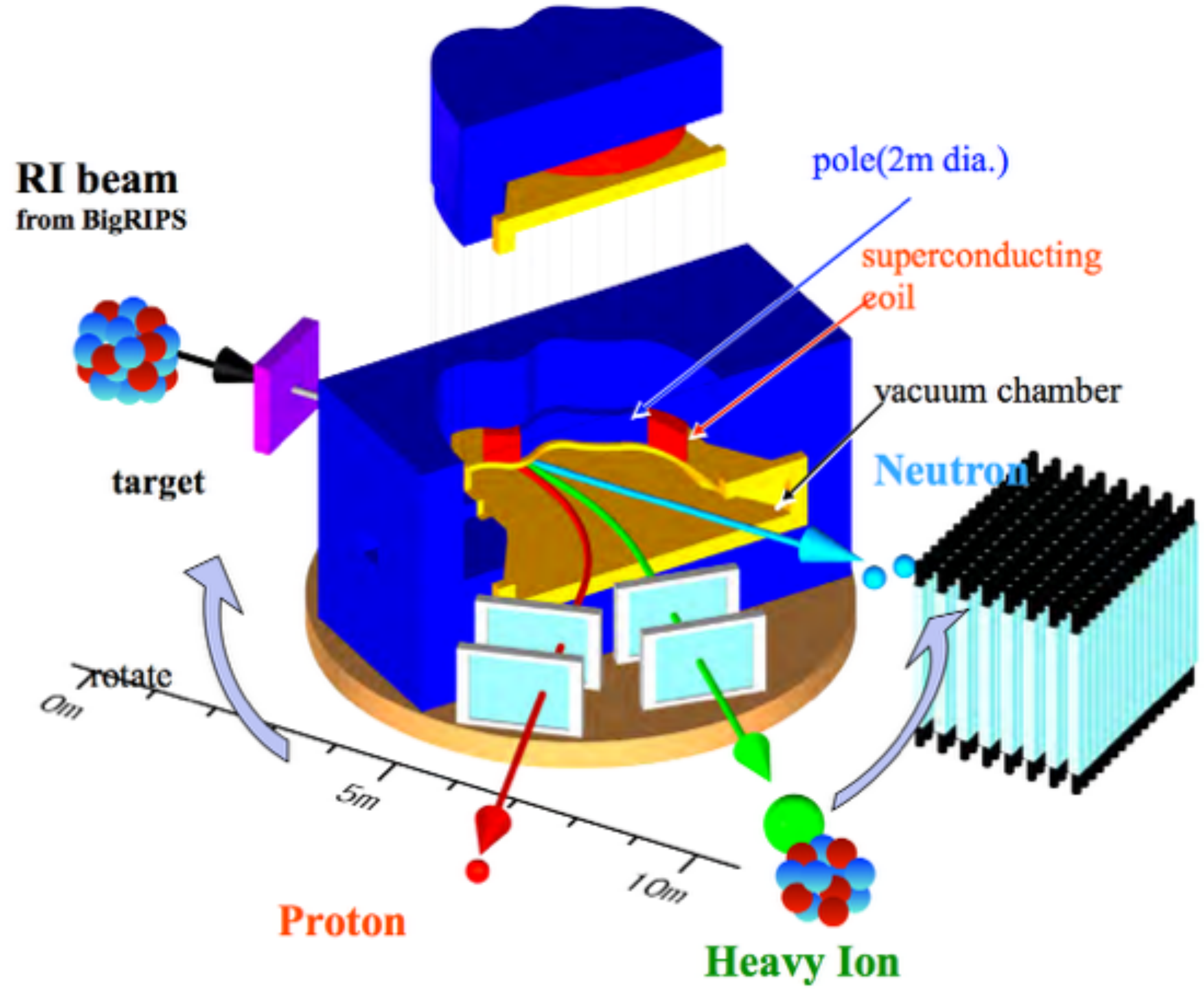
Y. Kondo et al., PLB 690 (2010) 245.



Large-accept. SAMURAI spectrometer at RIBF

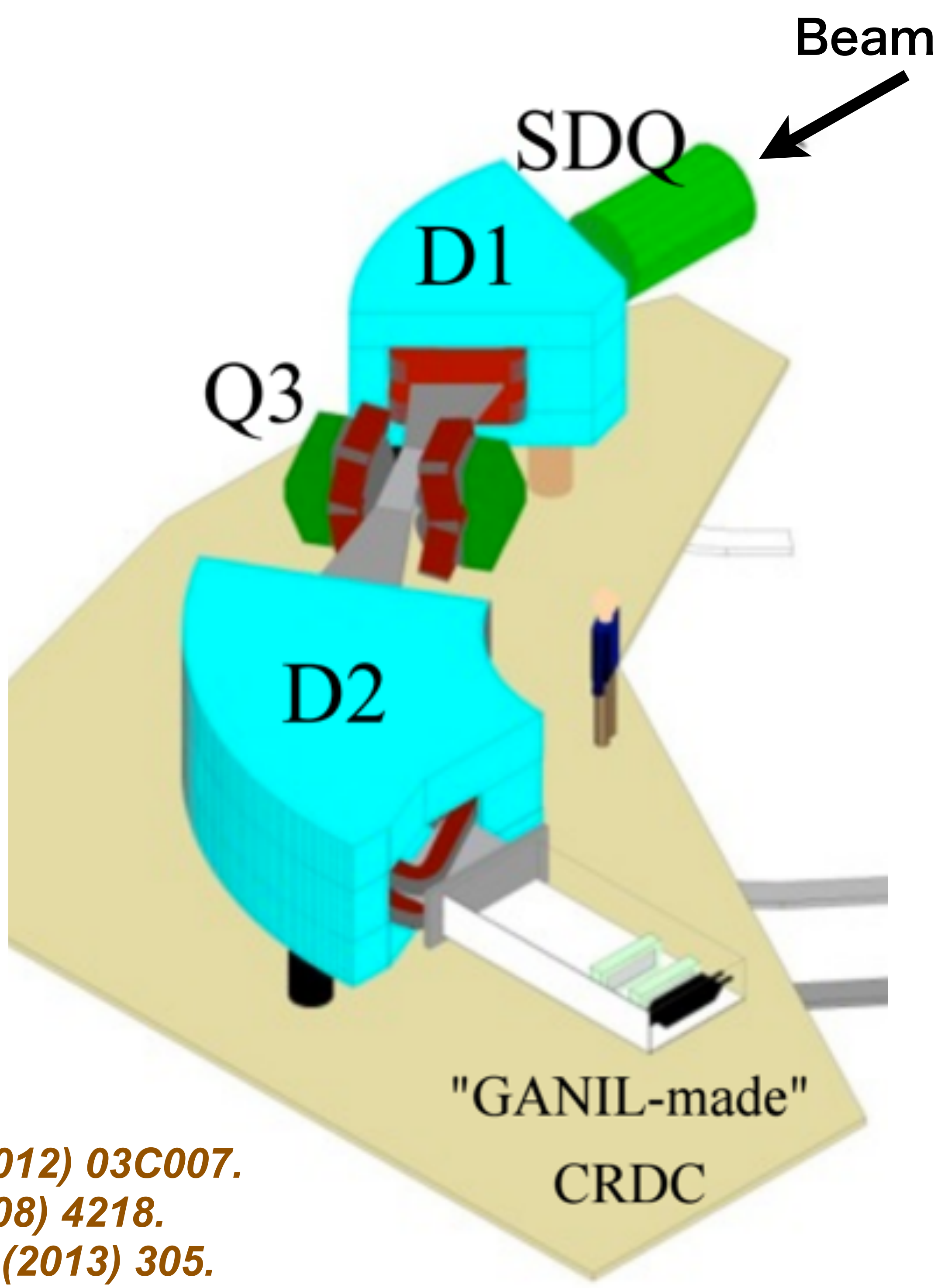
- Designed to perform invariant-mass spectroscopy of both neutron- and proton-unbound states.

T. Kobayashi et al., NIMB 317 (2013) 294.



High-resolution SHARAQ spectrometer at RIBF

- Maximum rigidity : 6.8 Tm
- Momentum resolution :
  dp/p = 1/14700
- Angular resolution : ~ 1 mrad
- Momentum acceptance : ±1%
- Angular acceptance : ~5 msr



Not suitable
for multi-particle detection . . .

T. Uesaka et al., PTEP 2012 (2012) 03C007.
T. Uesaka et al., NIMB 266 (2008) 4218.
S. Michimasa et al., NIMB 317 (2013) 305.

nucleon+HI coincidence measurement with SHARAQ

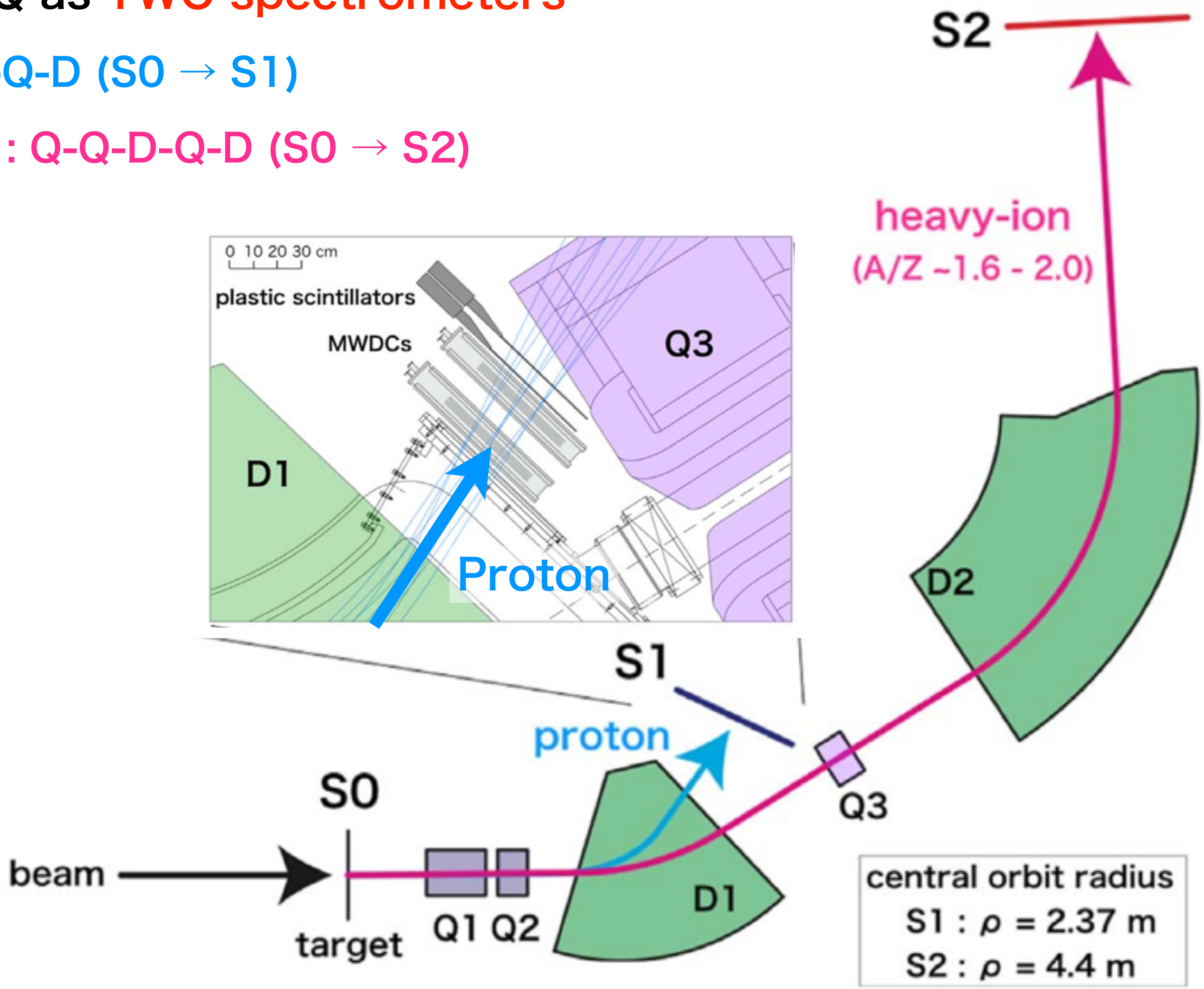
- Open up new experimental possibilities
  - Invariant-mass measurements with high momentum resolutions
    - PID of heavy isotopes
    - Momentum distribution measurements via knockout reactions
  - New type of missing-mass spectroscopy using a reaction probe with a particle-decay channel
    - e.g. : Parity-transfer (^{16}O,$^{16}F(0^-$, g.s.)$\rightarrow$$^{15}O$+p) reaction
      - Use $0^+ \rightarrow 0^-$ transition to excite a target nucleus
      - Selectively excite unnatural-parity states (0^-, 1^+, 2^-, . . .)

Separated flow mode

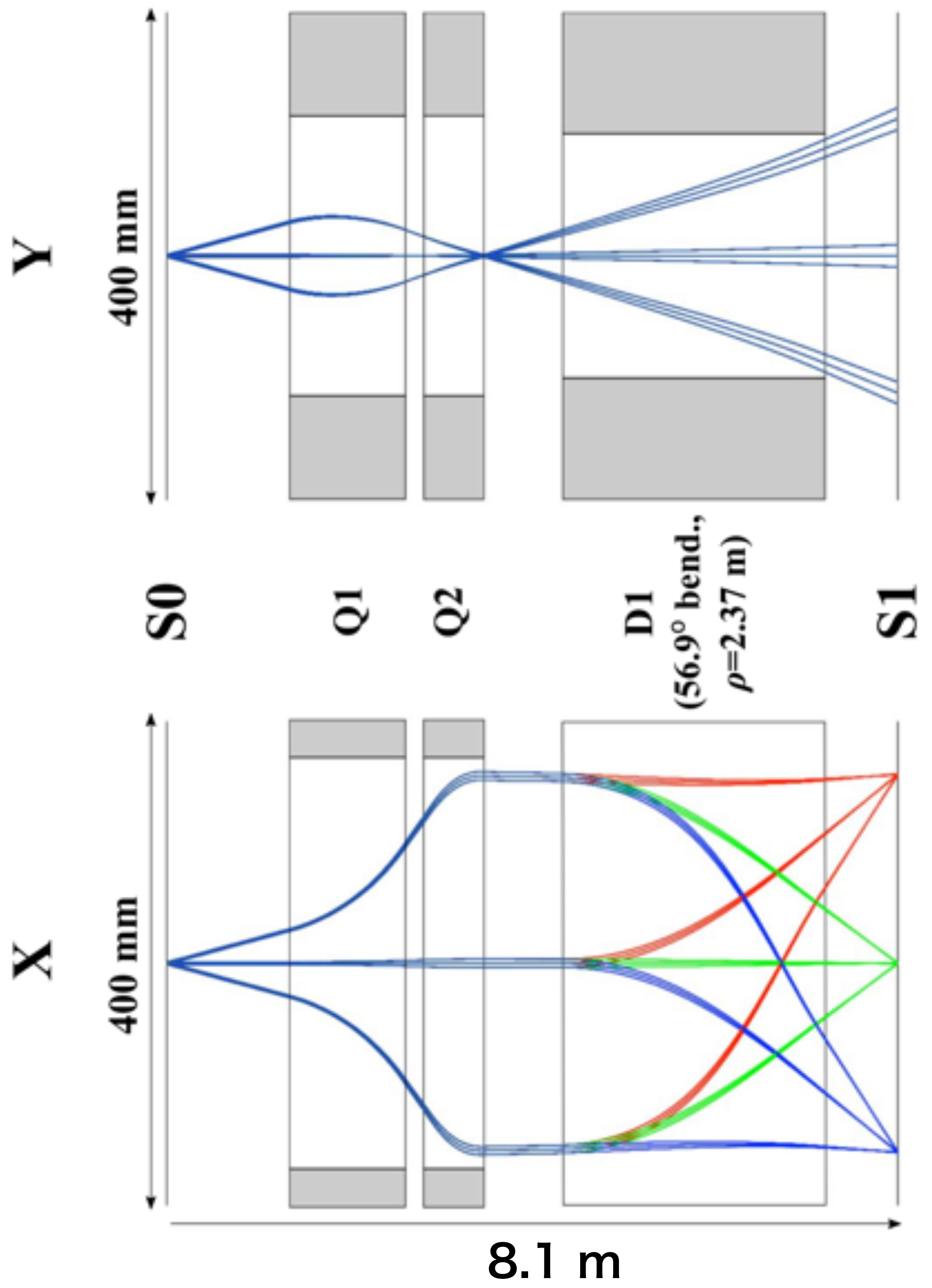
~ new ion-optical mode of SHARAQ for in-flight proton-decay experiments~

Separated flow mode of SHARAQ

- Use SHARAQ as TWO spectrometers
  - Proton : Q-Q-D (S0 → S1)
  - HI (A/Z~2) : Q-Q-D-Q-D (S0 → S2)



Proton trajectories from S0 to S1

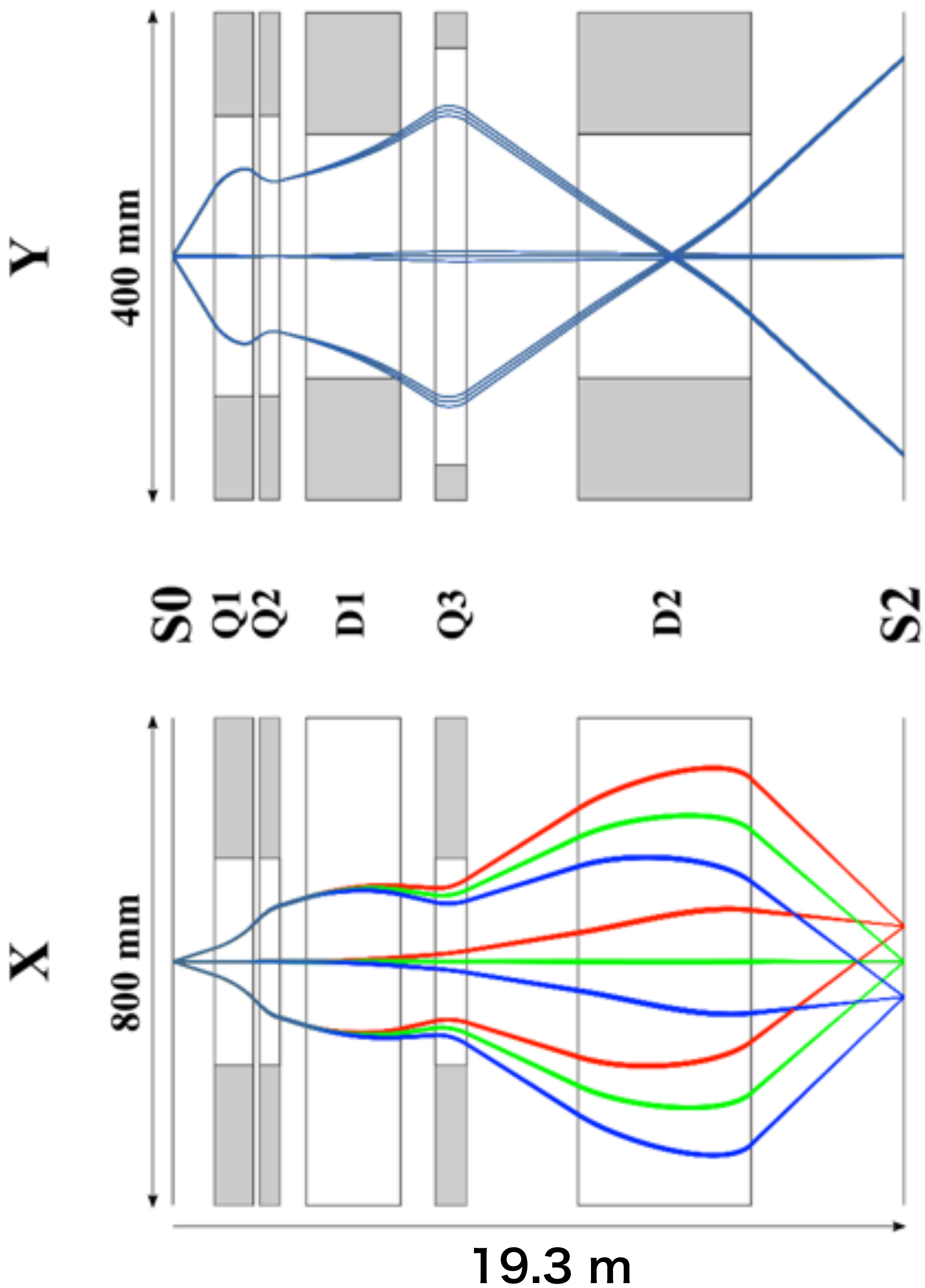


1st order calc. (COSY)

X_{S0}={0,±1mm}, Y_{S0}={0,±1mm}
A_{S0}={0,±25mr}, B_{S0}={0,±25mr}
Δp/p={0,+10%,-10%}

Mom. Reso. :	1/4330
Ang. Reso. :	~2 mrad
Mom. Accept. :	±12%
Ang. Accept. :	2.2 msr

HI trajectories from S0 to S2



1st order calc. (COSY)

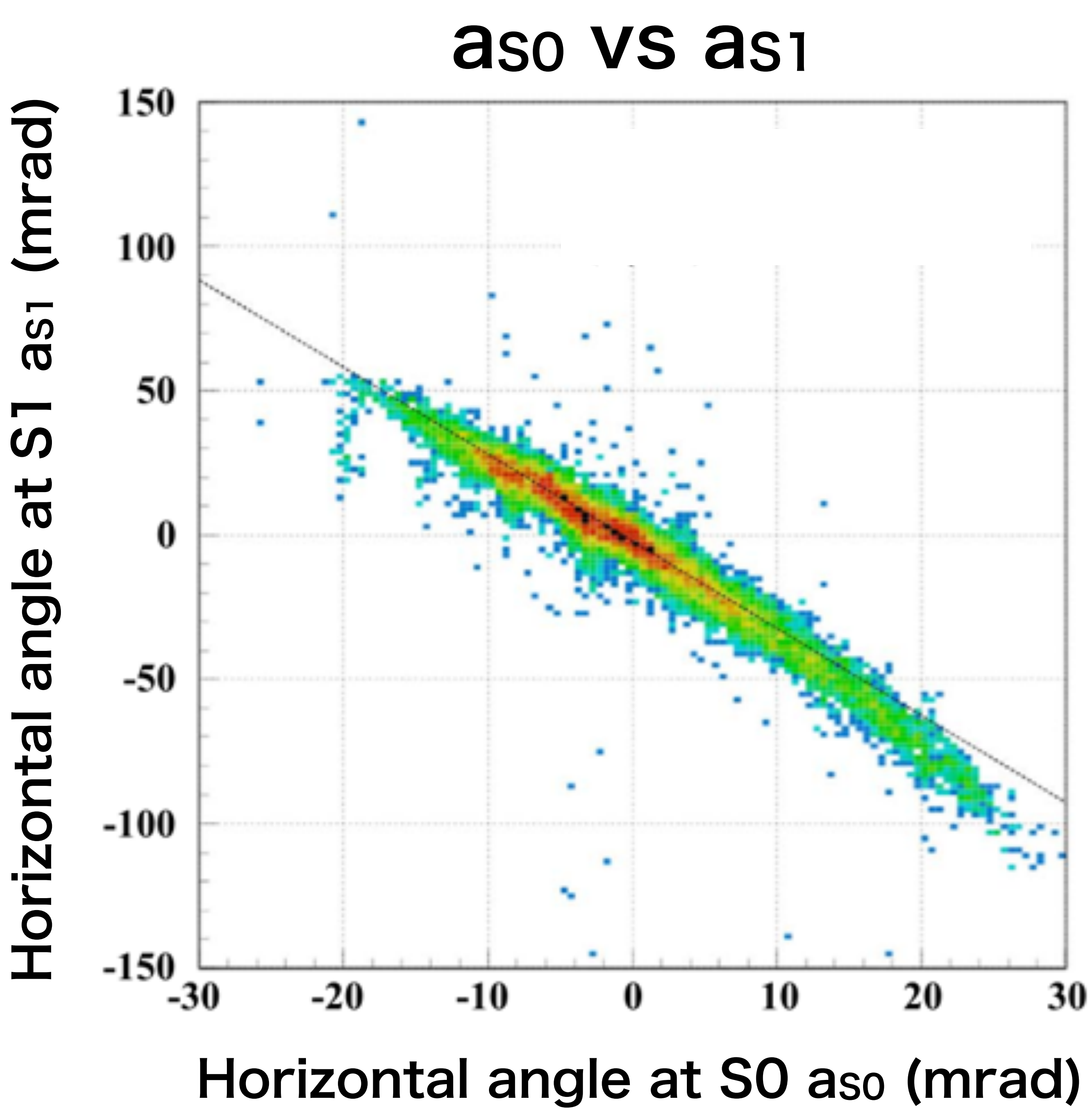
X_{S0}={0,±1mm}, Y_{S0}={0,±1mm}
A_{S0}={0,±20mr}, B_{S0}={0,±50mr}
Δp/p={0,+1%,-1%}

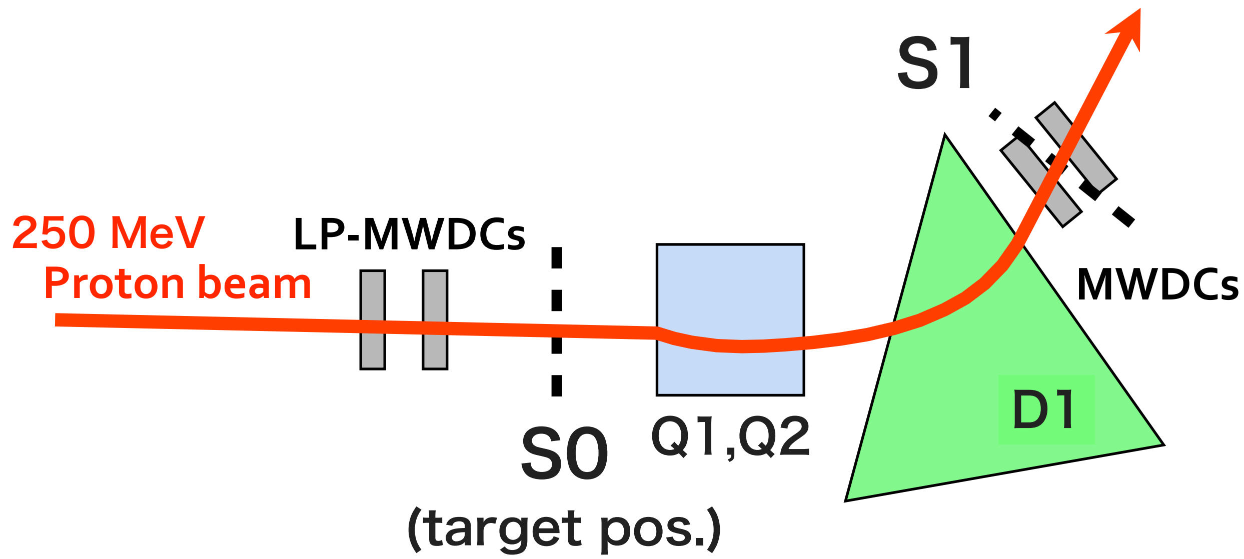
※ blue is for standard mode

Mom. Reso. :	1/15300 (1/14700)
Ang. Reso. :	<1 mrad (<1 mrad)
Mom. Accept. :	±1% (±1%)
Ang. Accept. :	3.8 msr (4.8 msr)

Ion-optics study with proton beam

- We measured proton trajectories at S0 and S1





1st [2nd]-order gradient corresponds to (a|a) [(a|aa)]

$(a|a) = -3.03 \pm 0.01$

$(a|aa) = -24.0 \pm 0.8\ \mathrm{rad}^{-1}$

Transfer-matrix elements of S0-S1 system

x			a		
$(x\|x)_{S1}$	-0.34 ± 0.01	(-0.36)	$(a\|x)_{S1}$ [rad/m]	-1.43 ± 0.01	(-1.53)
$(x\|a)_{S1}$ [m/rad]	0.01 ± 0.01	(0.00)	$(a\|a)_{S1}$	-3.03 ± 0.01	(-2.75)
$(x\|\delta)_{S1}$ [m]	-1.5703 ± 0.0002	(-1.56)	$(a\|\delta)_{S1}$ [rad]	-0.70 ± 0.05	(-0.75)
$(x\|aa)_{S1}$ [m/rad^2]	0.80 ± 0.74		$(a\|aa)_{S1}$ [rad^{-1}]	-24.0 ± 0.8	
$(x\|a\delta)_{S1}$ [m/rad]	0.40 ± 0.14		$(a\|a\delta)_{S1}$	11.5 ± 0.2	
$(x\|\delta\delta)_{S1}$ [m]	-7.319 ± 0.001		$(a\|\delta\delta)_{S1}$ [rad]	1.5 ± 0.2	
$(x\|aaa)_{S1}$ [m/rad^3]	-820 ± 31		$(a\|aa\delta)_{S1}$ [rad^{-1}]	80 ± 16	
$(x\|a\delta\delta)_{S1}$ [m/rad]	-57 ± 1		$(a\|a\delta\delta)_{S1}$	-12 ± 4	
$(x\|\delta\delta\delta)_{S1}$ [m]	-29.23 ± 0.05		$(a\|\delta\delta\delta)_{S1}$ [rad]	8 ± 6	
$(x\|a\delta\delta\delta)_{S1}$ [m/rad]	-690 ± 35		$(a\|aa\delta\delta)_{S1}$ [rad^{-1}]	910 ± 320	

y		
$(y\|y)_{S1}$	-9.55 ± 0.02	(-9.00)
$(y\|b)_{S1}$ [m/rad]	-4.70 ± 0.05	(-4.50)
$(y\|ab)_{S1}$ [m/rad^2]	-36 ± 3	
$(y\|y\delta)_{S1}$	34.0 ± 0.4	
$(y\|b\delta)_{S1}$ [m/rad]	23.5 ± 0.9	
$(y\|ab\delta)_{S1}$ [m/rad^2]	231 ± 73	
$(y\|b\delta\delta)_{S1}$ [m/rad]	-74 ± 19	

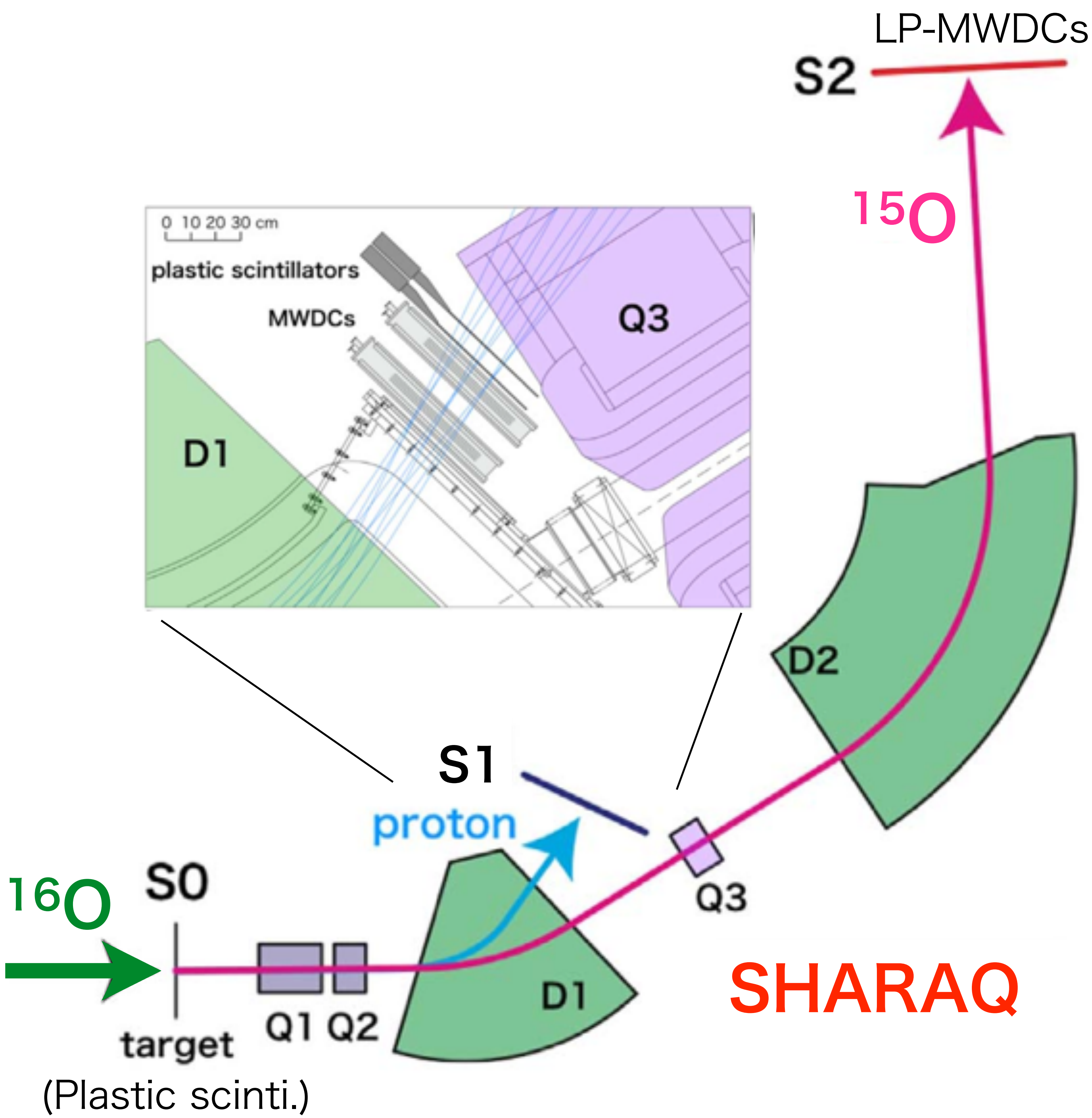
- 1st-order terms are in good agreement with design values
- Higher-order terms are too large to be neglected

(^{16}O,^{16}F->^{15}O+p) experiment

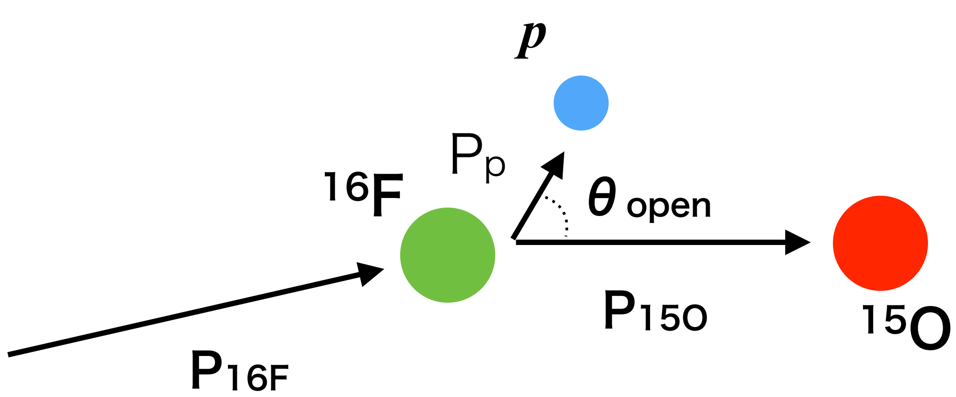
~ Performances of separated flow mode ~

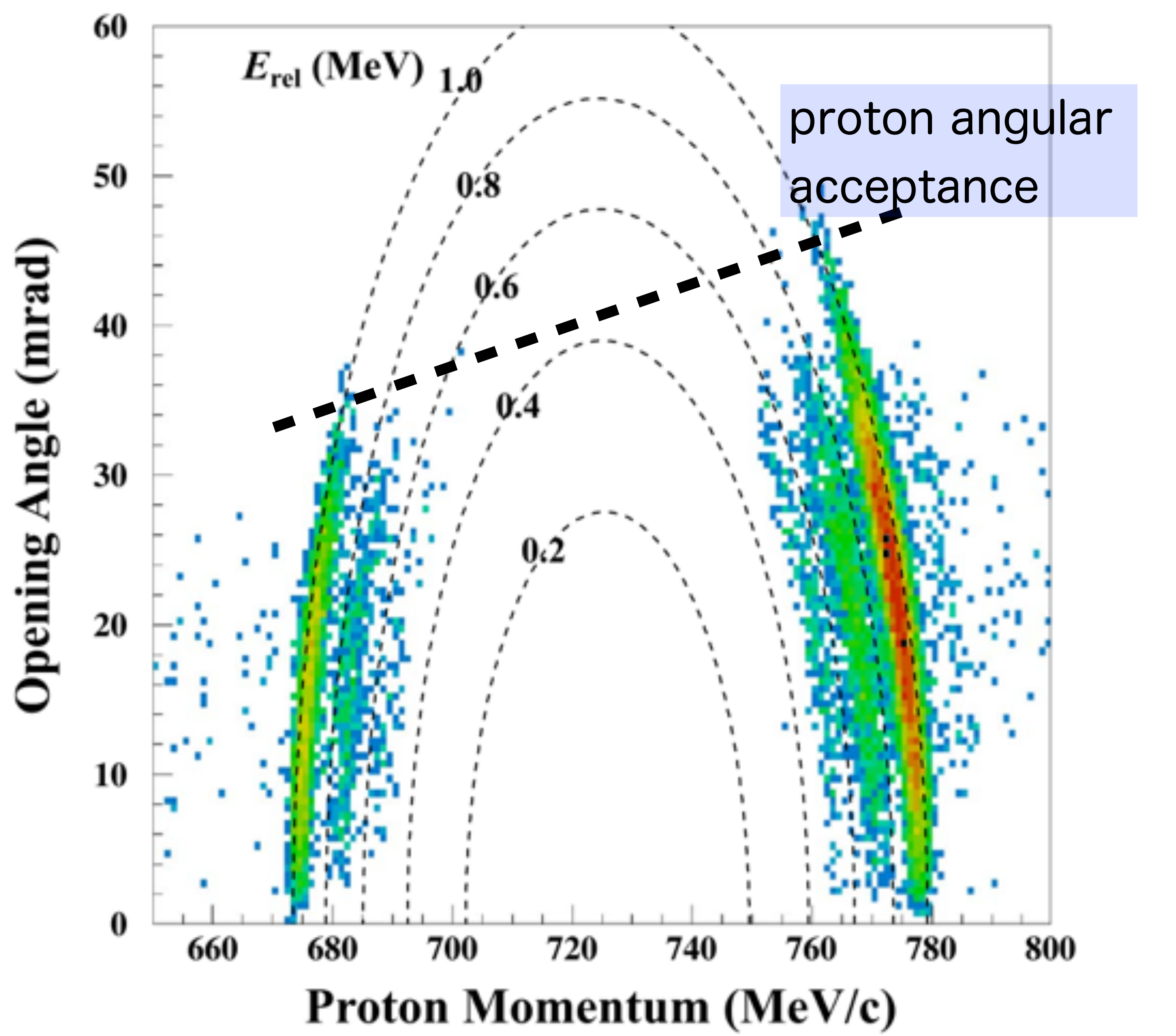
(^{16}O,^{16}F→^{15}O+p) experiment

- Beam : Primary ^{16}O
  - 250 MeV/u, 10^7 pps
  - Dispersion matched beam
- Target : Plastic scinti.
  - 1 mm thickness
- Coincidence measurement of ^{16}F -> ^{15}O + p
  - Separated flow mode
    - ^{15}O : 2 LP-MWDCs @ S2
    - p : 2 MWDCs @ S1



$^{16}F \rightarrow ^{15}O + p$ decay



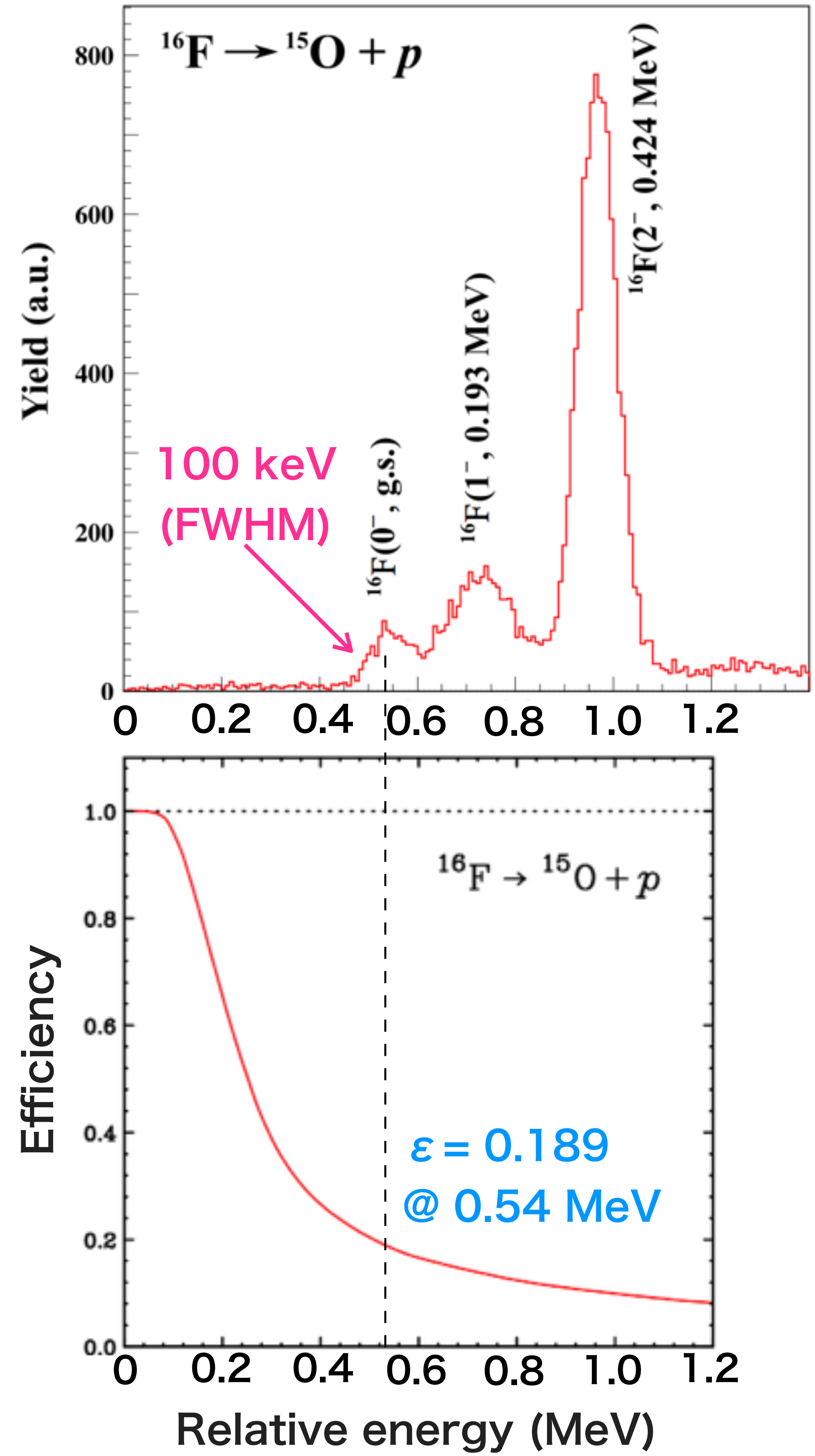


- Kinematics curves are clearly observed

$^{16}F \rightarrow ^{15}O + p$ decay

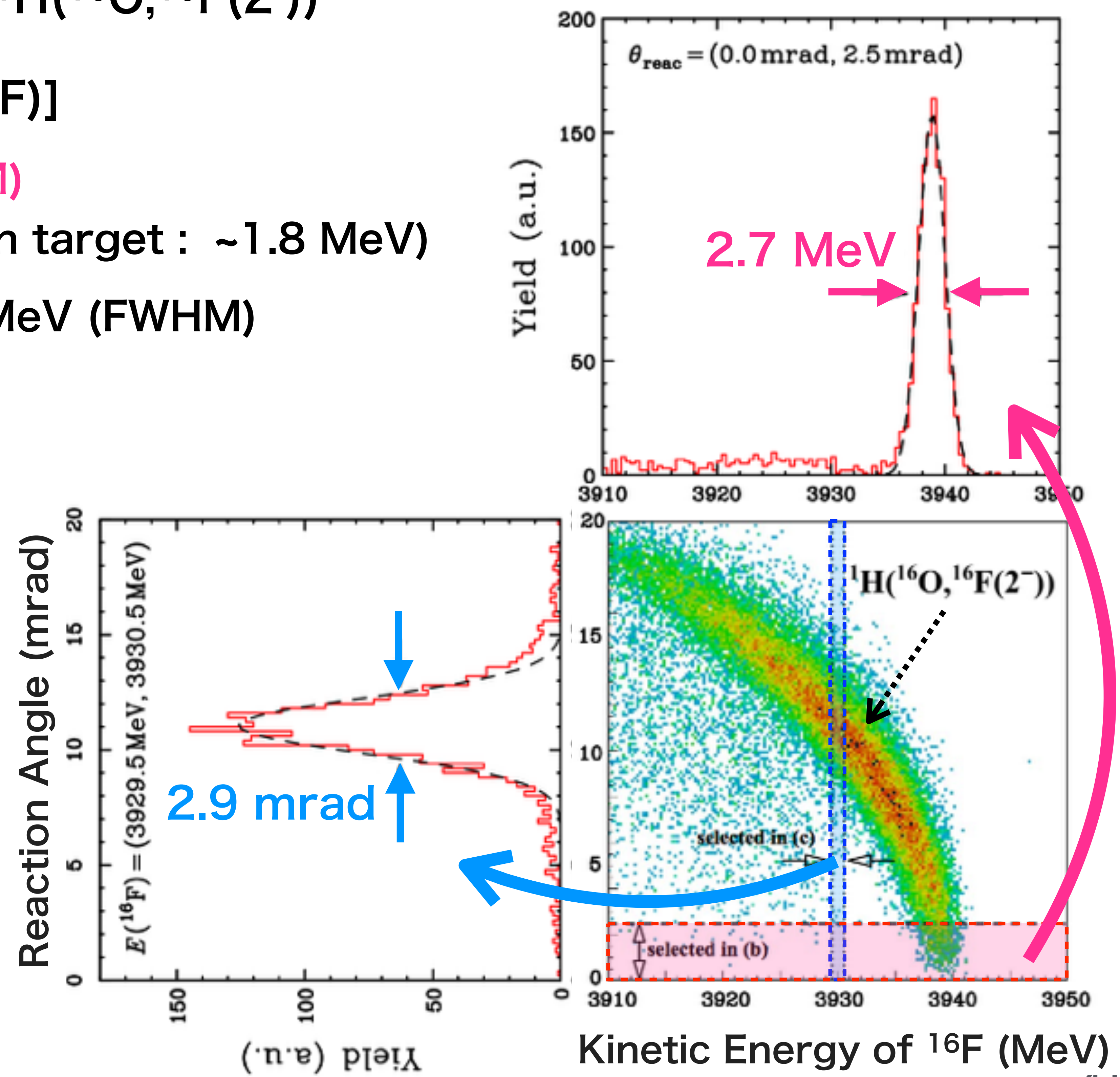
- Relative energy (E_{rel})
  - δE_{rel} = 100 keV (FWHM)
    @ E_{rel} = 0.54 MeV
    ⇒ Clear separation
    between $^{16}F(0^-, 1^-, 2^-)$!

- Detection efficiency (ε)
  (Monte Carlo simulation)
  - ε = 0.189 @ E_{rel} = 0.54 MeV
  - Due to ang. accpt. for proton



(^{16}O,^{16}F(2$^-$)) reaction

- Kinematic correlation for ^{1}H(^{16}O,^{16}F(2$^-$))
- Kinetic energy of ^{16}F [E(^{16}F)]
  - δE(^{16}F) = 2.7 MeV (FWHM)
    (Includes energy stragg. in target : ~1.8 MeV)
  - ⇒ Intrinsic resolution ~2 MeV (FWHM)
- Reaction angle [θ_{reac}]
  - $\delta\,\theta_{reac}$ = 2.9 mrad
  - (Includes ang. spread of beam : ~3 mrad)



Comparison with other system

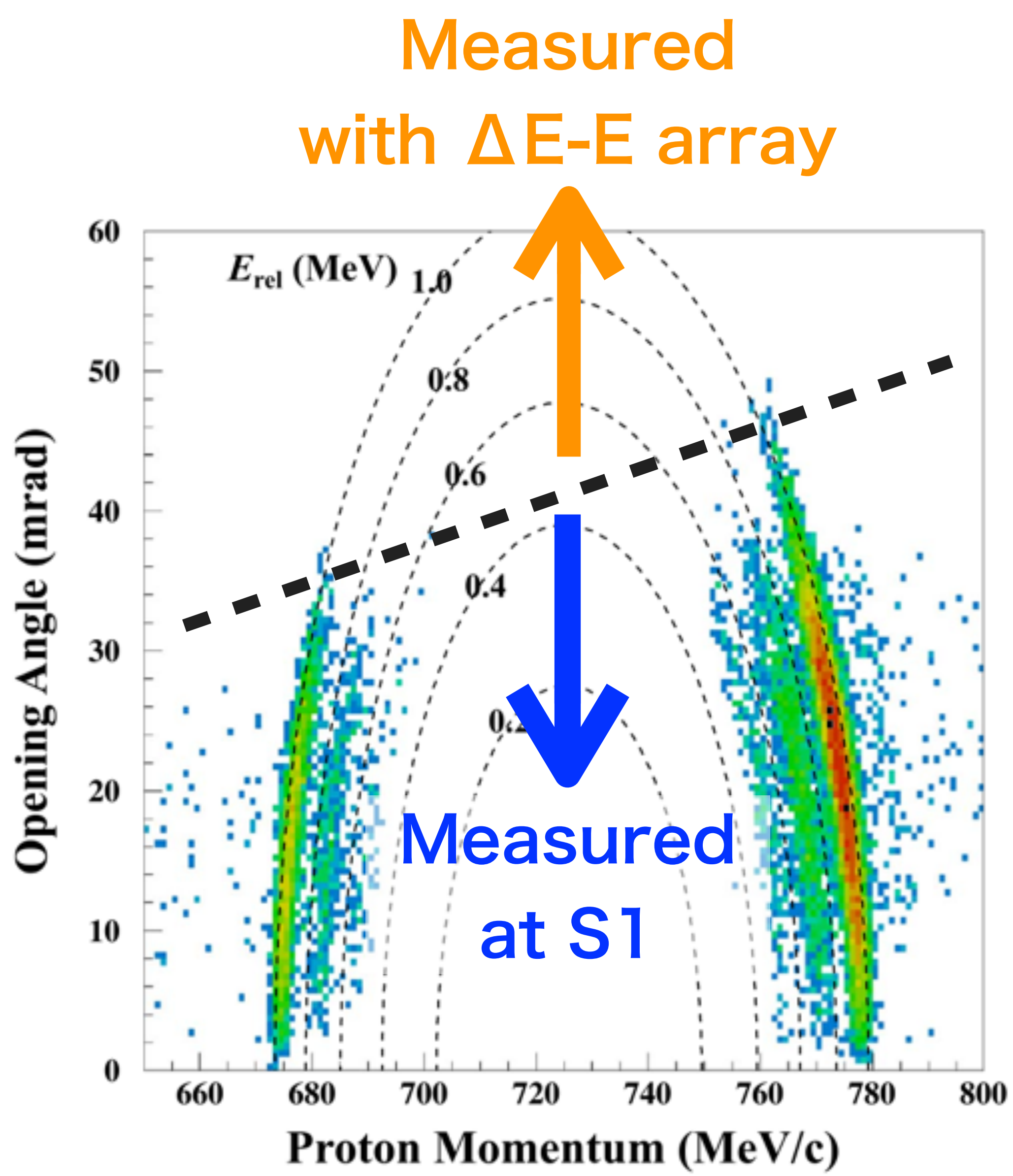
	This work	Iwasa et al. *PRL 83 (1999) 2910*
Spectrometer	SHARAQ @ RIBF	KaoS @ GSI
Beam energy	247 MeV/u	254 MeV/ nucleon
Measured product	$^{16}F \to {}^{15}O + p$	$^{8}B \to {}^{7}Be + p$
Relative energy resolution	0.10 MeV at $E_{rel} = 0.535$ MeV	0.26 MeV at $E_{rel} = 0.6$ MeV
Efficiency	0.189 at $E_{rel} = 0.535$ MeV	~0.8 at $E_{rel} = 0.6$ MeV
Kinetic energy resolution	2.7 MeV	
Reation angular resolution	2.9 mrad	

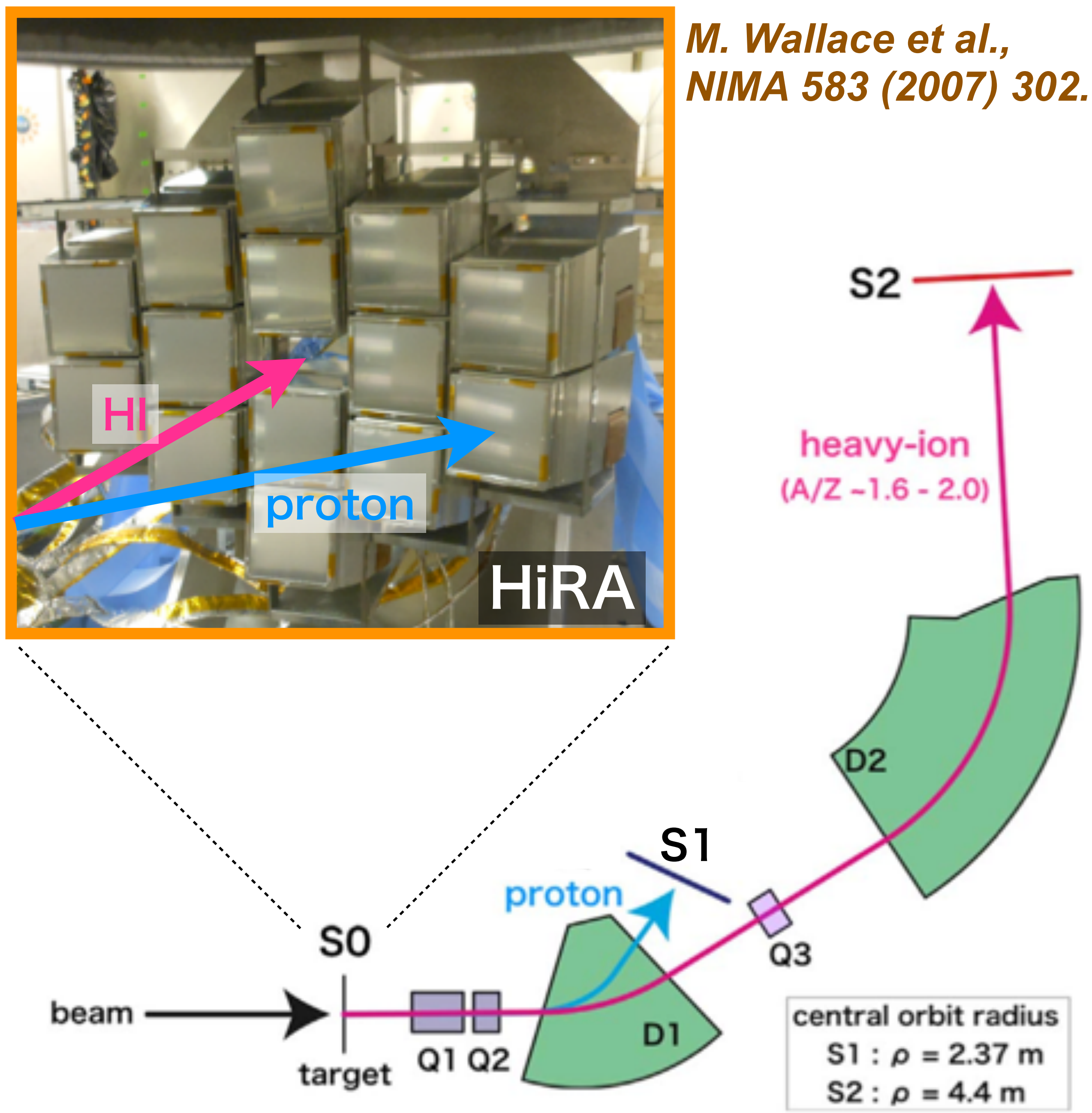
← Better by a factor of ~2.5

← Smaller by a factor of ~4

SHARAQ + ΔE-E array

- More efficient measurements may be made possible by combination with a ΔE-E array similar to HiRA





M. Wallace et al., NIMA 583 (2007) 302.

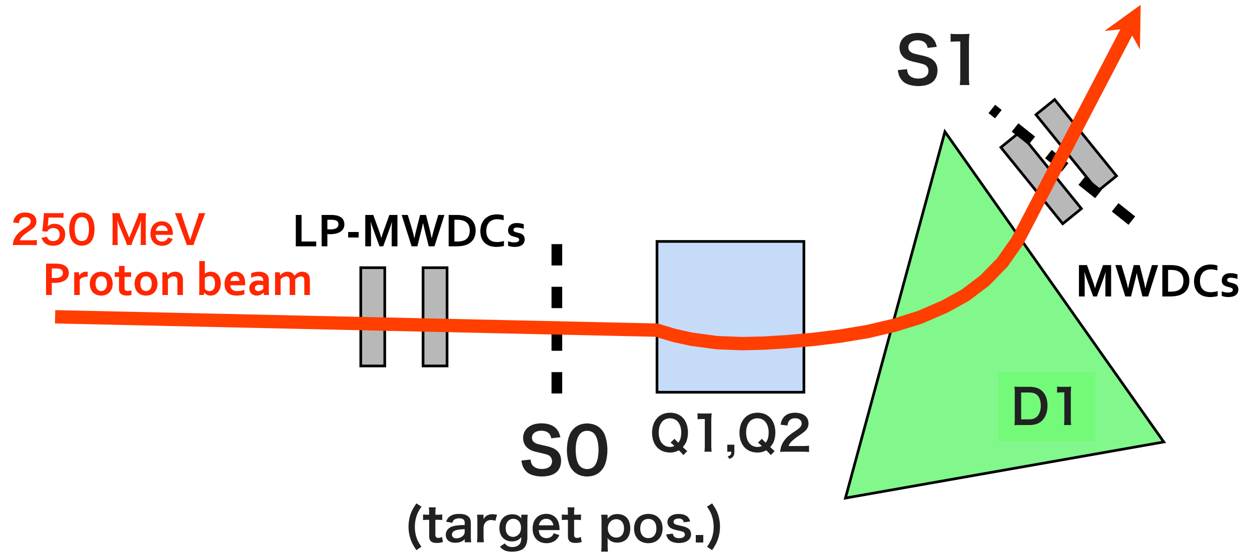
Summary

- Separated flow mode of SHARAQ
  - Use SHARAQ as two spectrometers
    ⇒ Allow coincidence measurements of proton and heavy-ion pairs
  - The transfer-matrix elements were experimentally determined including higher-order terms by using a secondary proton beam
- (^{16}O,^{16}F) experiment
  - High energy resolutions were achieved
    - Relative energy : δE_{rel} = 100 keV (FWHM) @ E_{rel}=0.54 MeV
    - Kinetic energy of ^{16}F : $\delta E(^{16}F)$=2.7 MeV (FWHM) @ $E(^{16}F)$=3940 MeV

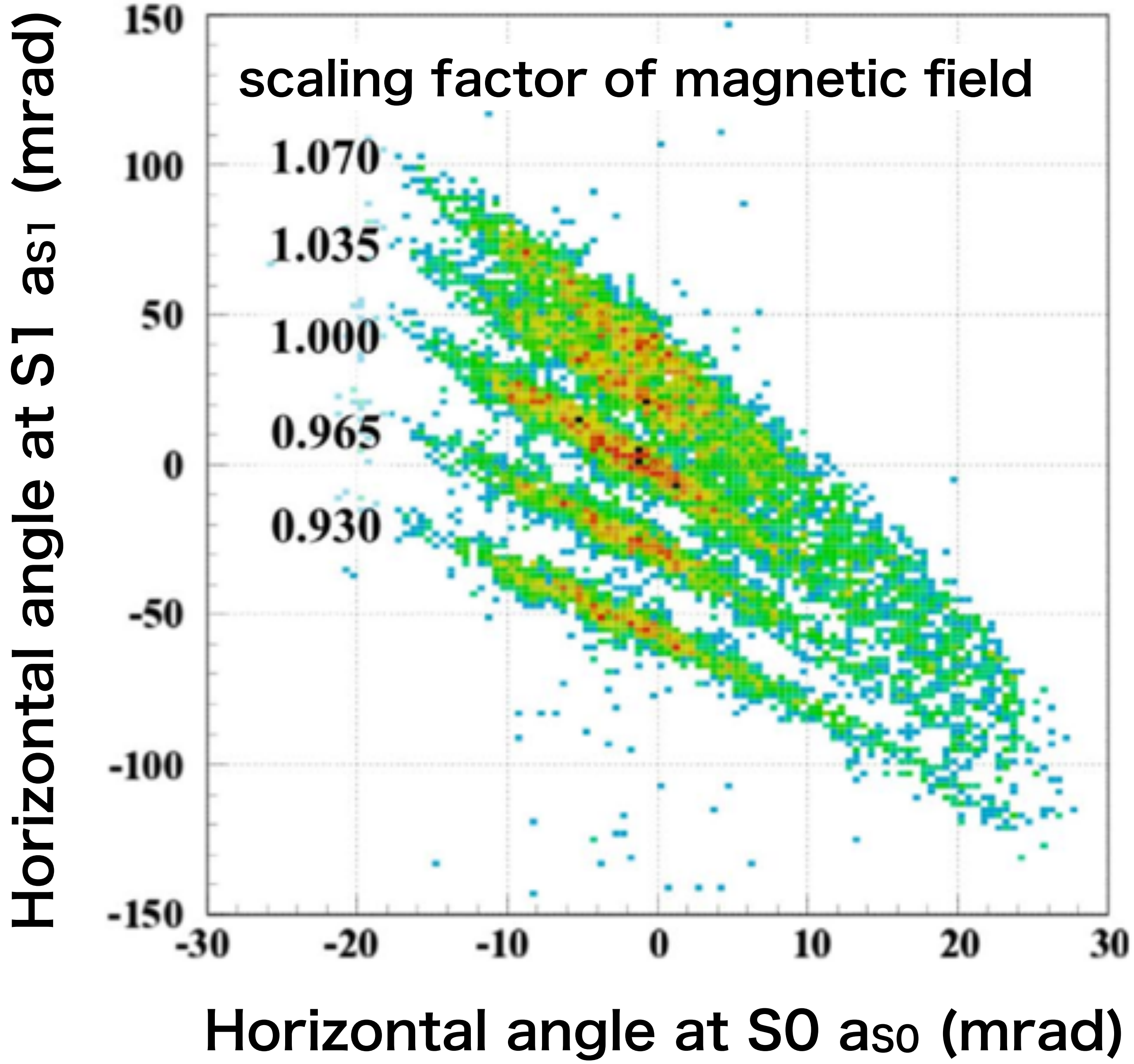
Missing-mass + invariant-mass measurement
gives unique opportunities
to explore little-studied excitation modes in nuclei
using new types of reaction probes with particle-decay channels

Ion-optics study with proton beam

- We measured proton trajectories at S0 and S1



a_{S0} vs a_{S1}



δ-dep. terms were also determined by scaling magnetic field of SHARAQ