Parity-transfer reaction for study of spin-dipole 0^- mode

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Scientific motivation

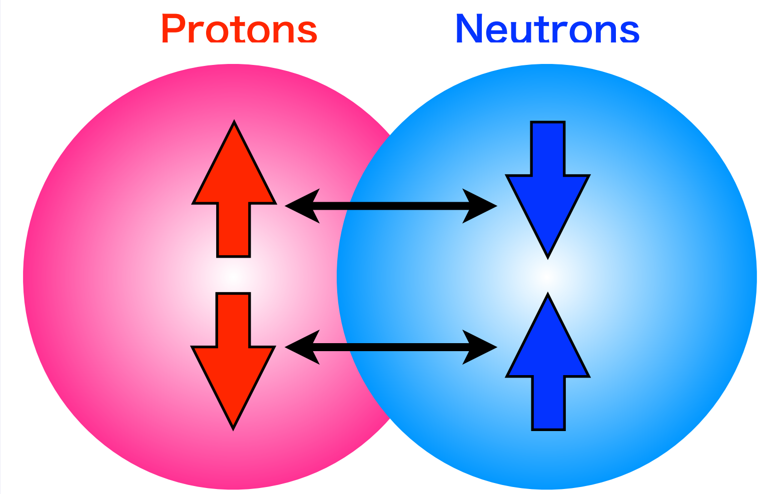
Spin-isospin modes (ΔS=1, ΔT=1) in nuclei play an essential role in understanding of nuclear structure

M. N. Harakeh et al., "Giant Resonances", Oxford, 2001
M. Ichimura et al., PPNP 56, 446 (2006).

- Spin-Dipole (SD) mode
  - (Isovector) SD operator

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

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



・Anti-phase vibration between protons and neutrons (ΔL=1, ΔT=1)
・Spin-flip mode (ΔS=1)

- SD 0^- mode (particular interest)
  - Carries quantum numbers of pion ($J^{\pi}=0^-$, T=1)
  - Reflects pion-like (tensor) correlations in nuclei

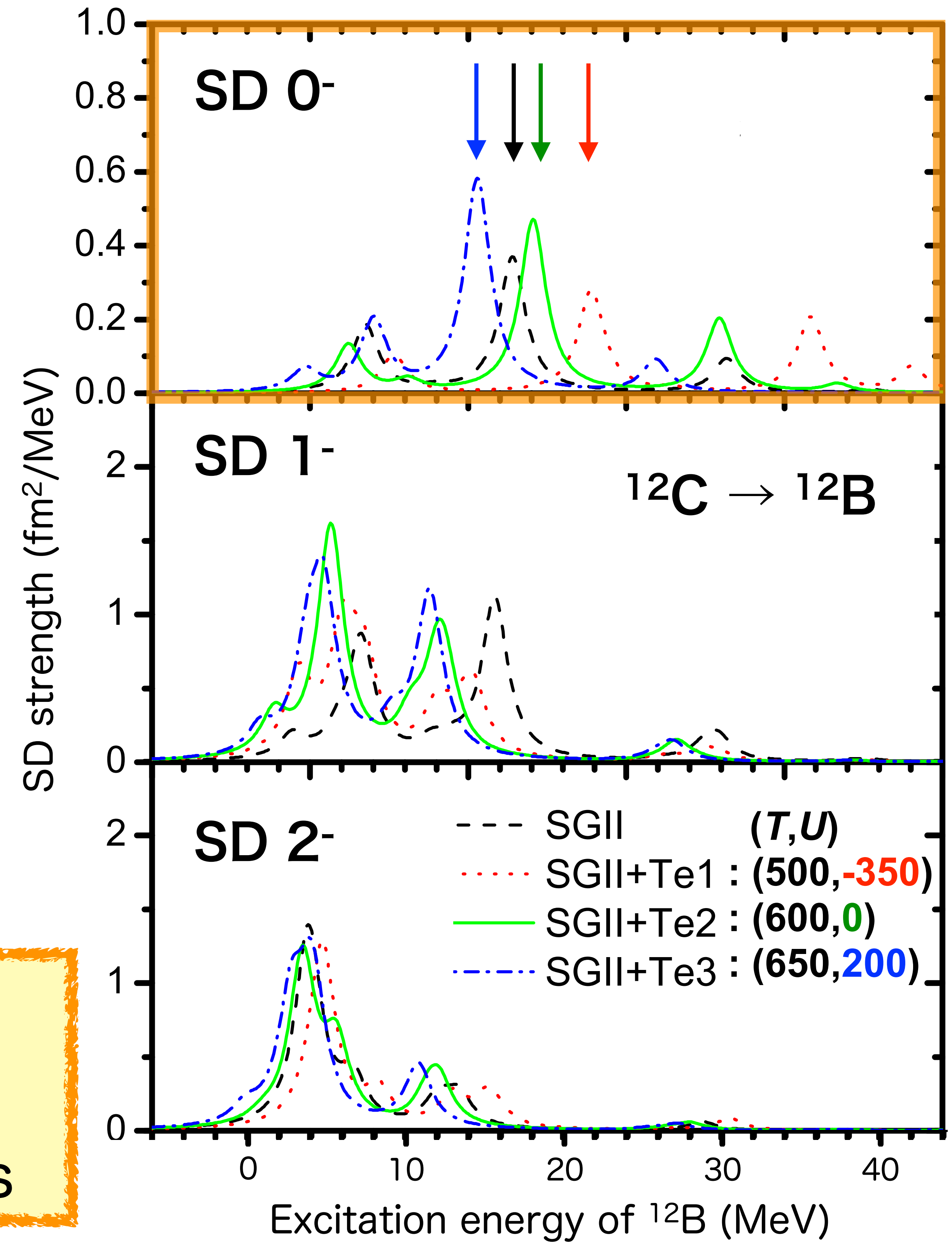
Tensor effects on 0^- strengths

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

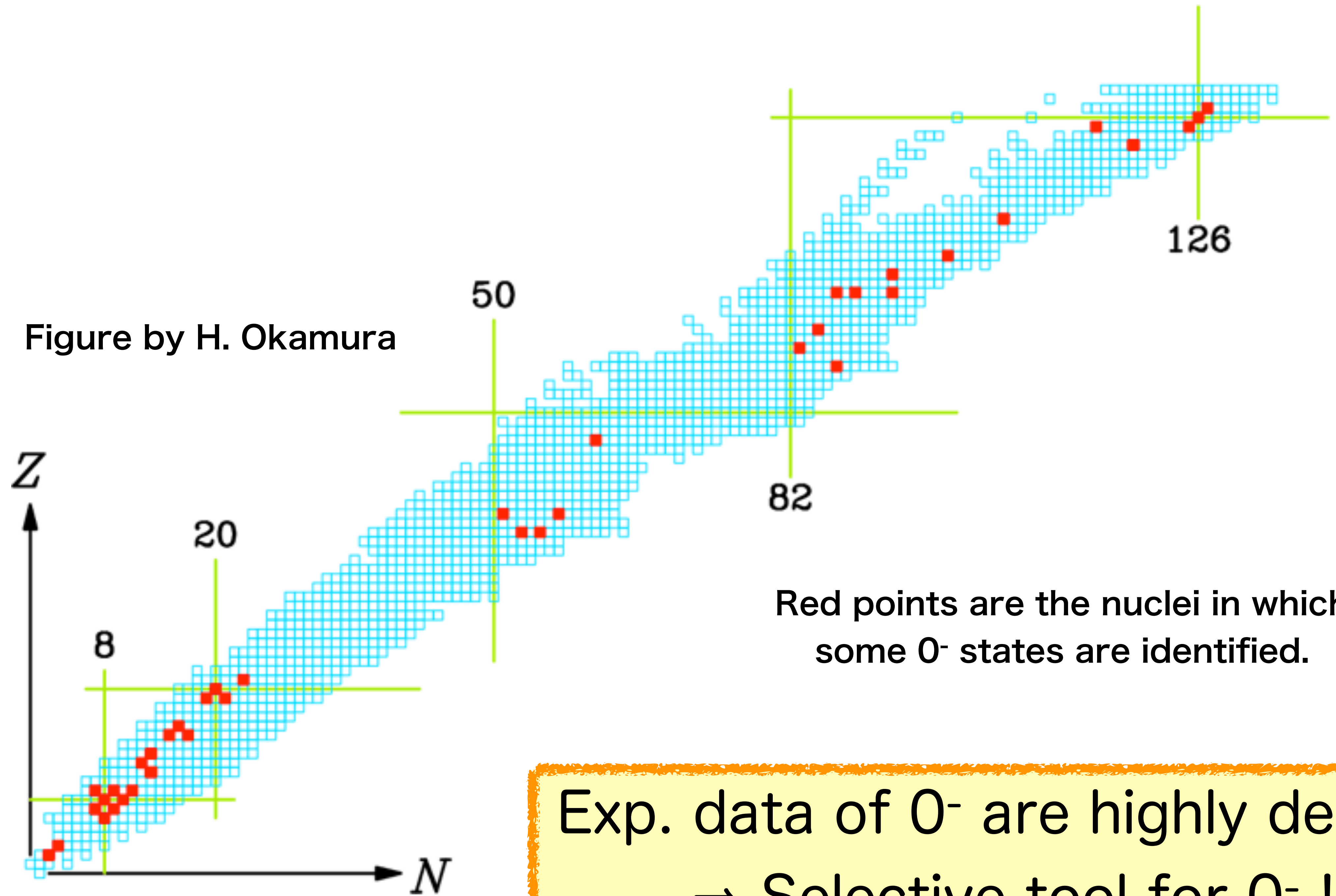


Figure by H. Okamura

Red points are the nuclei in which some 0^- states are identified.

Exp. data of 0^- are highly desired

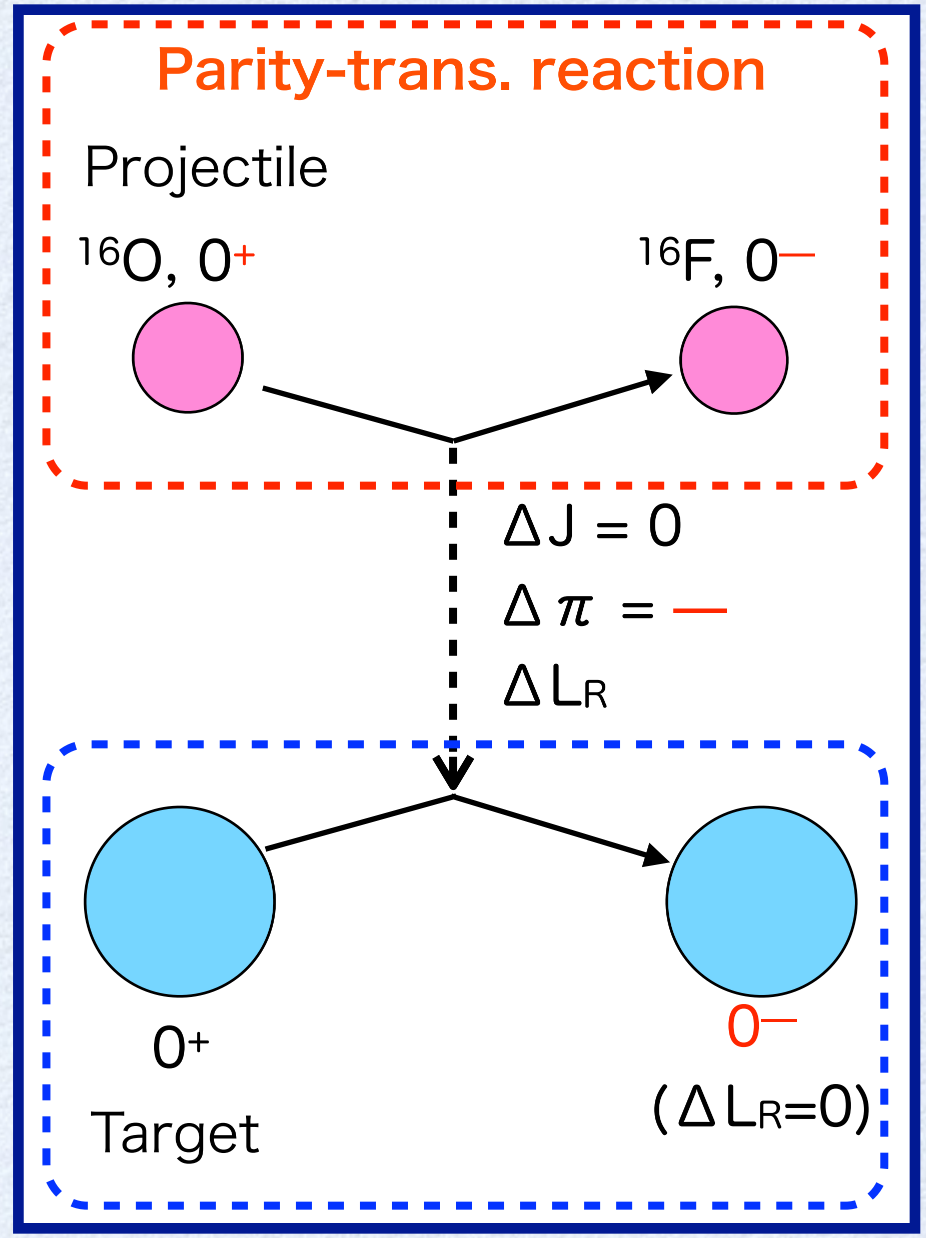
⇒ Selective tool for 0^- !

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 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

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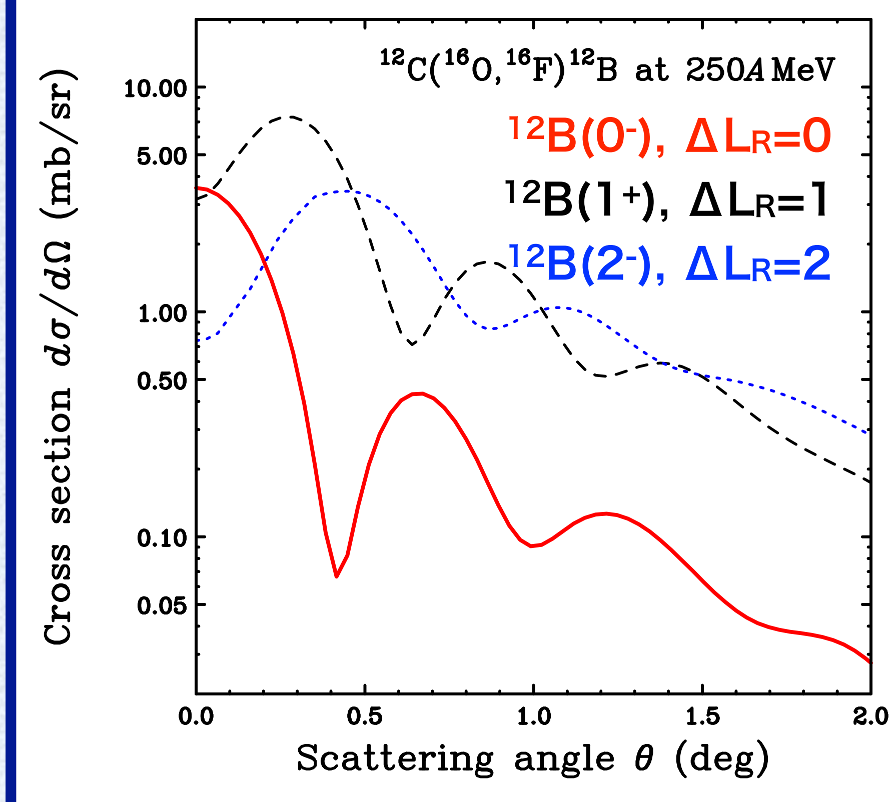
(p,n),(d,^{2}He) etc.	0^+,1^+	0^-, 1^-, 2^-	1^+, 2^+, 3^+	…

DWBA calculations with FOLD/DWHI



Clean probe for SD 0^- search

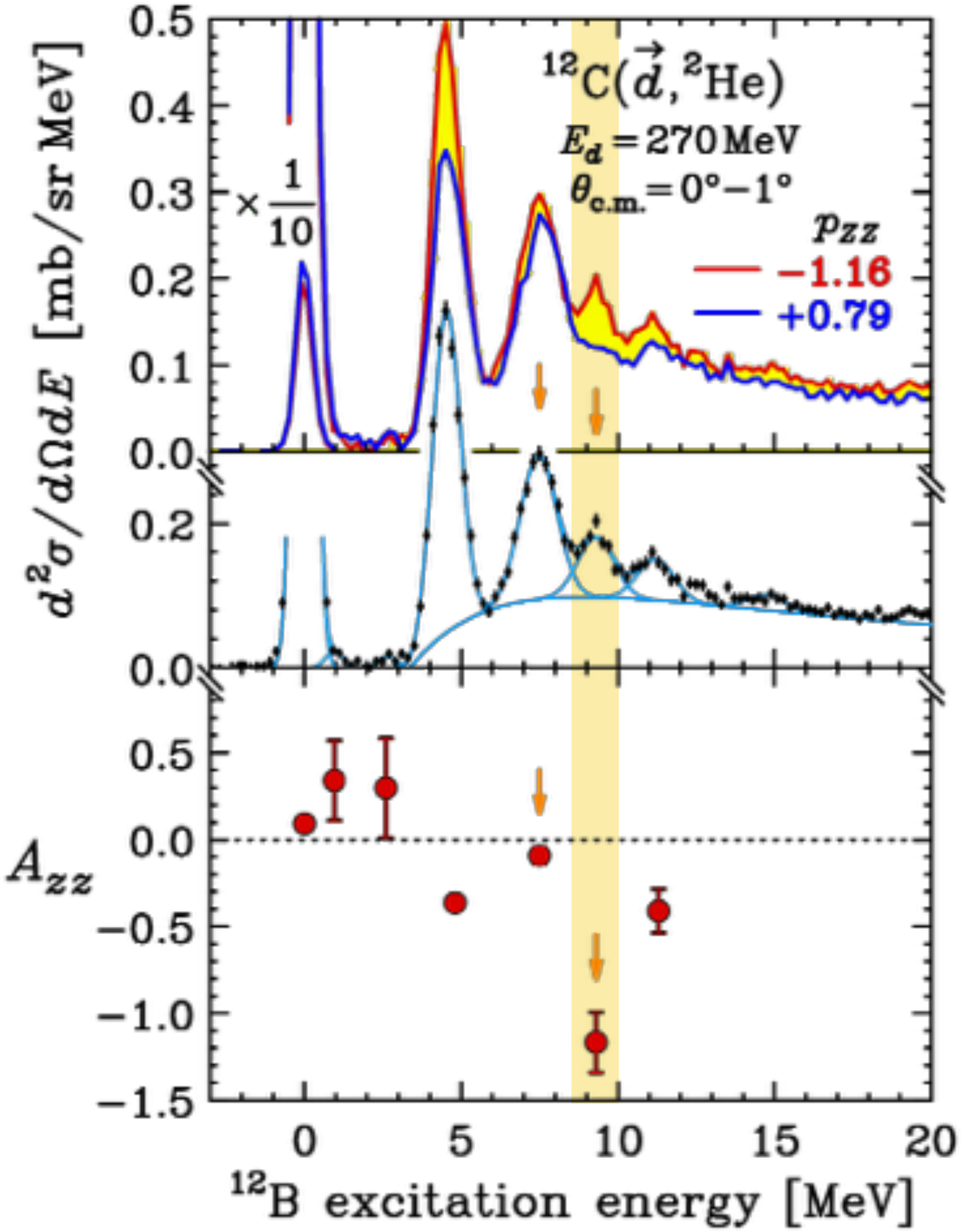
First parity-transfer measurement : $^{12}C(^{16}O,^{16}F(0^-))^{12}B$ at 250 MeV/u

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 parity-trans. reaction as a new tool for the 0^- study

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

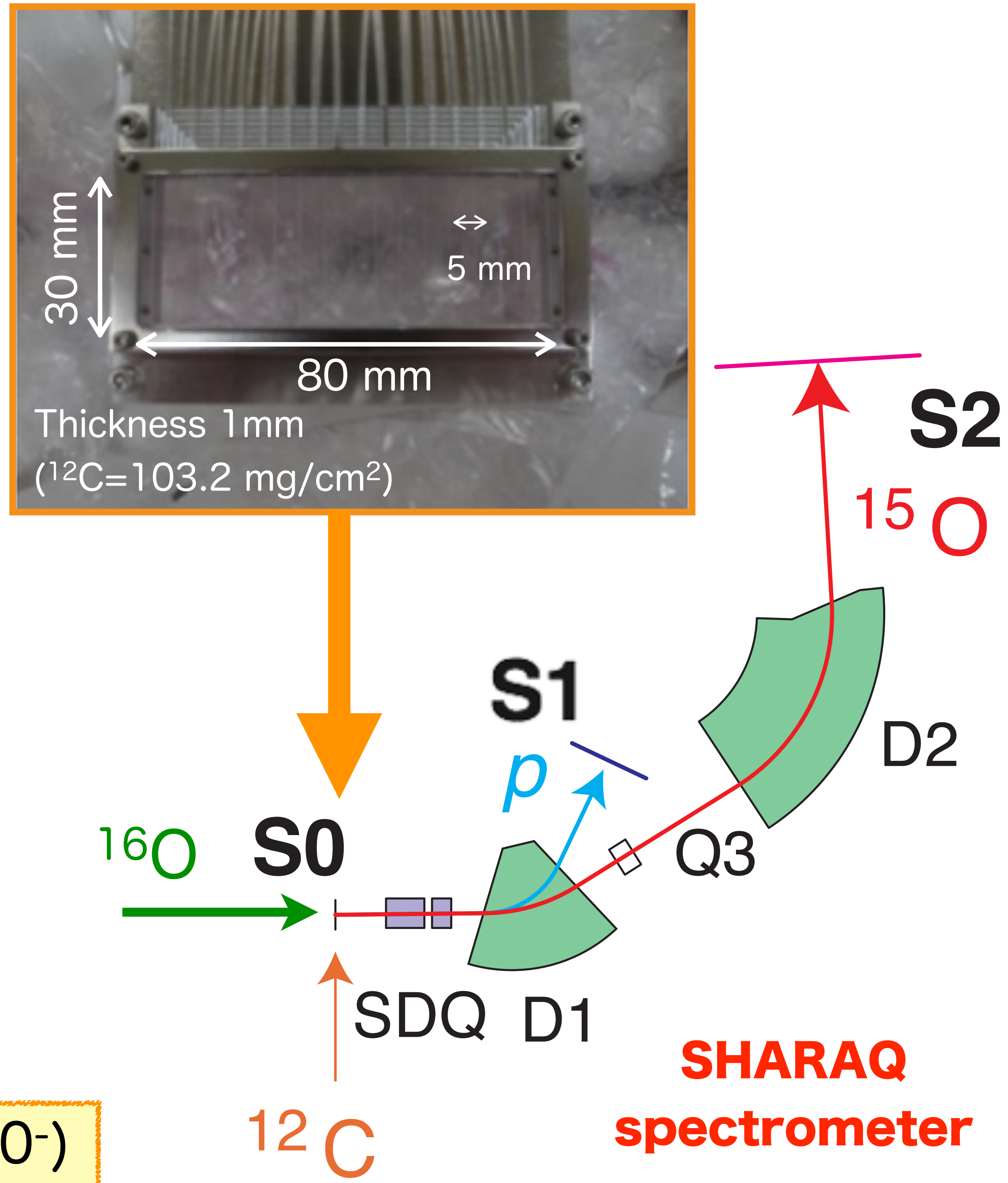


^{12}C(^{16}O,^{16}F(0^-)) experiment @ RIBF & SHARAQ

- Beam : Primary ^{16}O
  - 250MeV/u, 10^7 pps (radiation limit)
  - Dispersive matched beam
    - $(\Delta P/P)_{beam}$ ~ 0.1%
    - $(x|\delta)_{beamline}$ = -10 m
- Target : ^{12}C
  - Segmented plastic scinti. (active C target, 103.2 mg/cm^2)
  - Determine beam x-position @ S0 (NOT used in present analysis)
- Coincidence measurement of ^{16}F -> ^{15}O + p
  - ^{15}O : 2 LP-MWDCs @ S2
  - p : 2 MWDCs @ S1

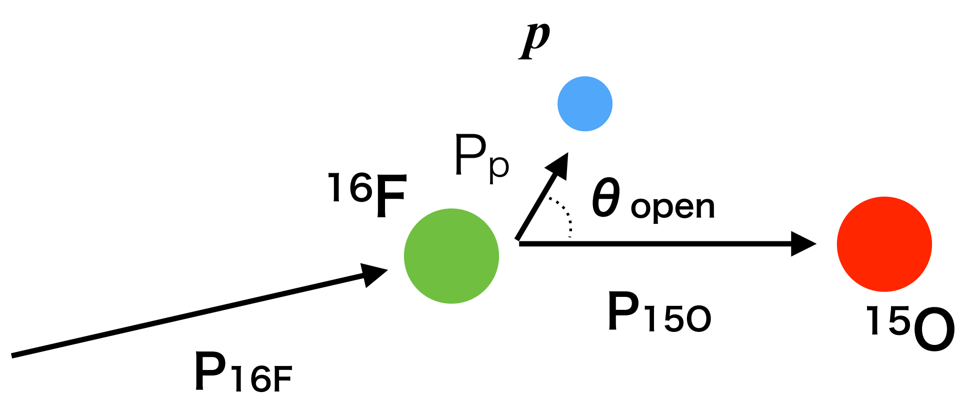
· Invariant-mass of ^{15}O+p ⇒ Identify ^{16}F(0^-)
· Missing-mass ⇒ Deduce E_x in ^{12}B and θ

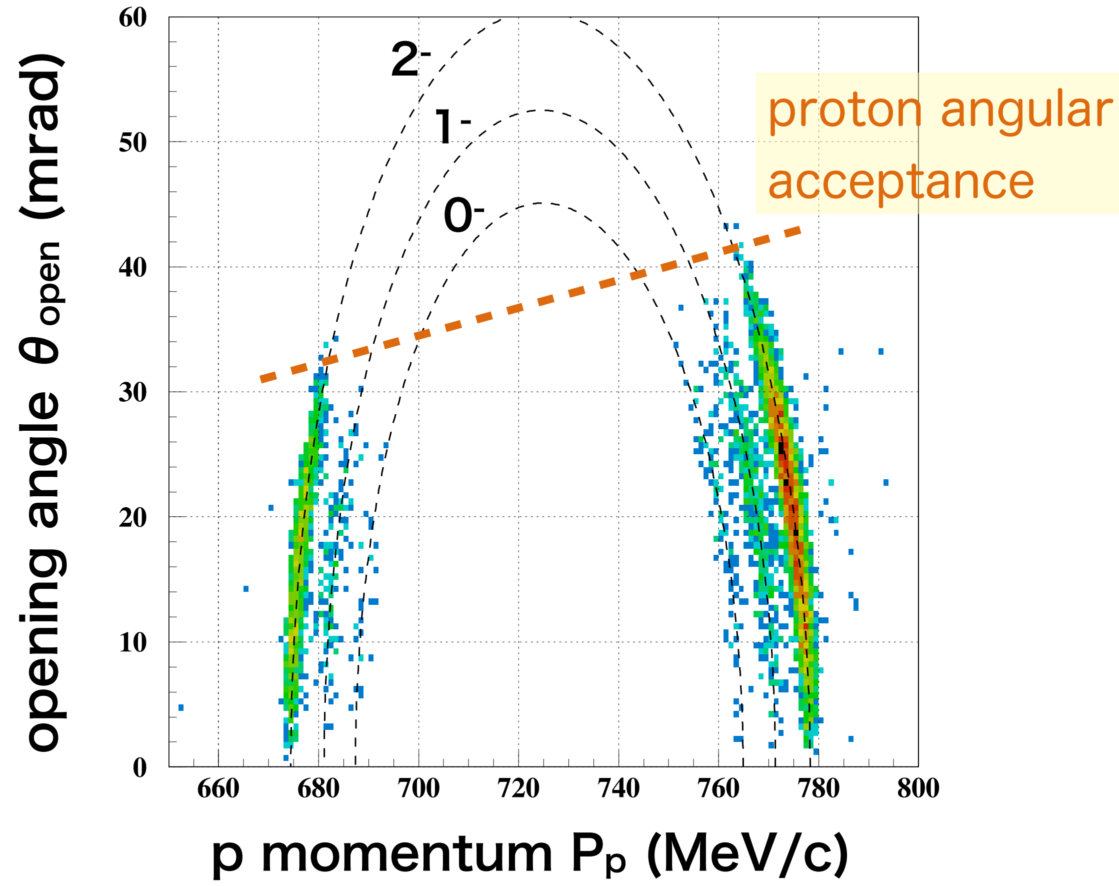
Segment scinti.

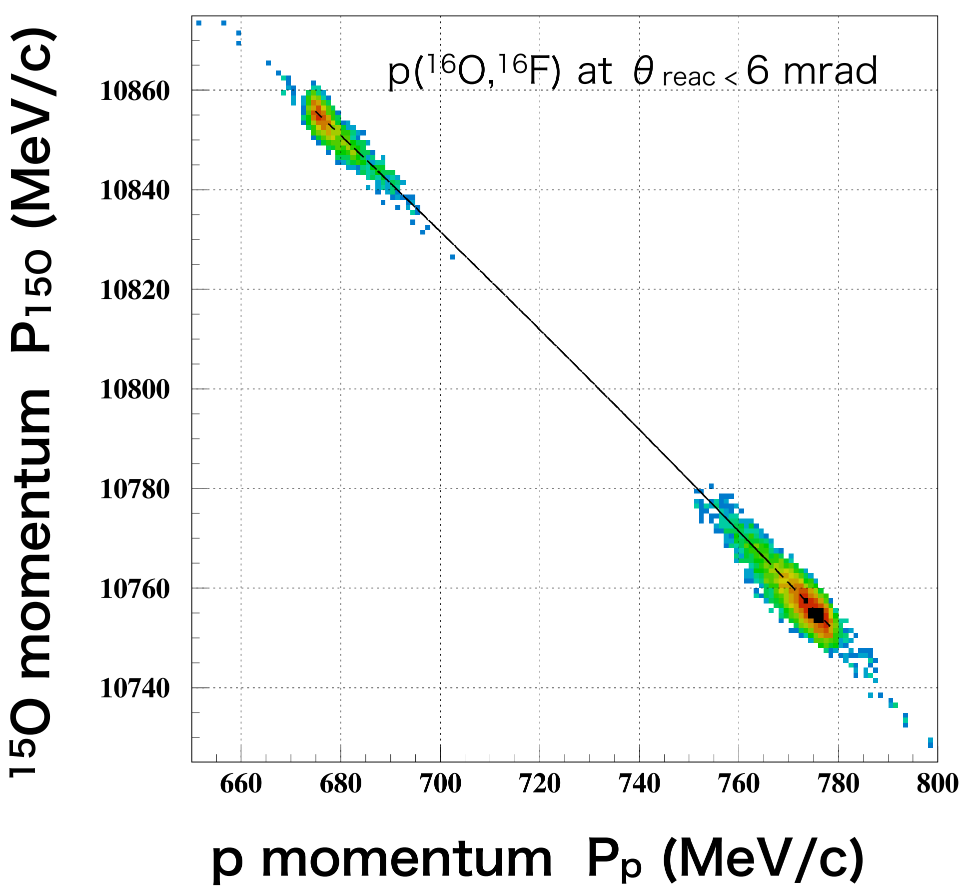


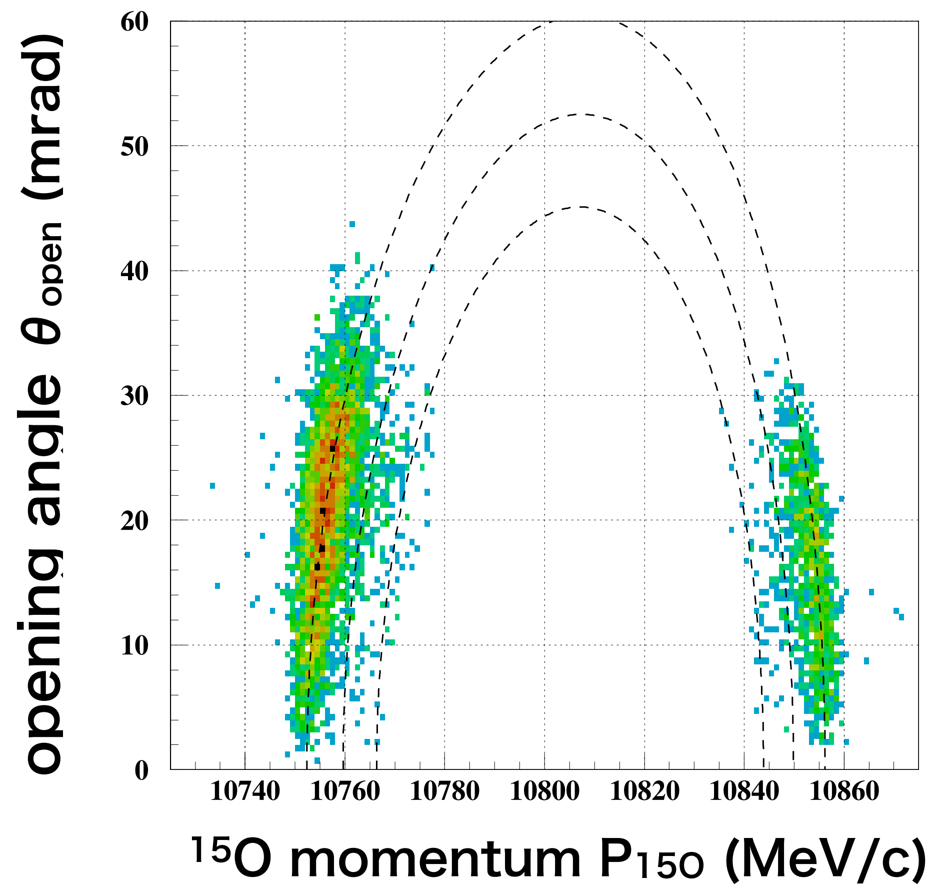
$^{16}F \rightarrow ^{15}O + p$ decay

Decay kinematics curves are clearly observed

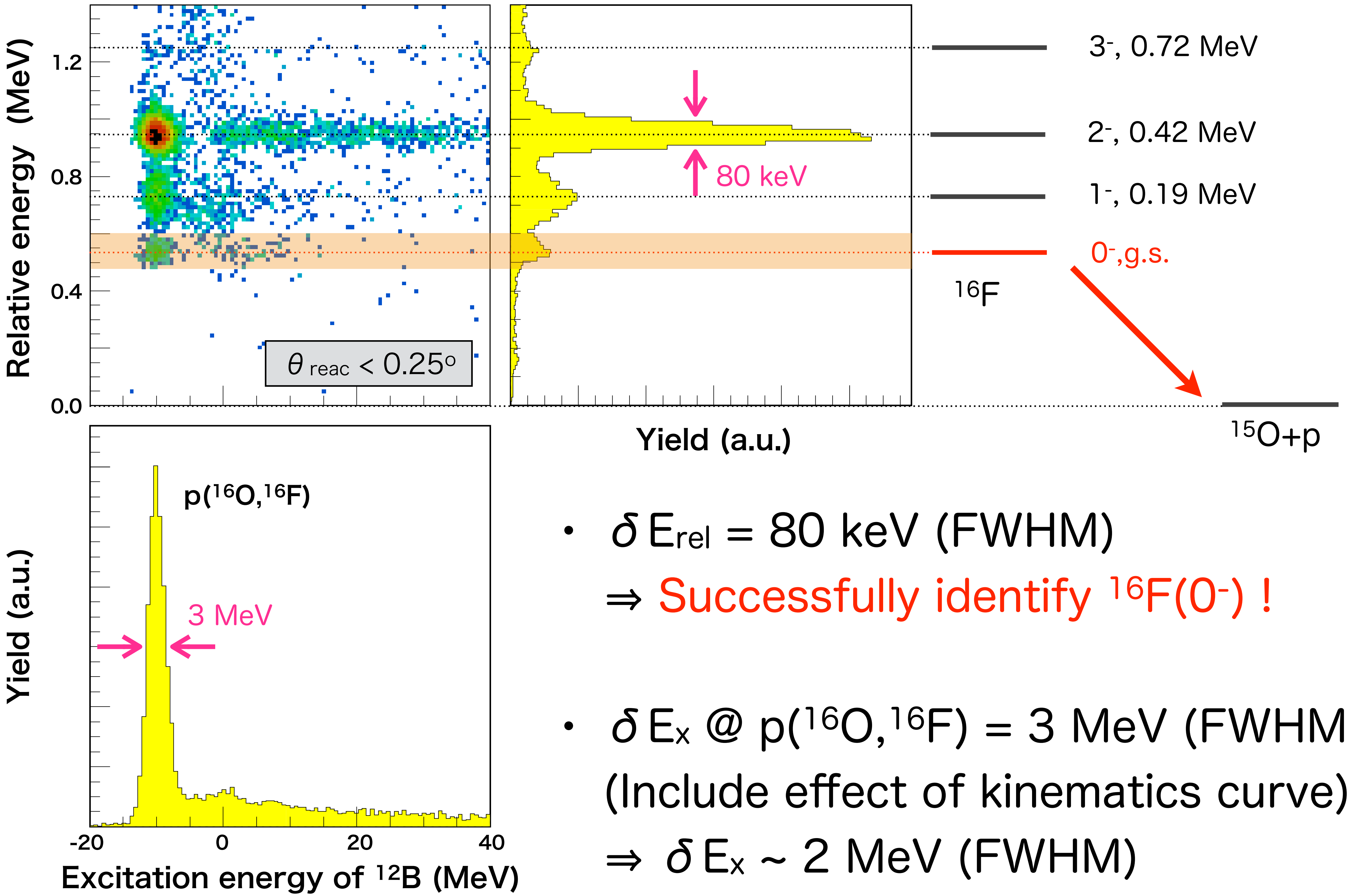








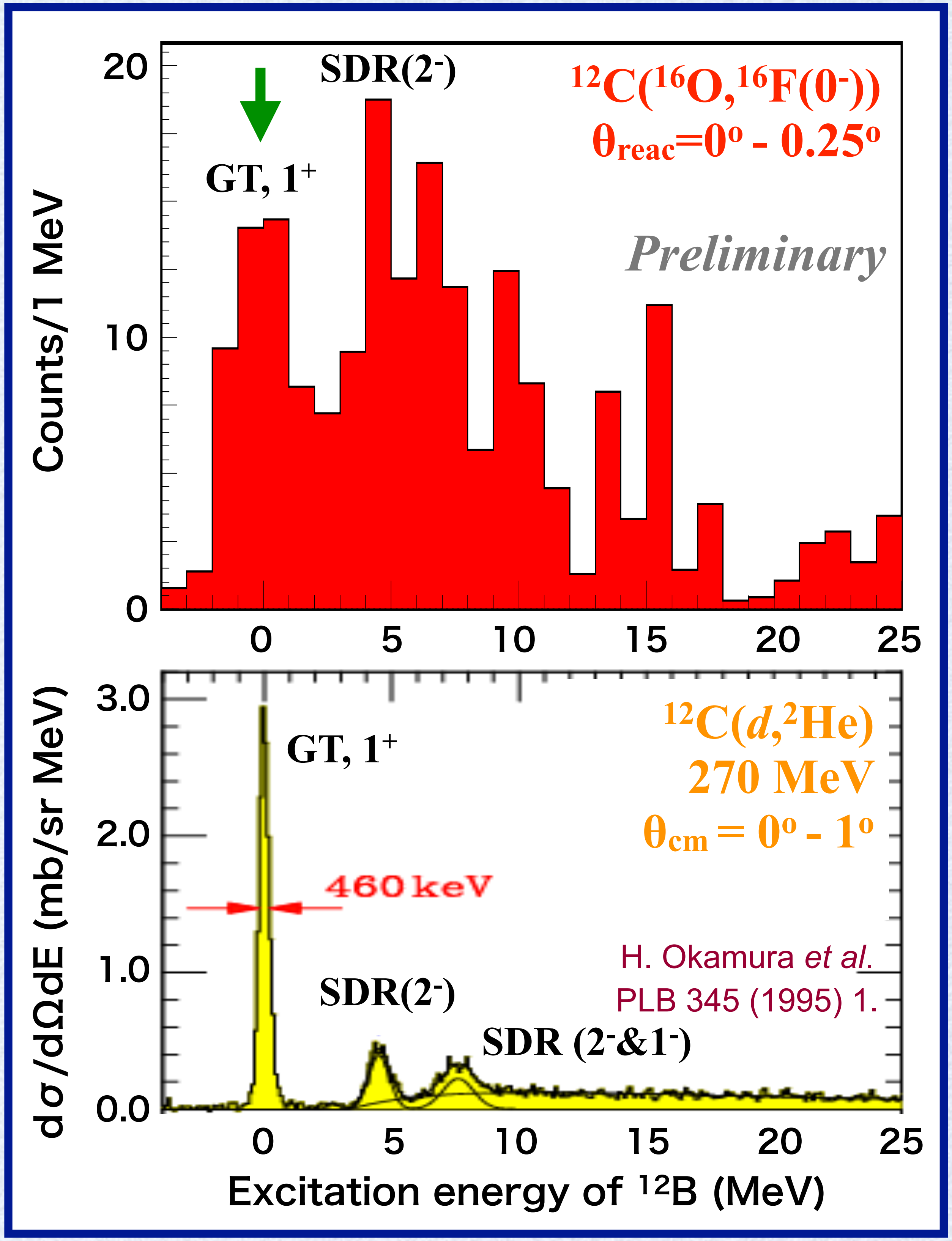
Relative energy E_{rel} vs Excitation energy E_x



- δE_{rel} = 80 keV (FWHM)
  ⇒ Successfully identify $^{16}F(0^-)$!
- δE_x @ p(^{16}O,^{16}F) = 3 MeV (FWHM)
  (Include effect of kinematics curve)
  ⇒ δE_x ~ 2 MeV (FWHM)

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

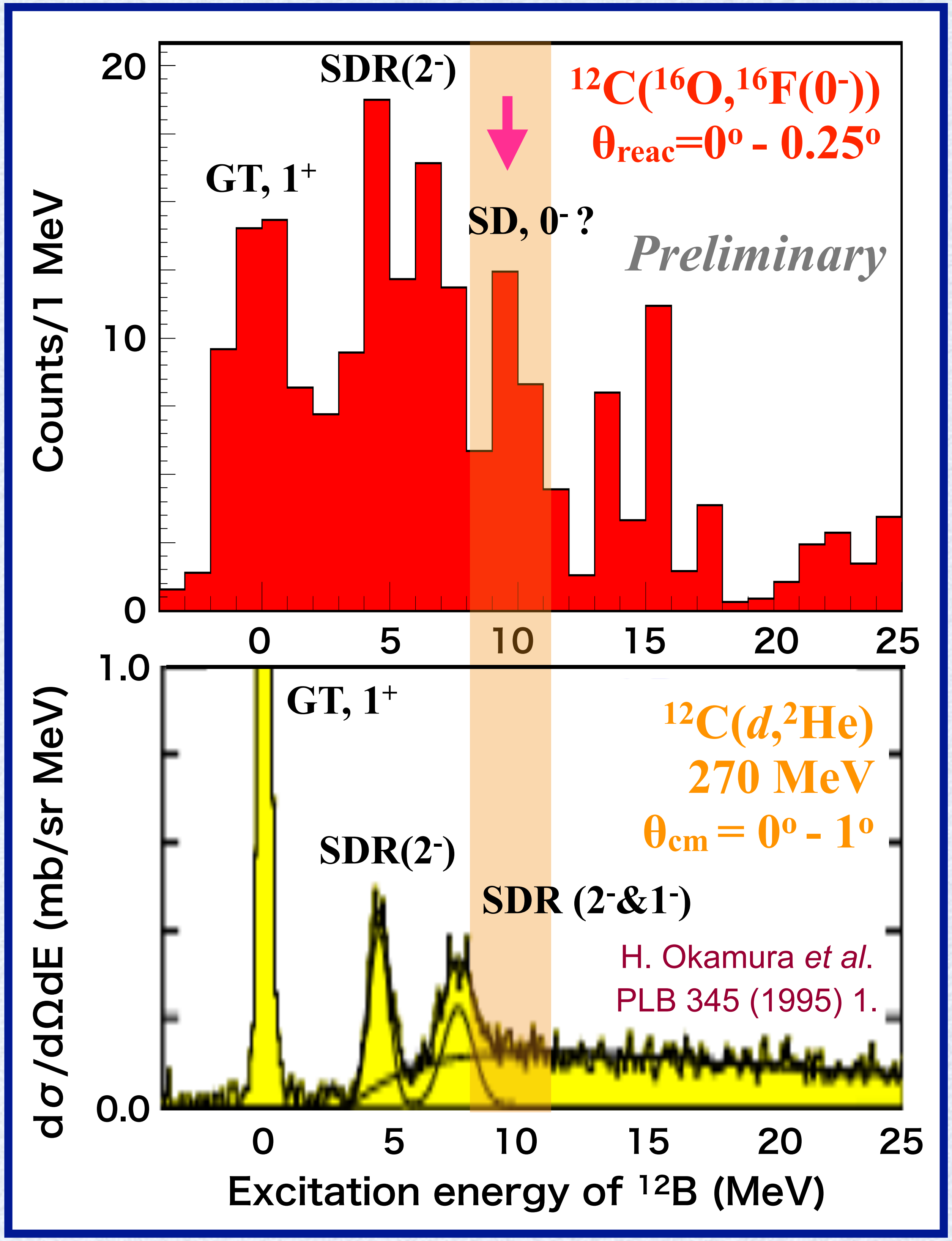
- Different structure compared with $(d,^2He)$
  - GT(1^+) at 0 MeV
    - Hindered



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

- Different structure compared with $(d,^2He)$
  - GT(1^+) at 0 MeV
    - Hindered
  - SDR(2^-) at 4.5 MeV
  - SDR(2^- & 1^-) at 7.5 MeV
  - SD 0^- at 9.3 MeV ?
    - Enhancement

More analysis (ang. dist. etc.) required, but
$(^{16}O,^{16}F(0^-))$ seems
promising for 0^- study



Summary

- We propose parity-transfer reaction (^{16}O,$^{16}F(0^-)$) for 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
- Preliminary results
  - Successful identification of $^{16}F(0^-)$
  - Enhancement at ~9 MeV in ^{12}B ⇒ Known 0^- at 9.3 MeV ?
    ⇒ (^{16}O,$^{16}F(0^-)$) seems promising for 0^- study

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

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

Backup

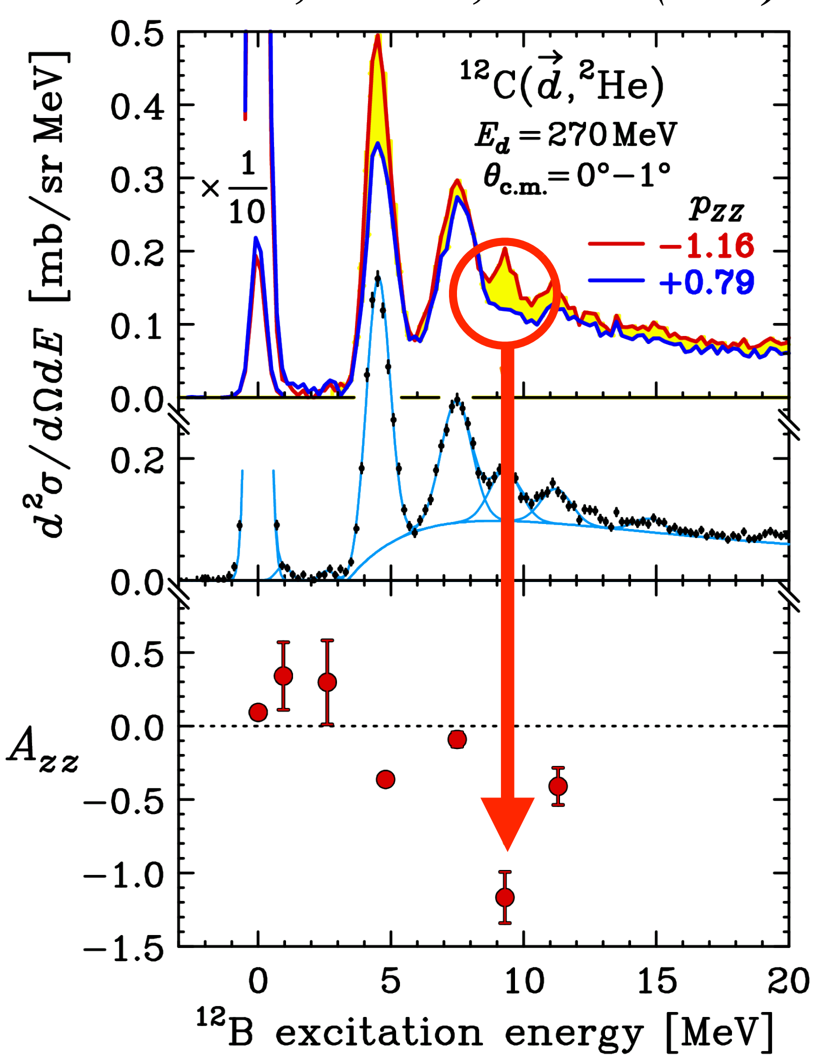
0^- Search via Polarization Measurements

Need to separate SD $0^-,1^-,2^-$ ⇒ Polarization observables

A_{zz} in $^{12}C(d,^2He)$

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

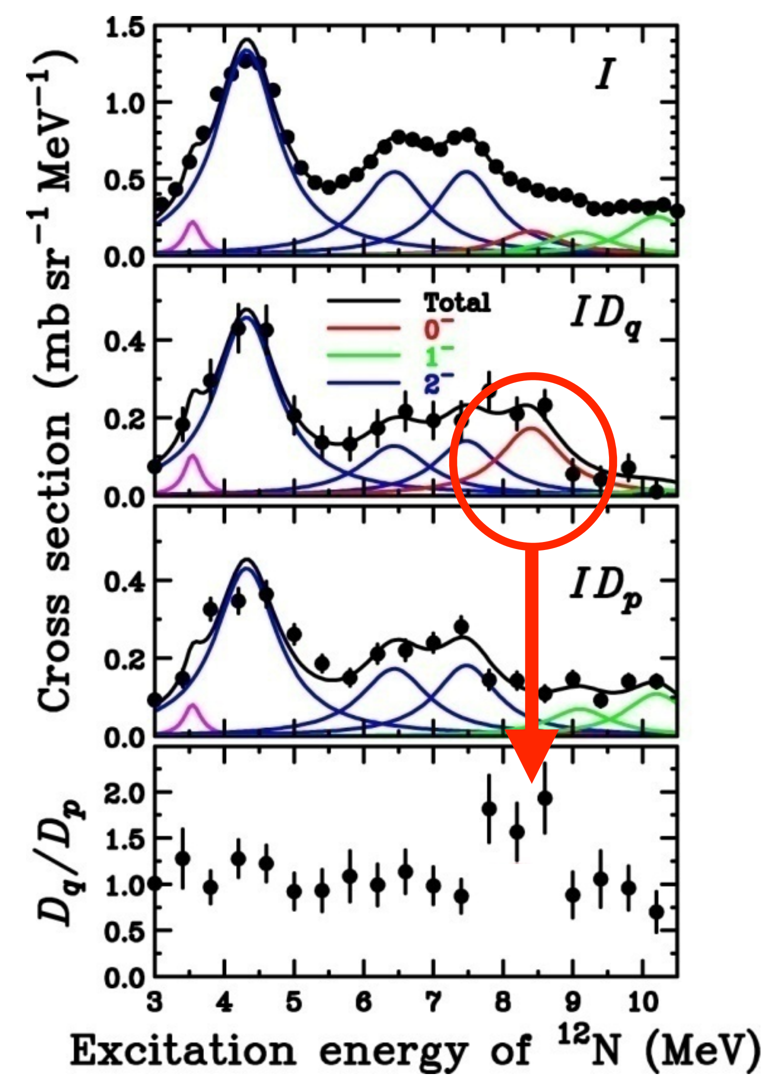
SDR	A
0	-2
1	+1
2	~0



D_{ij} in $^{12}C(p,n)$

M. Dozono et al., JPSJ 77, 014201 (2008).

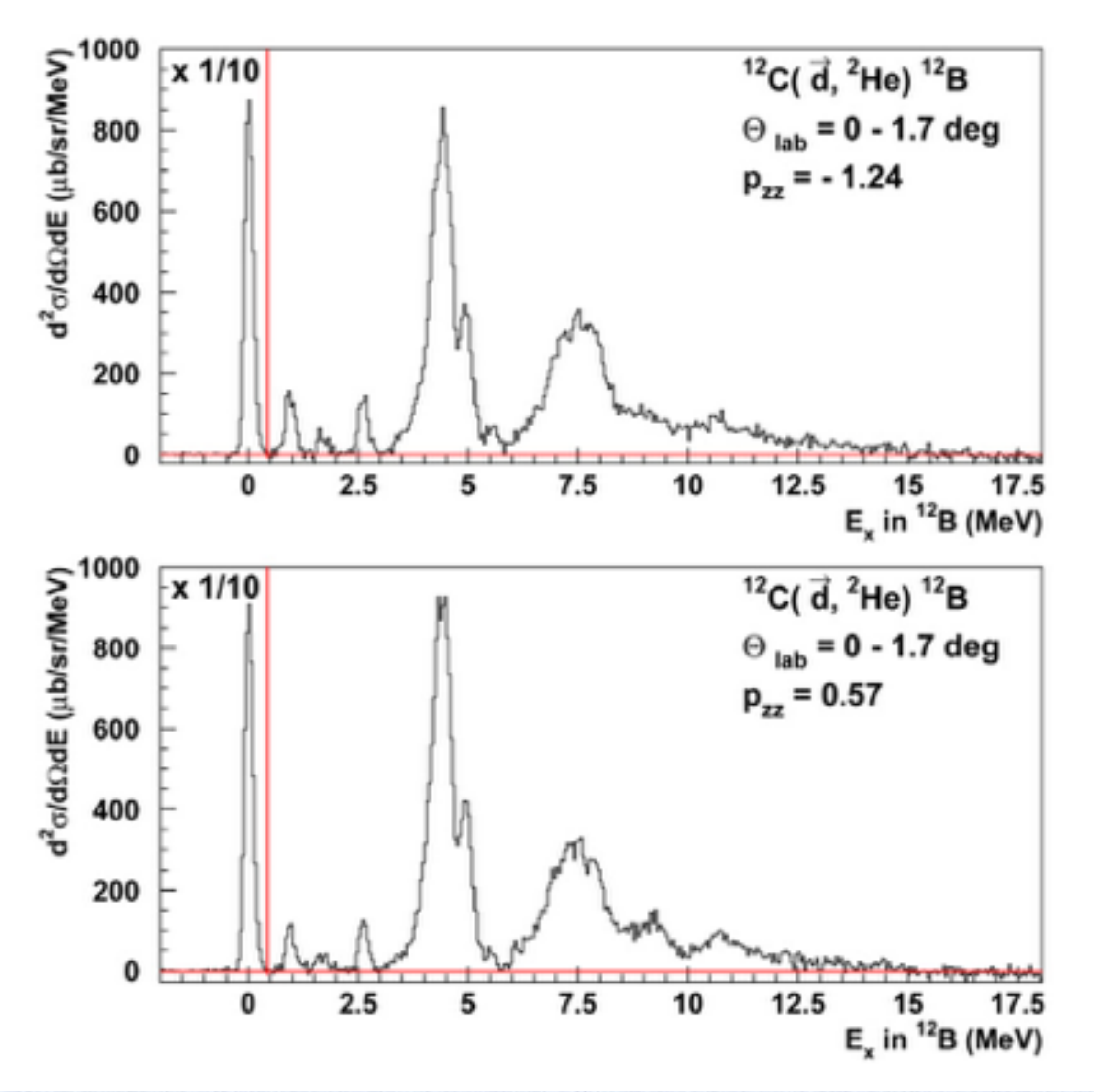
SDR	D
0	∞
1	0
2	~1



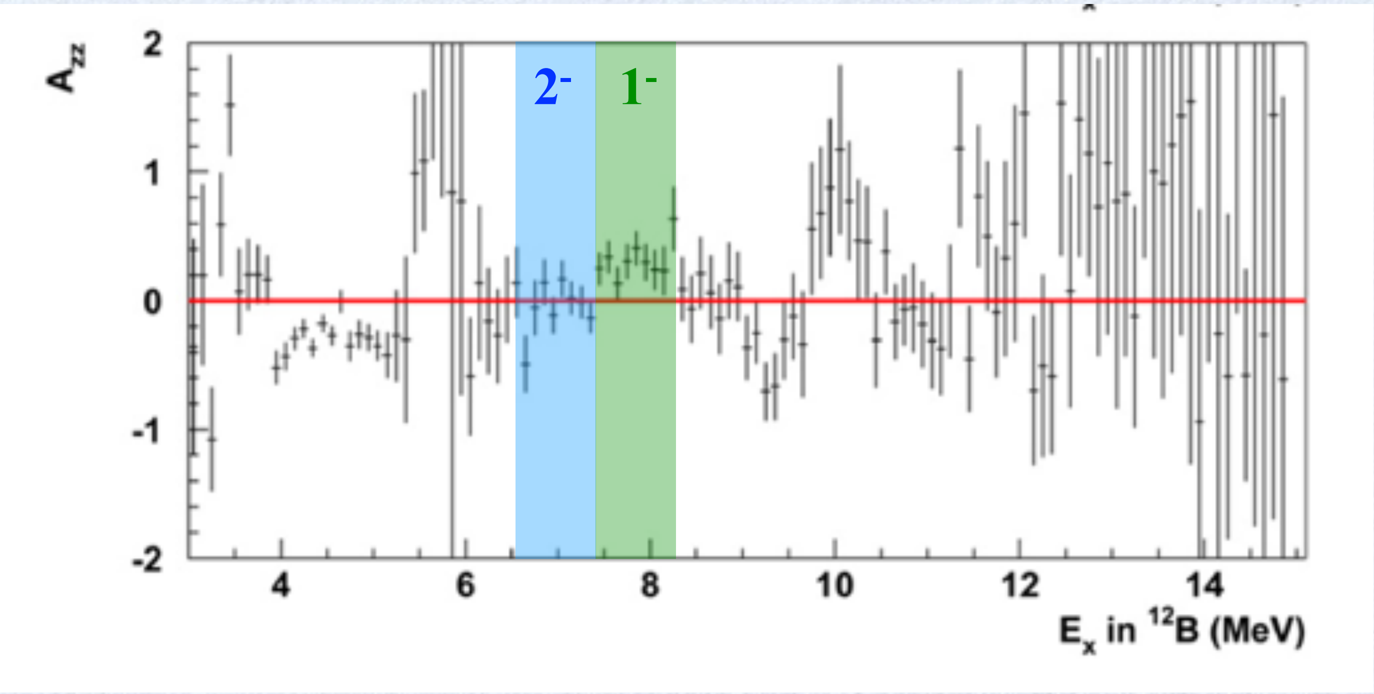
Clear observation of 0^- at E_x~9MeV in A=12 system

A_{zz} measurement for (d,^{2}He) at KVI

- SDR at 7.5 MeV
  - Low-energy part : 2^-
  - High-energy part : 1^-

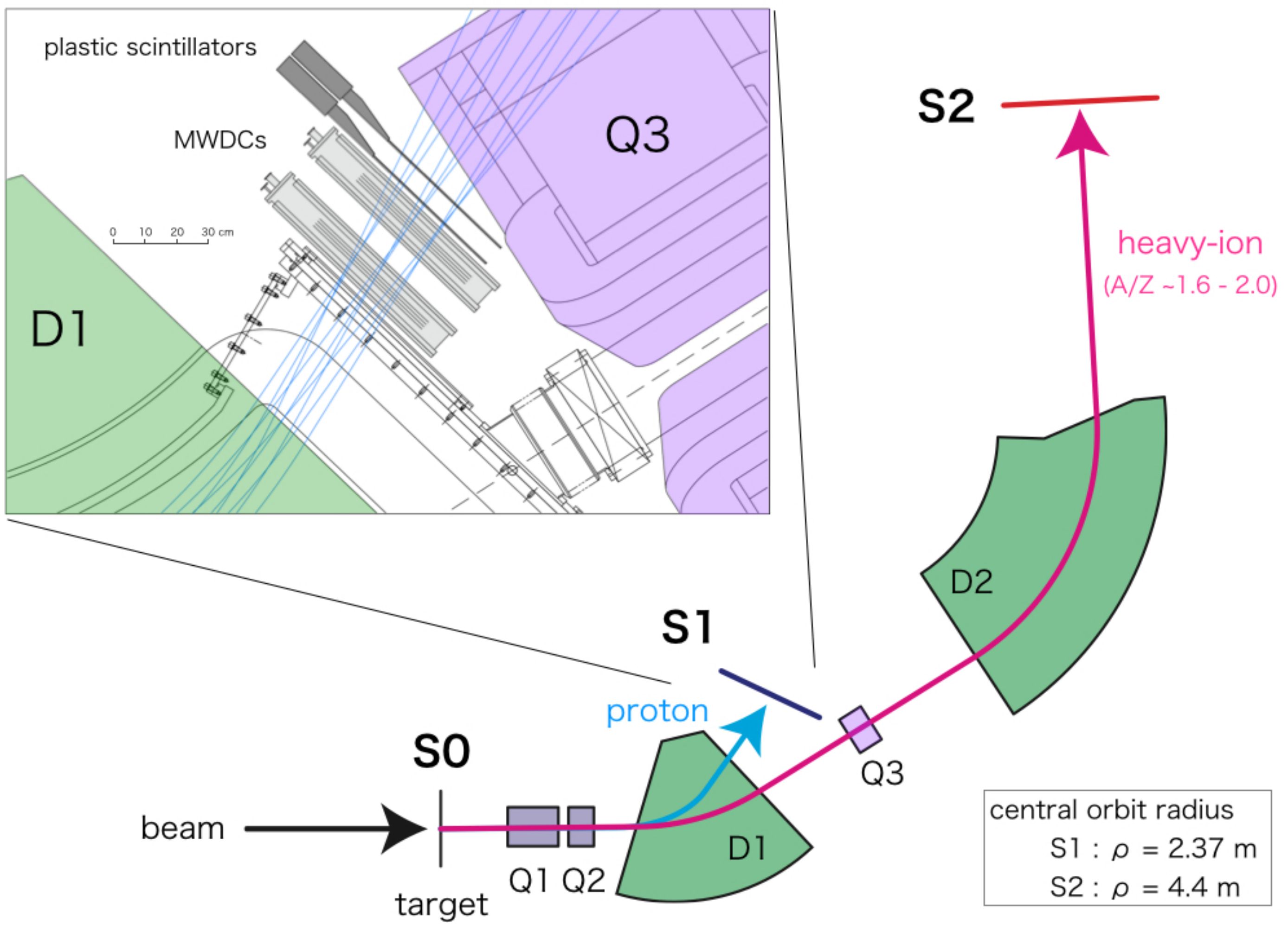


M.A. de Huu et al., PLB 649, 35 (2007).



Coincidence measurement of p + HI @ SHARAQ

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



Proton (S0→S1)
Momentum resolution : dp/p = 1/4330
Angular resolution : ~ 2 mrad
Momentum acceptance : ±12%
Angular acceptance : ~2.2 msr

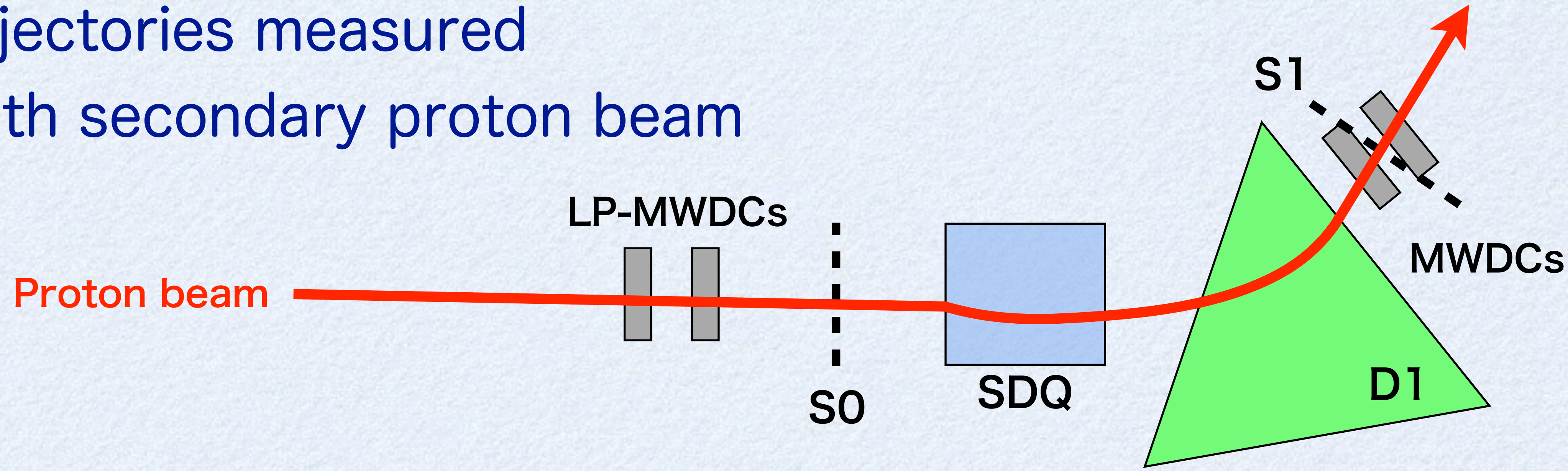
HI (S0→S2)
Momentum resolution : dp/p = 1/15300
Angular resolution : ~ 1 mrad
Momentum acceptance : ±1%
Angular acceptance : ~3 msr

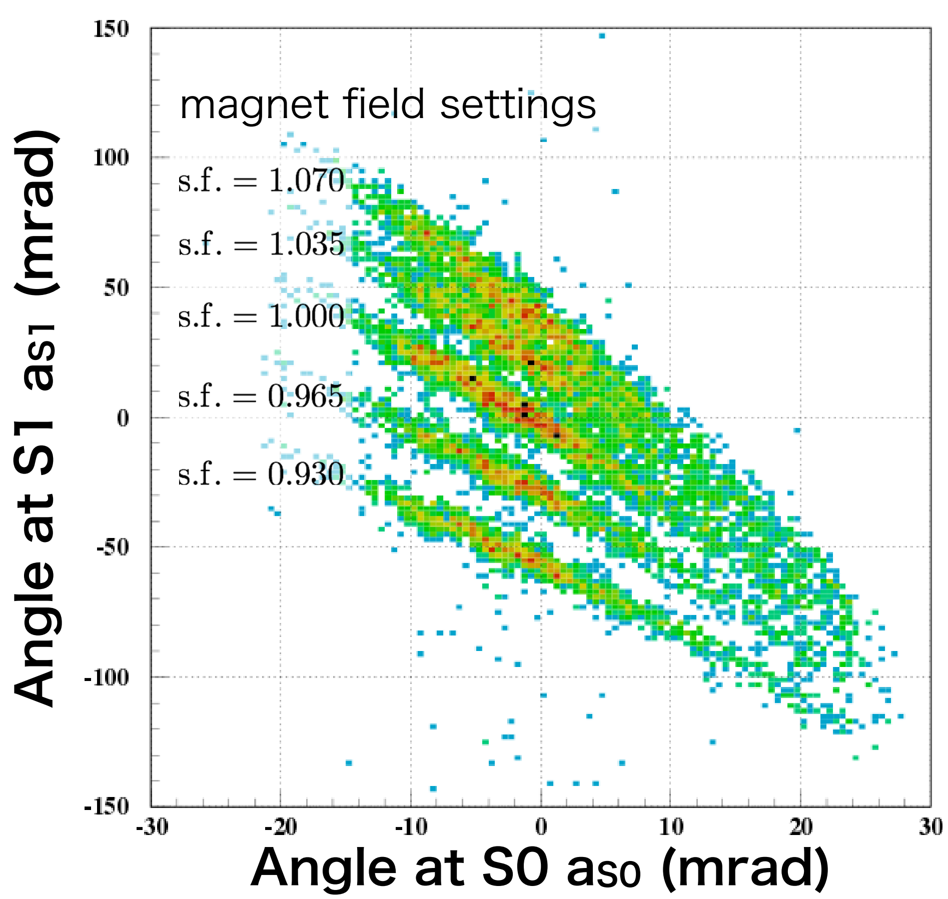
↓

Invariant mass resolution : ~100 keV
Missing mass resolution : ~1 MeV

Ion-optics study of S0 → S1

- Trajectories measured with secondary proton beam





Measured matrix elements (units: m,rad)

x		a		y	
$(x\|x)_{S1}$	-0.35	$(a\|x)_{S1}$	-1.43	$(y\|y)_{S1}$	-9.55
$(x\|a)_{S1}$	0.01	$(a\|a)_{S1}$	-3.03	$(y\|b)_{S1}$	-4.70
$(x\|\delta)_{S1}$	-1.57	$(a\|\delta)_{S1}$	-0.70		
$(x\|aa)_{S1}$	0.80	$(a\|aa)_{S1}$	-24	$(y\|ab)_{S1}$	-36
$(x\|a\delta)_{S1}$	0.40	$(a\|a\delta)_{S1}$	11	$(y\|y\delta)_{S1}$	34
$(x\|\delta\delta)_{S1}$	-7.3	$(a\|\delta\delta)_{S1}$	1.5	$(y\|b\delta)_{S1}$	24
$(x\|aaa)_{S1}$	-820	$(a\|aa\delta)_{S1}$	80	$(y\|ab\delta)_{S1}$	230
$(x\|a\delta\delta)_{S1}$	-57	$(a\|a\delta\delta)_{S1}$	-12	$(y\|b\delta\delta)_{S1}$	24
$(x\|\delta\delta\delta)_{S1}$	-29	$(a\|\delta\delta\delta)_{S1}$	7.8		

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

- Comparison with (d,^{2}He)
  - GT(1$^+$) at 0 MeV
    - Hindered
  - SDR(2$^-$) at 4.5 MeV
  - SDR(2$^-$&1$^-$) at 7.5 MeV
  - SD 0$^-$ at 9.3 MeV
    - Enhancement ?

More analysis (ang. dist. etc.) required, but
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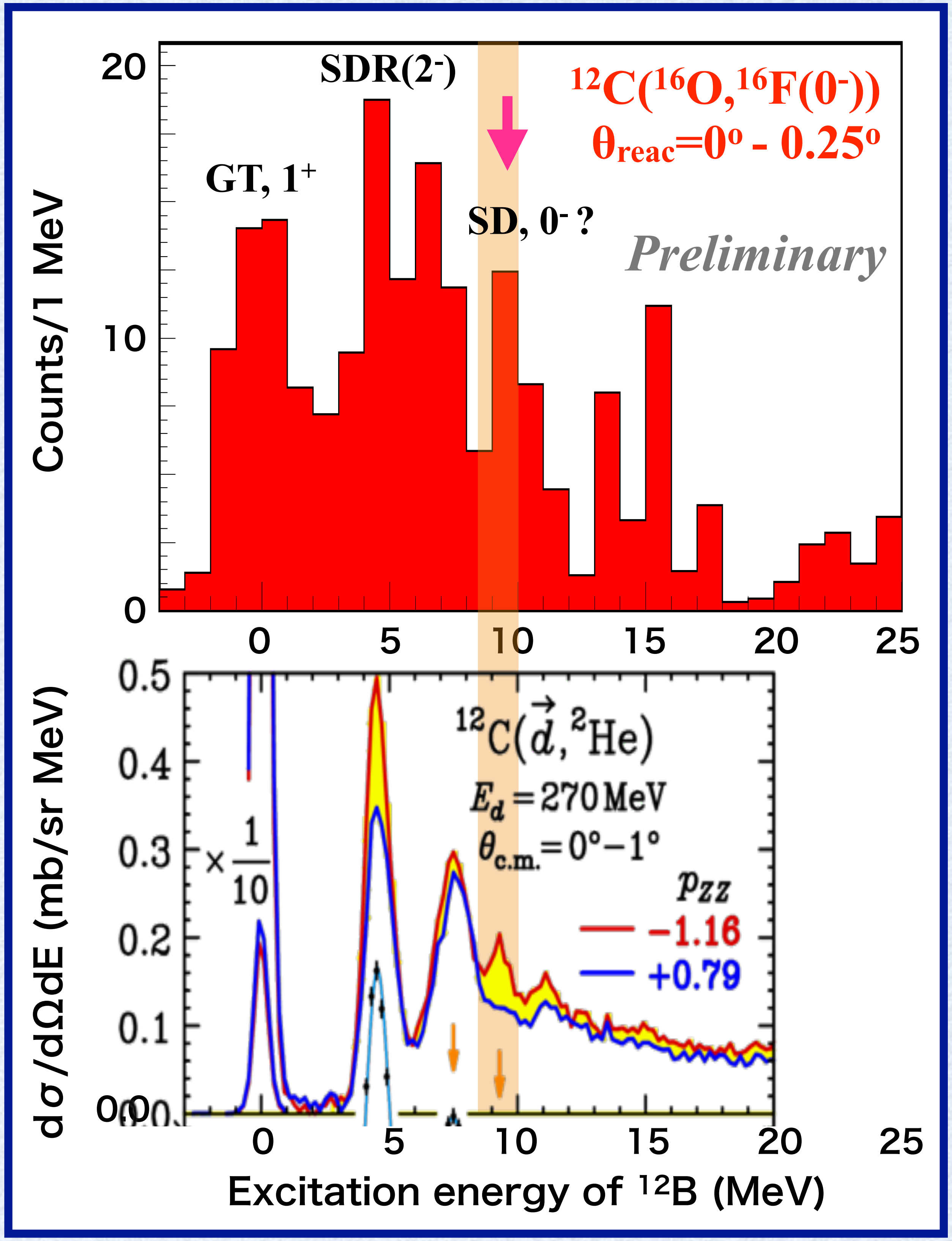

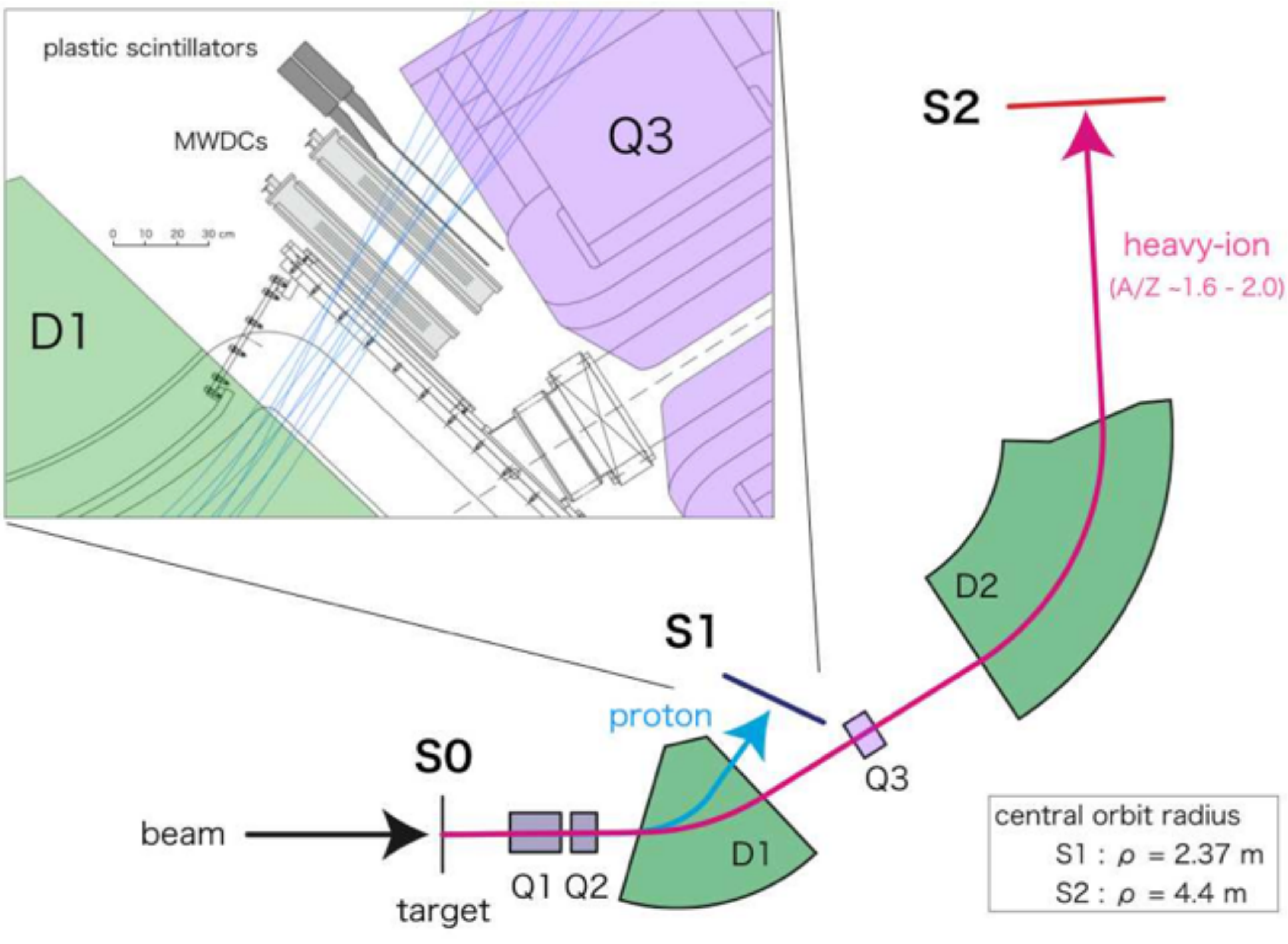

Figure 1: Schematic layout of the SHARAQ spectrometer.

Configuration	X - X' - Y - Y'
Effective area	480 mm^W × 240 mm^H
Cell size	12 mm^W × 10 mm^t
Numbers of channels	120
Anode wire	Au-W, 20 μm$^\phi$
Potential wire	Cu-W, 80 μm$^\phi$
Cathode plane	Al-Mylar, 2 μm^t
Counter gas	P10 : Ar - CH_4 (90 - 10), 1 atm
Gas window	Al-Mylar, 25 μm^t

Table 3: Specifications of the MWDCs. The X' (Y') plane is offset by half cell from the X (Y) plane.

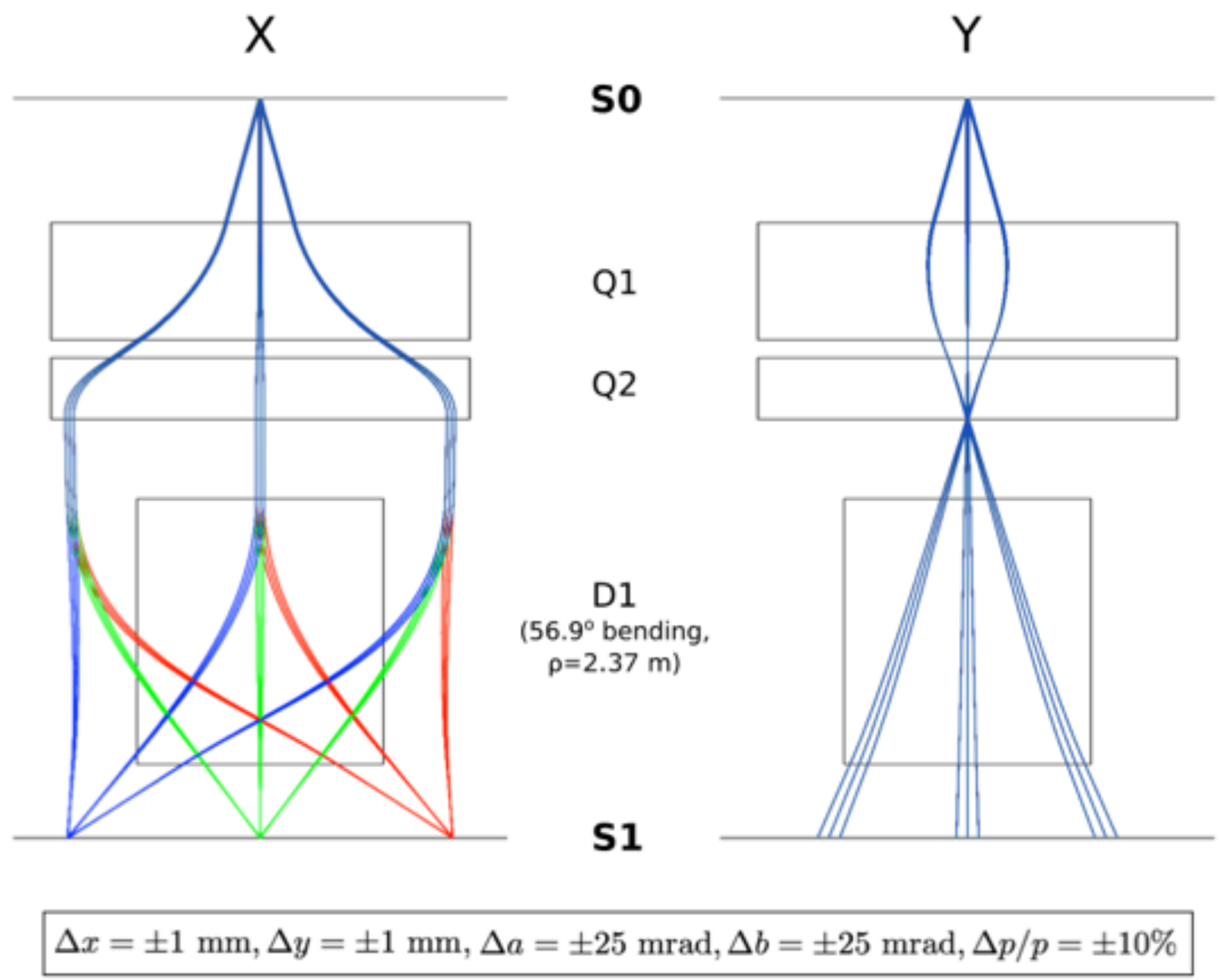

Figure 2: Results of the ion-optical calculations for the particle trajectries from S0 to S1. Left and right panels represent horizontal and vertical trajectories, respectively, for the particles with $\Delta x = \pm 1$ mm, $\Delta y = \pm 1$ mm, $\Delta a = \pm 25$ mrad, $\Delta b = \pm 25$ mrad, and $\Delta p/p = \pm 10\%$.

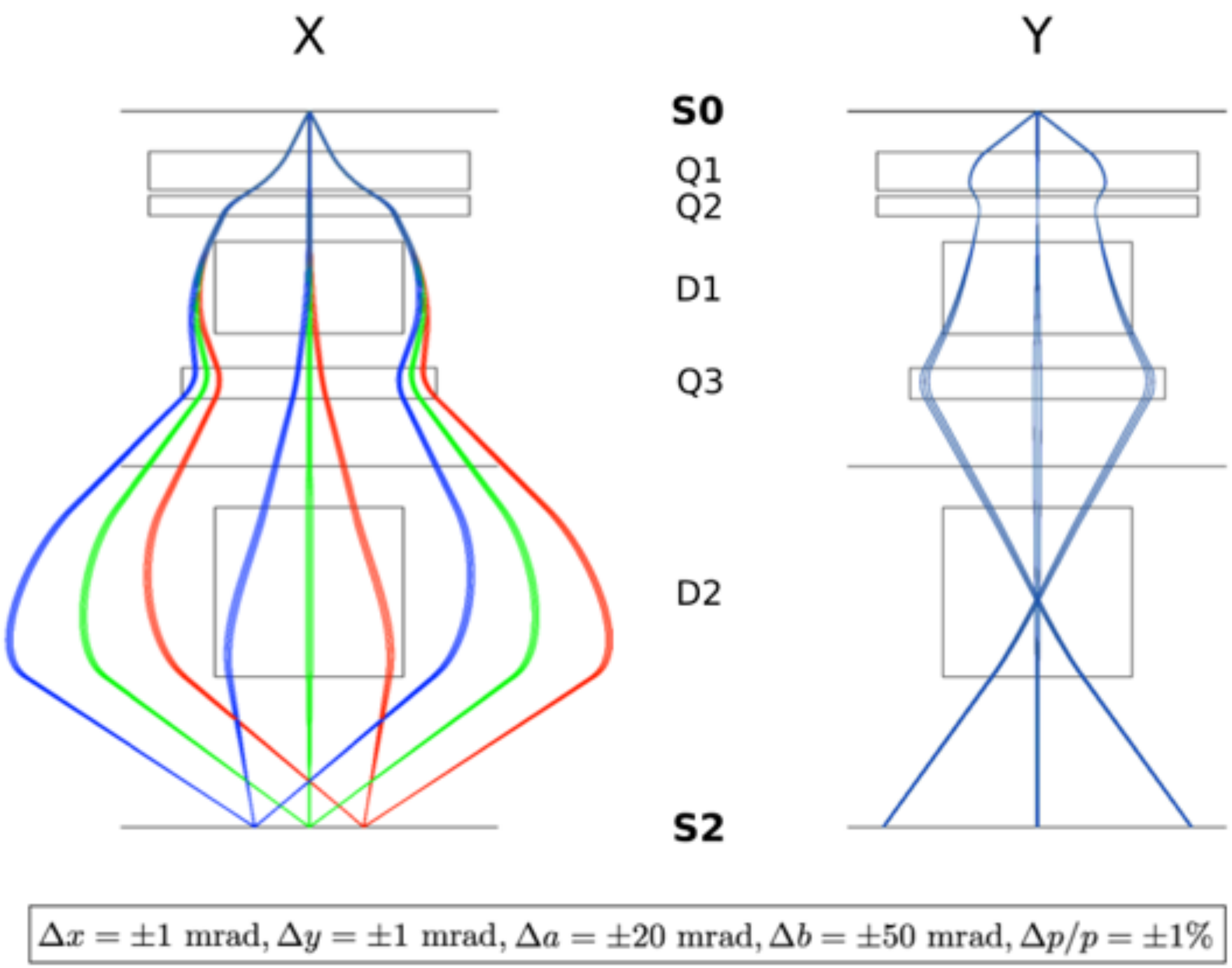

Figure 3: Results of the ion-optics calculations for the particle trajectries from S0 to S2. Left and right panels represent horizontal and vertical trajectories, respectively, for the particles with $\Delta x = \pm 1$ mm, $\Delta y = \pm 1$ mm, $\Delta a = \pm 20$ mrad, $\Delta b = \pm 50$ mm, and $\Delta p/p = \pm 1\%$.

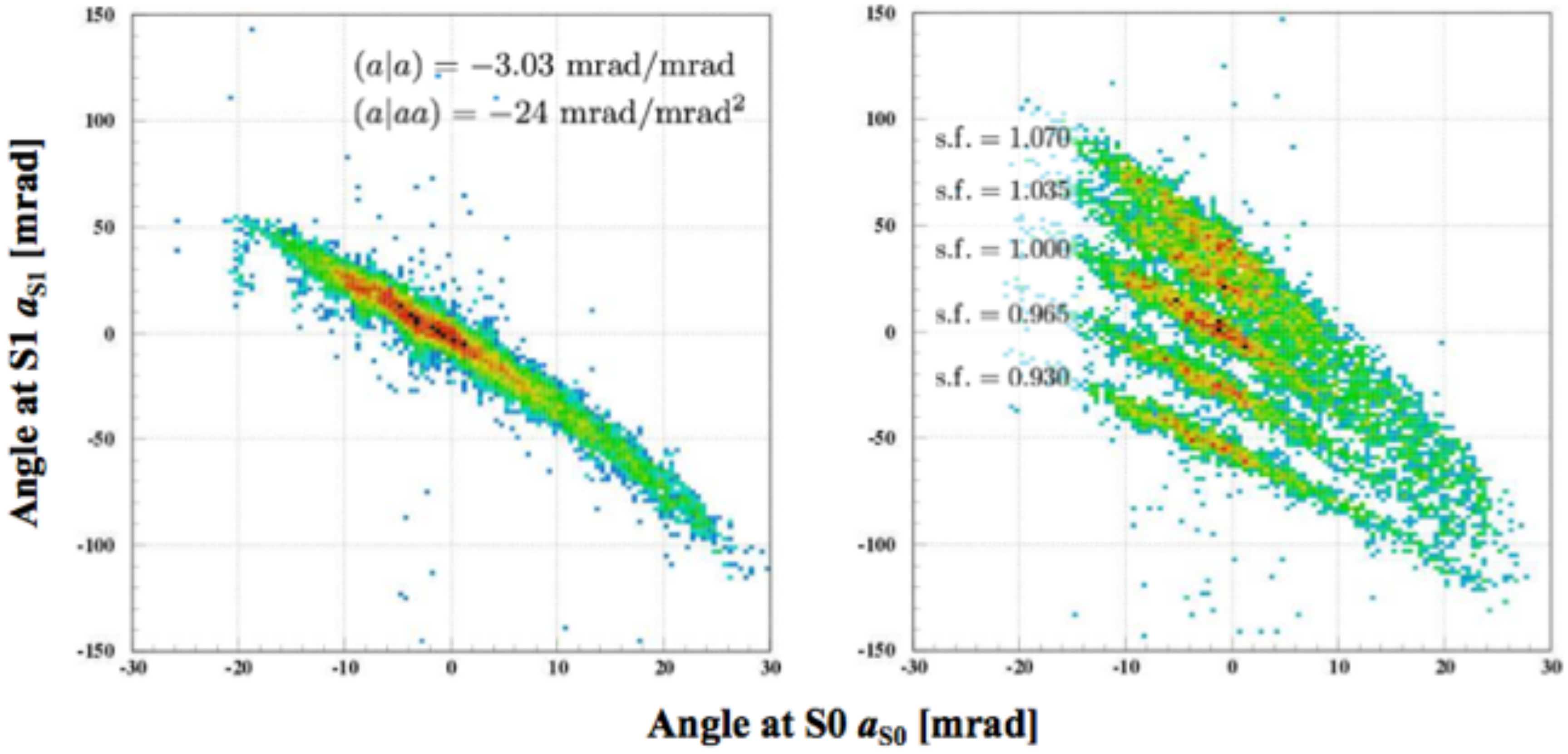

Figure 4: Correlation between the angle at the focal plane S1 and the angle at the focal plane S0 for a proton beam.

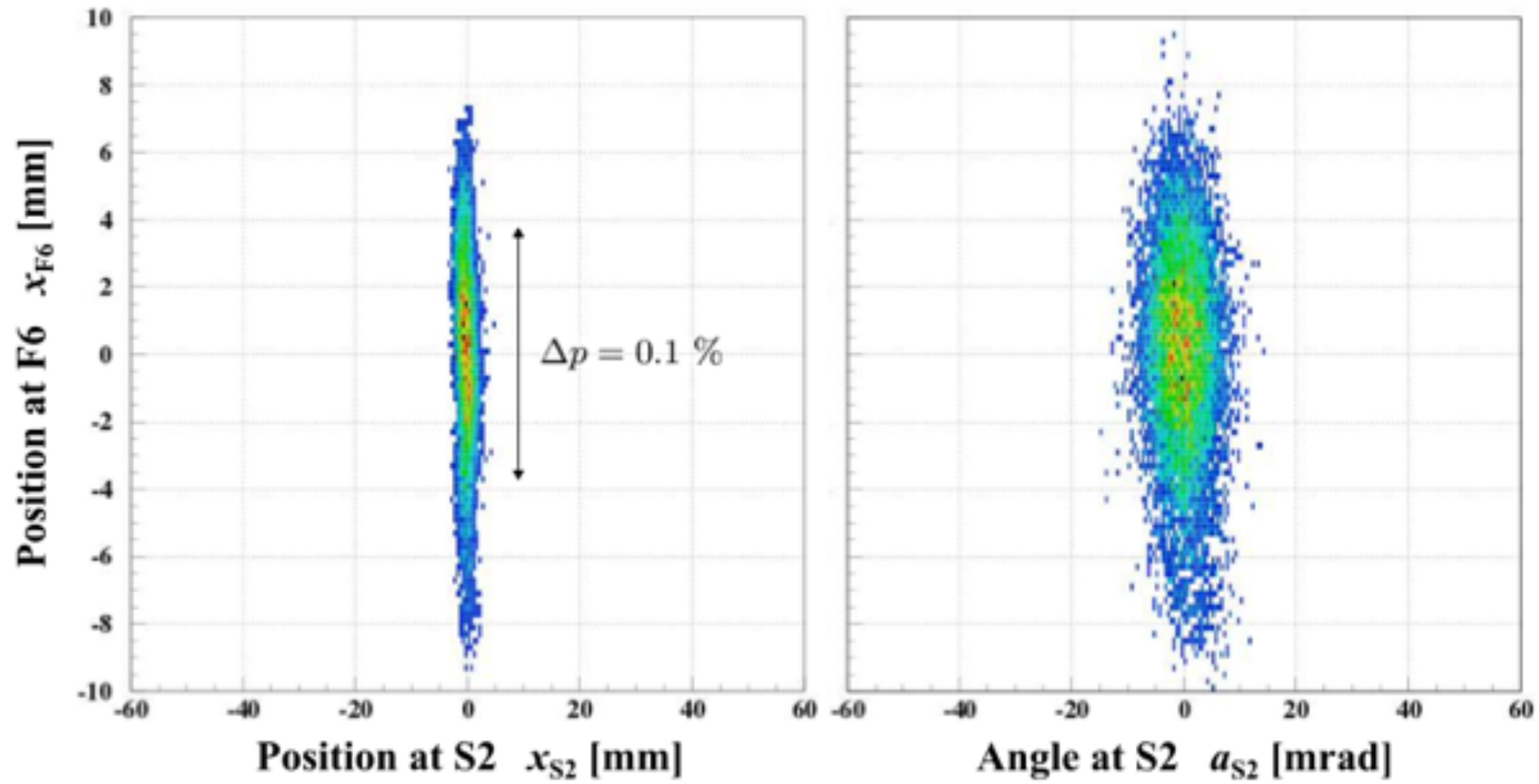

Figure 7: Correlation between x_{F6} and the position (left) and angle (right) at S2 for a ^{16}O beam at 247 MeV/u. Upright correlations observed in the figures indicate that the lateral and angular dispersion-matching conditions are fulfilled.

0⁻遷移とパイ中間子(テンソル)相関

- なぜ0⁻はパイ中間子(テンソル)相関に敏感か？
  - 純粋なπ交換($\sigma\cdot q$)による遷移
    ⇔ 他のスピン･アイソスピン遷移
    (1^+,2^-,…)にはρ交換($\sigma\times q$)も混じる
  - 高運動量($q\sim2$ fm^{-1})で大きな遷移密度
    ⇒ π交換力に敏感
    (π交換力は高運動量領域で大)
    ⇔ 例えば、
    GT 1^+は$q\sim0$ fm^{-1}で大きな密度