The SHARAQ spectrometer and its physics opportunities

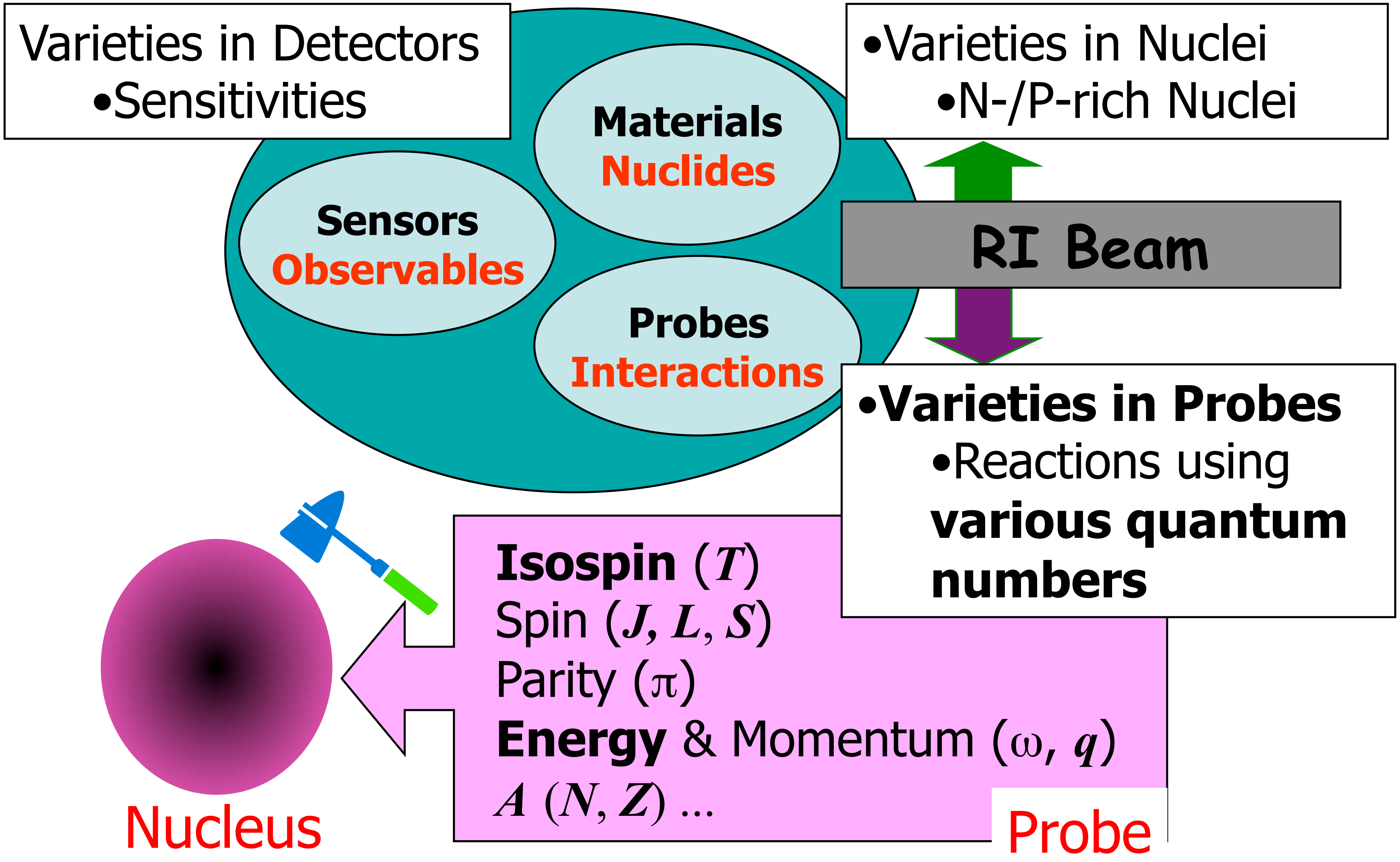
S. Shimoura

CNS, University of Tokyo

for SHARAQ Collaboration

Introduction

- Exp. Studies of Nuclear Many-body System



Points of View

- Response of Nuclear System using Intermediate-Energy direct reactions
  - Studies using New Quantum Probe－RI beam－ Large Isospin and Mass Excess、Various I^{π} ("Excited states")
    - Controlling Transferred Momenta, Q-values, Spin, Isospin
    - ΔS, ΔT, **q-ω**
    - Accessing kinematical area/conditions inaccessible by stable nuclear beam
    - Ordinary kinematics (Missing mass spectroscopy)

      -> High Resolution Spectrometer + High Quality RI Beam

      \+ (Detectors of decaying particles)
  - Asymmetric nuclear System studied using stable probes
    - Inverse kinematics + Invariant Mass / γ-decay / Recoil

      and **High-resolution missing-mass spectroscopy**

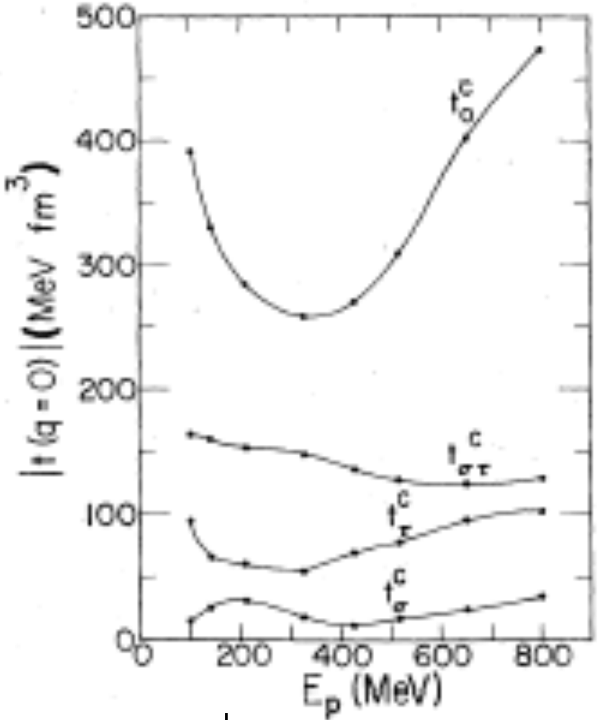
We may free from conventional (kinematical) conditions

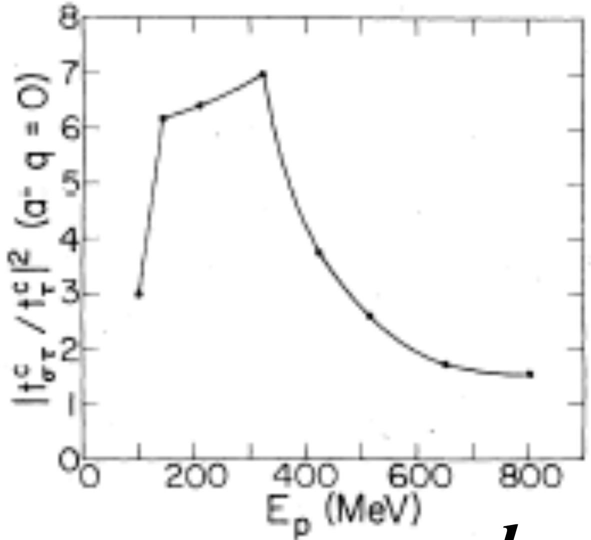
HI Direct Reactions @ intermediate energy

- Semi Classical
  - short wave length
    - Trajectory => WKB, Eikonal, Glauber, esp. for forward direction
- (Relatively) Large distortion
  - Nuclear potential + Coulomb potential
  - Strong absorption / diffractive
    - Direct reaction at surface
    - How strong at energy above 100 A MeV ?
- Large (relative) angular momenta
  - QM treatment of transition + semi-classical view of relative motion (L <=> b)
- Relativistic effect
  - Magnetic excitation by relativistic Coulomb potential
  - Impulse for composite particle?

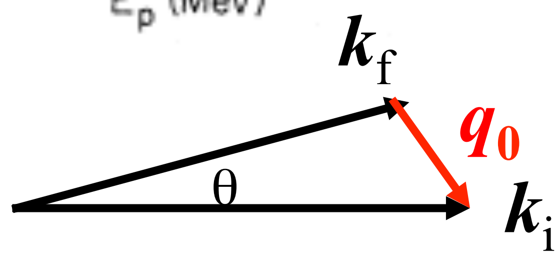
Direct reactions (intermediate energy)

- Energy dependence of
  - Distortion : Central force
  - Effective Interaction : Spin-Isospin modes (e-capture,ν-)





$$\frac{d\sigma}{d\Omega}(\theta)\Big|_{PWIA} \approx C\left|t_{ST}(q_0)\cdot\tilde{\rho}_{fi}(\vec{q}_0)\right|^2$$



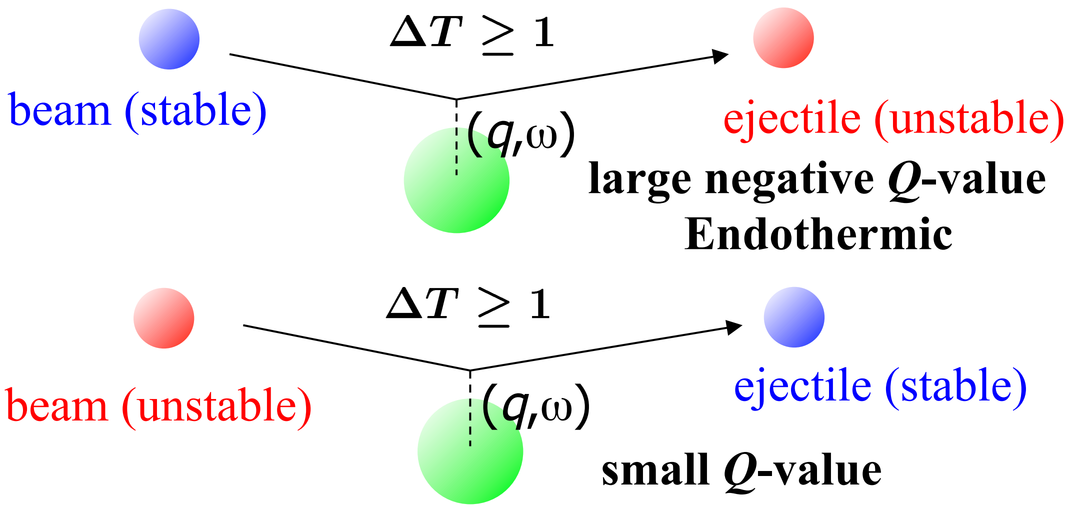
$$\tilde{\rho}_{fi}(\vec{q}) = \int d^3r\,\rho_{fi}(\vec{r})e^{i\vec{q}\cdot\vec{r}} = \int dr\,r^2 R_\ell^{tr}(r)j_\ell(qr)Y_{lm}(\hat{q})$$

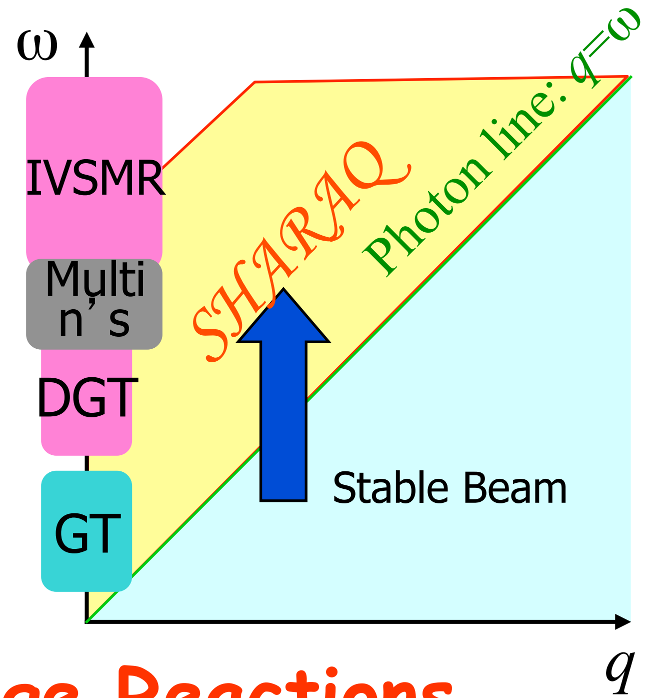
SHARAQ

Spectroscopy with High-resolution Analyzer of RadioActive Quantum beams

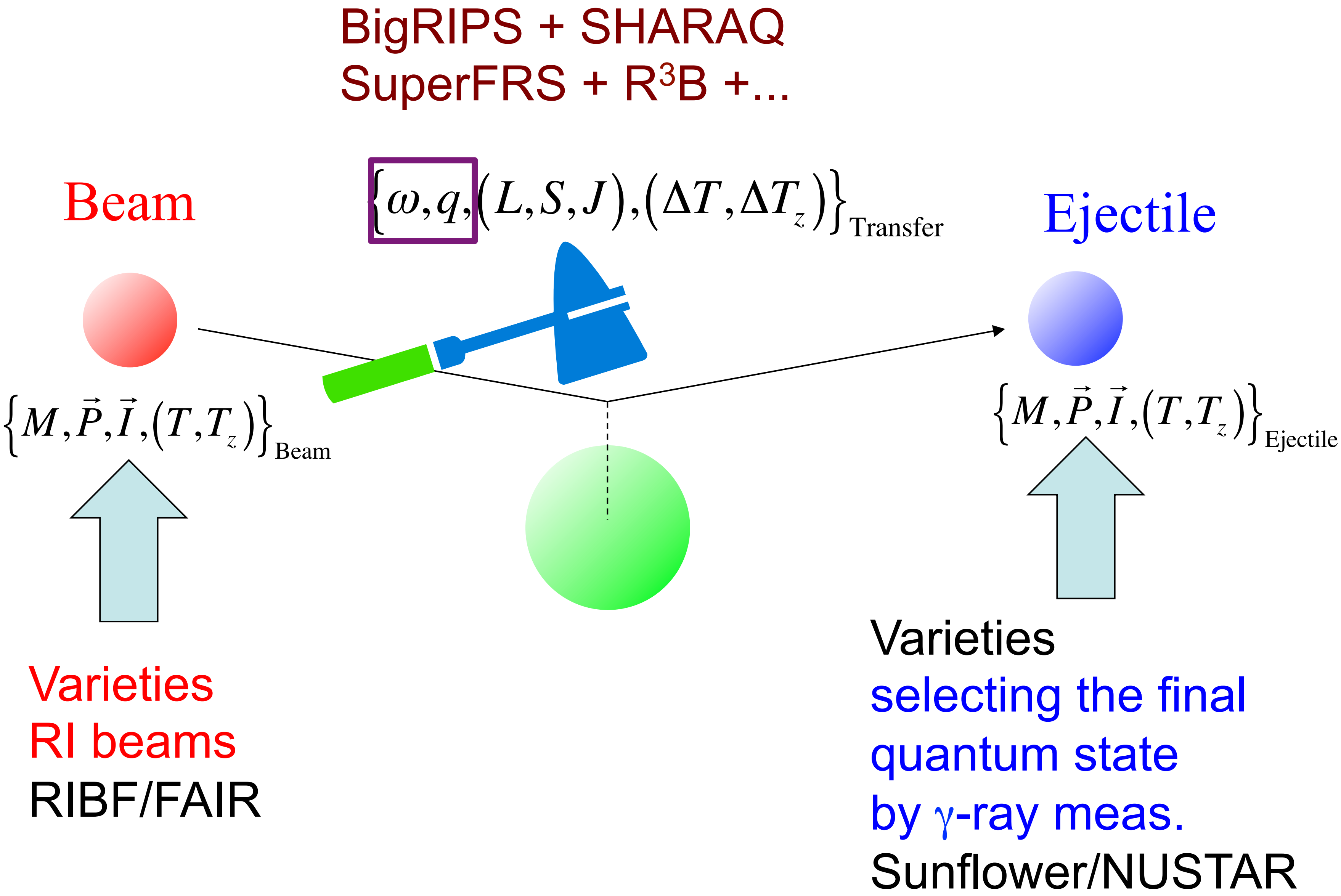
RI Beam (E = 150−400 MeV/A) as a new PROBE to nuclear systems

- Large Isospin — iso-tensor excitations
- Large internal energy — (q,ω) inaccessible by stable beams

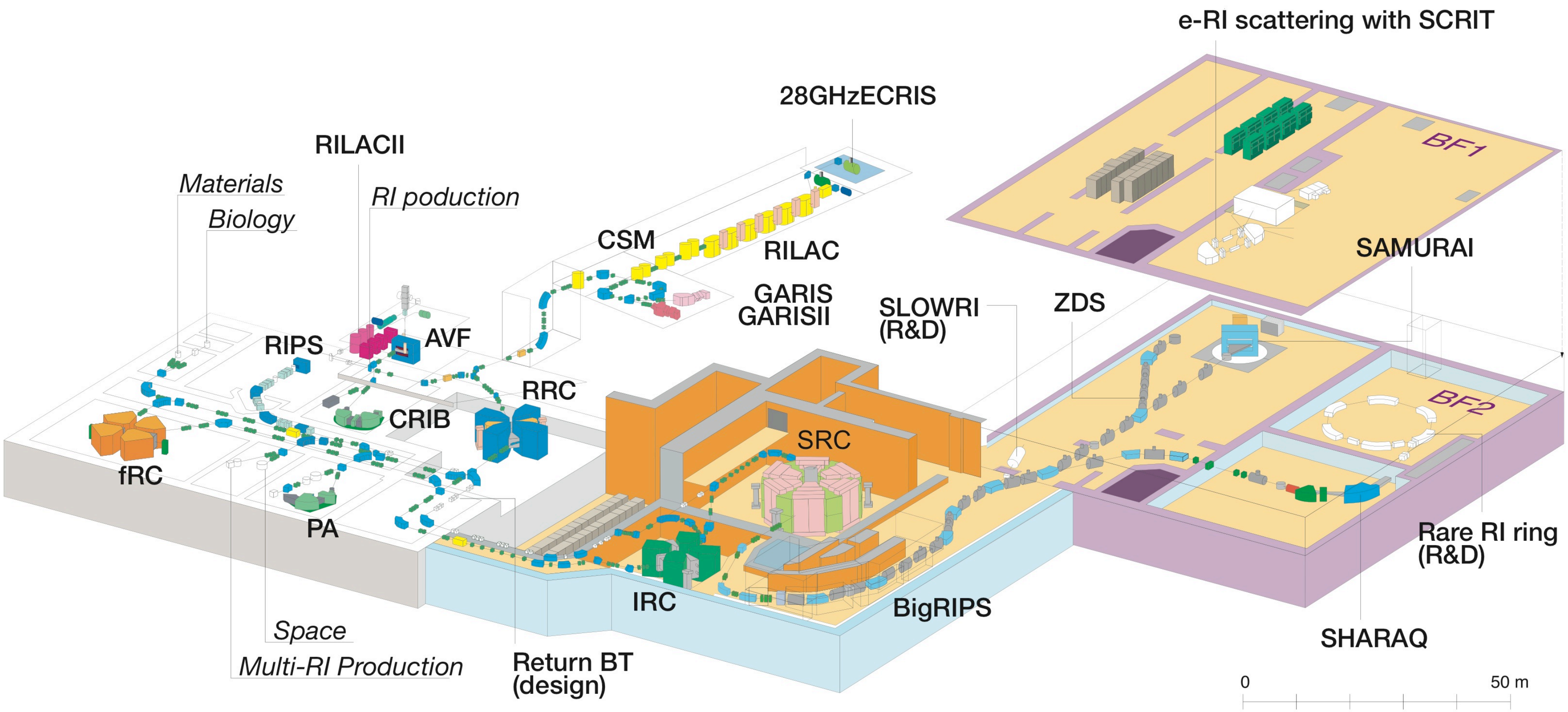




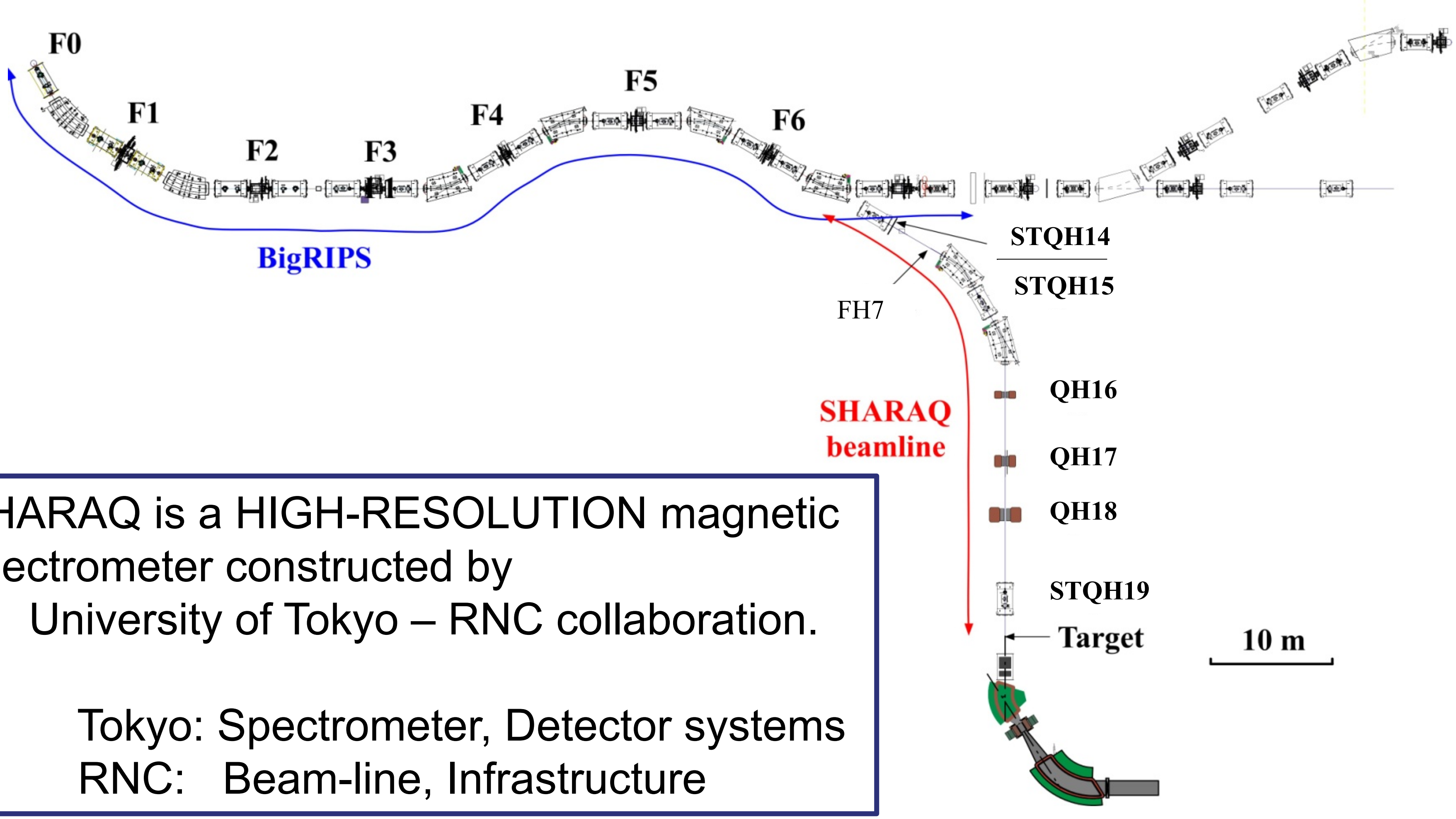
Exothermic Charge Exchange Reactions


BigRIPS + SHARAQ
SuperFRS + R^3B +...
Beam
$\{\omega, q, (L,S,J), (\Delta T, \Delta T_z)\}_{\text{Transfer}}$
Ejectile
$\{M, \vec{P}, \vec{I}, (T, T_z)\}_{\text{Beam}}$
$\{M, \vec{P}, \vec{I}, (T, T_z)\}_{\text{Ejectile}}$
Varieties
RI beams
RIBF/FAIR
Varieties
selecting the final
quantum state
by γ-ray meas.
Sunflower/NUSTAR

RI Beam Factory at RIKEN



SHARAQ @ RI beam factory



SHARAQ is a HIGH-RESOLUTION magnetic spectrometer constructed by
University of Tokyo – RNC collaboration.

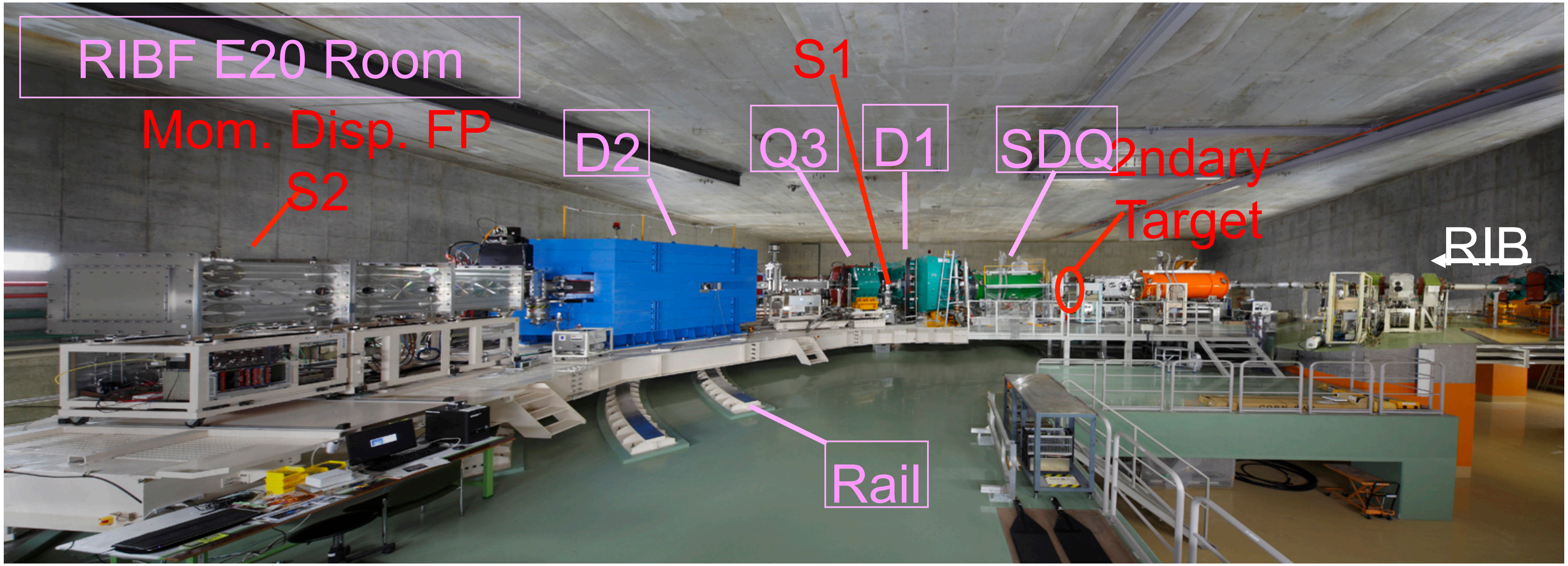
Tokyo: Spectrometer, Detector systems
RNC: Beam-line, Infrastructure

Maximum rigidity **8.4 Tm** (190 A MeV for A/Z = 4)

Dispersion @ target **15000 (DM mode):** +/- 9cm image for +/- 0.3% $\Delta p/p$

SHARAQ spectrometer

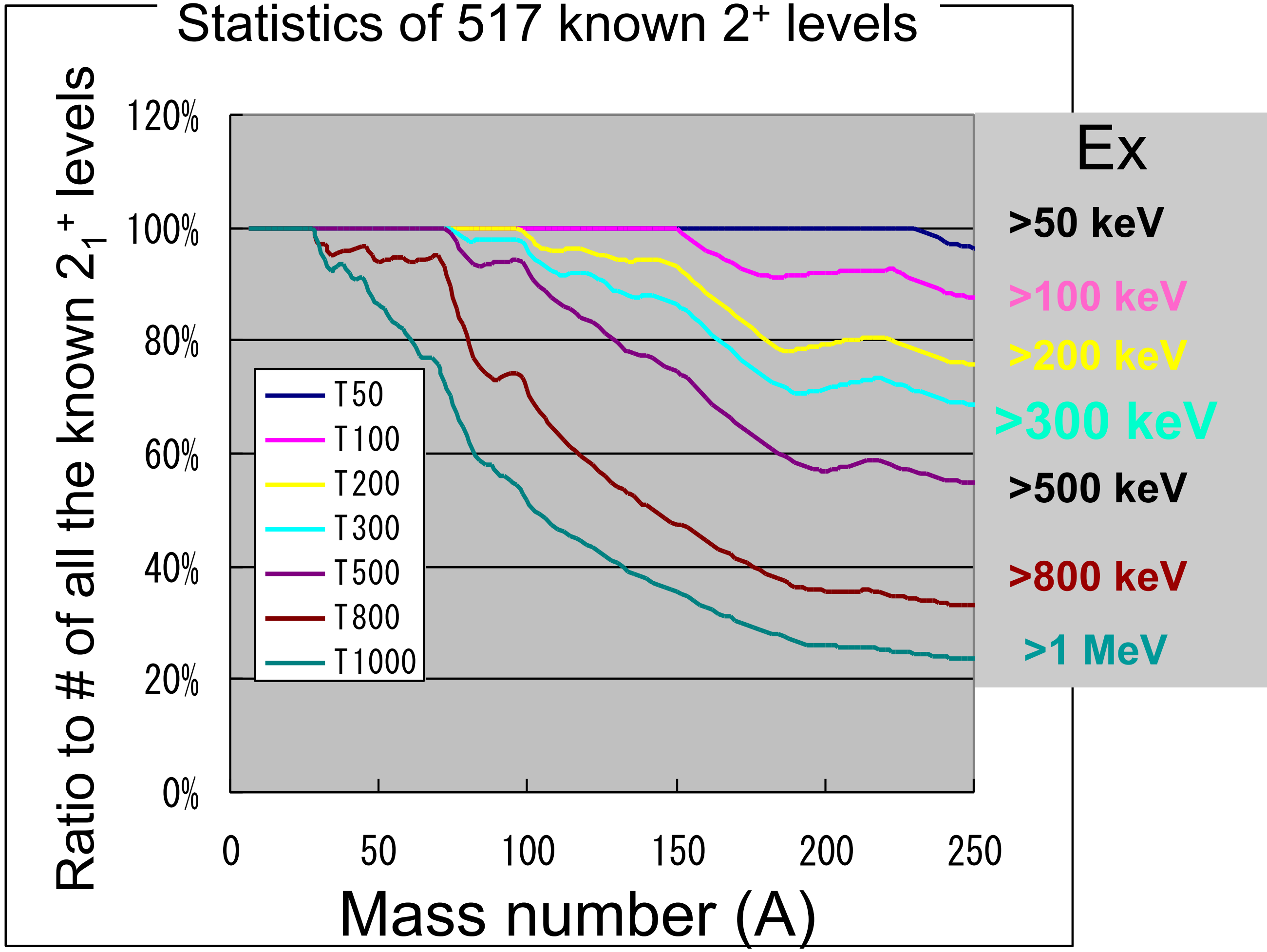
T. Uesaka et al.,
NIMB B **266** (2008) 4218.



Maximum rigidity	**6.8 Tm**	(440MeV for A/Z = 2; 250MeV for A/Z = 3)
Momentum resolution	**d*p*/*p* = 1/14700**	(300keV for 0.2*10 GeV beam)
Angular resolution	**~ 1 mrad**	(10 MeV/c for 0.2*10 GeV beam)
Momentum acceptance	**± 1%**	
Angular acceptance	**~ 5 msr**	
Rotatable	**15 degree**	

銀杏 ICHOR

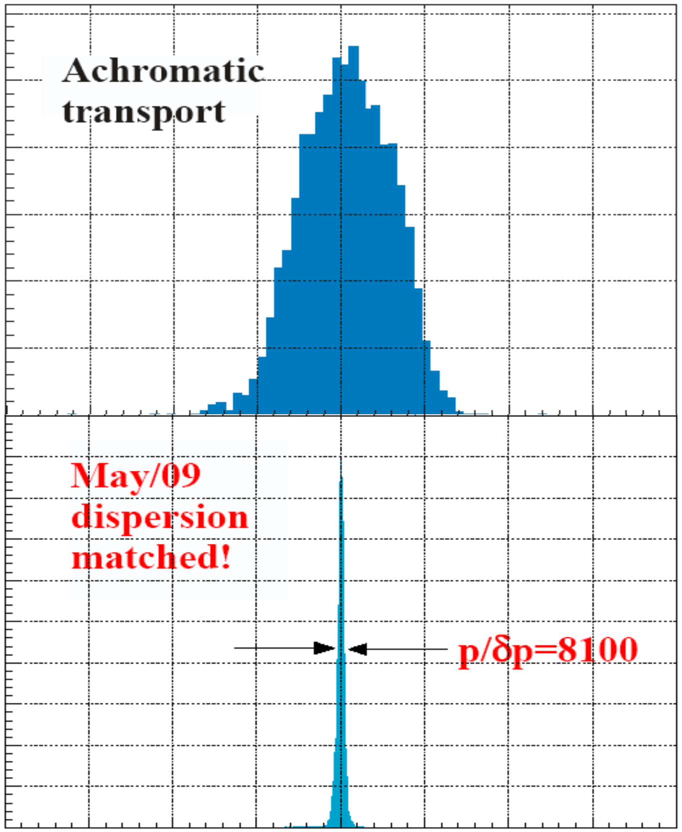
Energy resolution

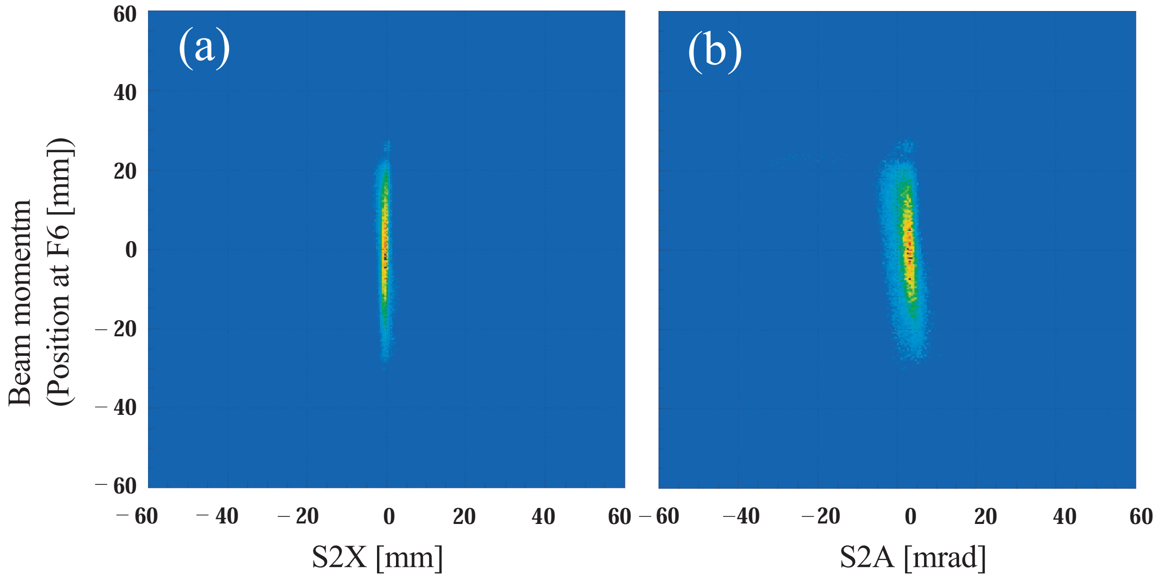


100% for A<75
90% for A<125
80% for A<160
70% for all

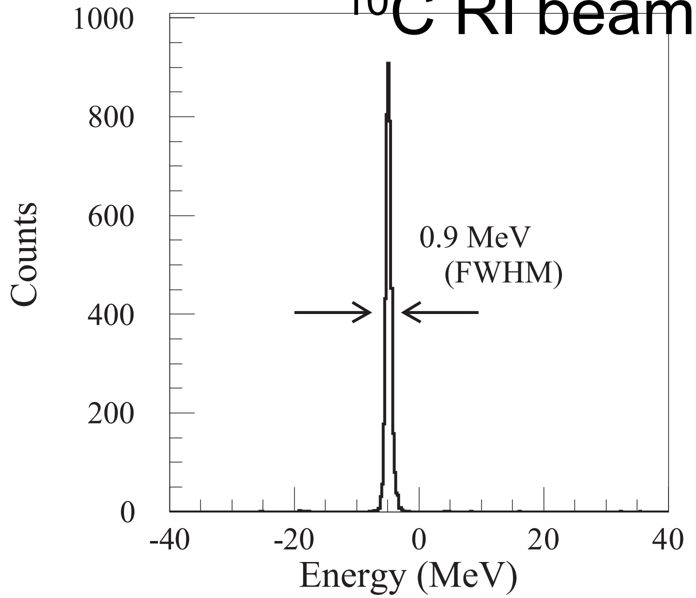
Dispersion Matching Mode

^{14}N primary beam





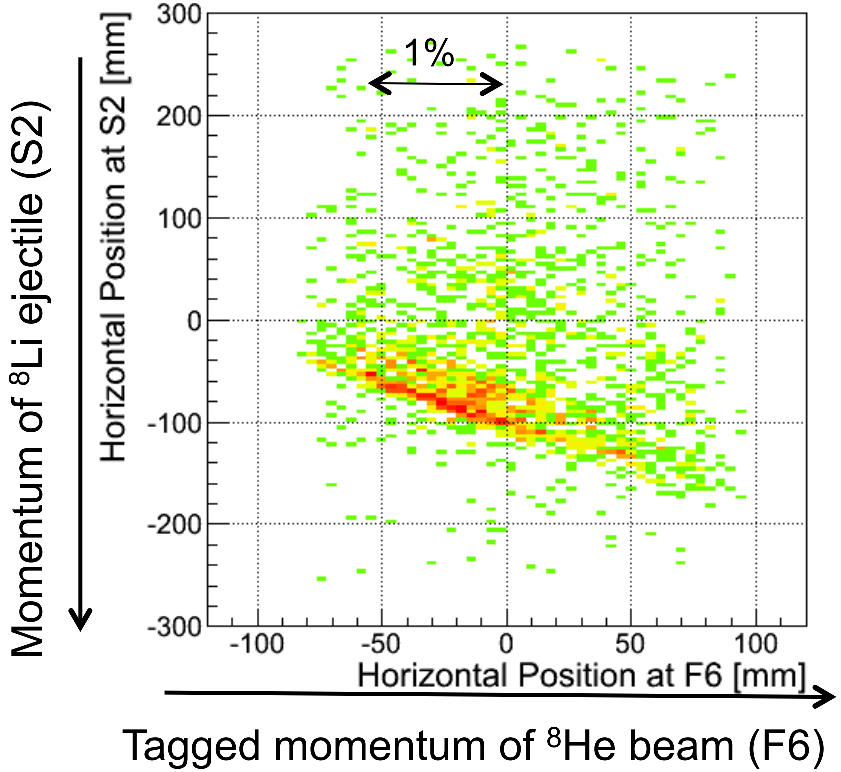
^{10}C RI beam @ 200 A MeV



p/δp~4000

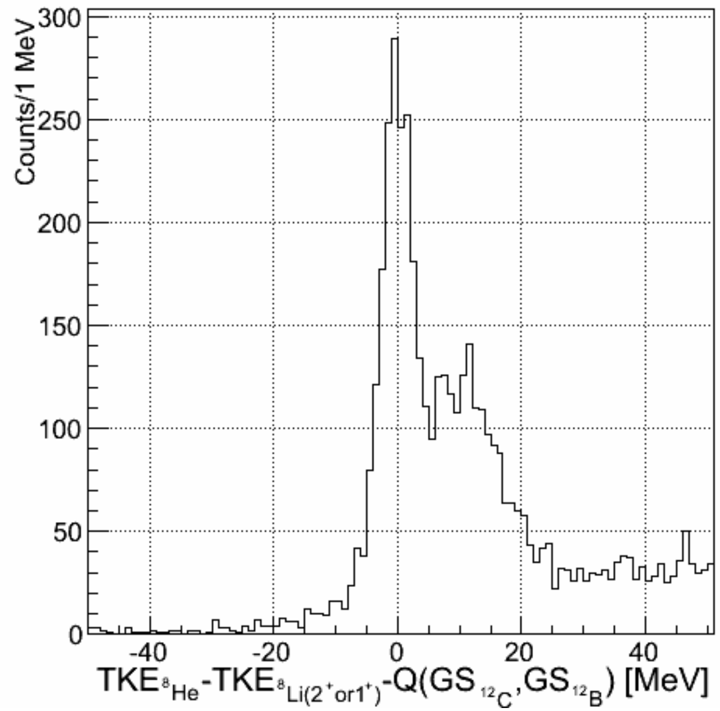
High Resolution Achromatic Mode

Beam momentum is tagged at F6 ((x|d)~7000)
Ejectile momentum is measured by SHARAQ



Preliminary momentum spectrum of $^{12}C(^{8}He,^{8}Li)^{12}B$

E(^{8}He) = 760 MeV



Preliminary missing mass spectrum $^{12}C(^{8}He,^{8}Li)^{12}B$ @190 A MeV

Scientific Programs

Missing mass spectroscopy by RI-beam induced reactions (normal kinematics)

$(t,{}^{3}He)$	β^{+}-type isovector spin monopole resonance (IVSMR)
$({}^{10}C,{}^{10}B(IAS))$	isovector non-spin monopole resonance
$({}^{12}N,{}^{12}C)$	β^{-}-type IVSMR via exothermic reaction
$({}^{8}He,{}^{8}Be)$	Search for tetra-neutron states
$({}^{8}He,{}^{8}Li(1+))$	CX or 4He (SDR)
$({}^{16}O,{}^{16}F(0^{-}))$	SDR of "pion"-mode

Performed

Inverse kinematics

${}^{14,22-24}O(p(pol),pN)$	Spin-orbit splitting in oxygen isotopes
${}^{12}Be(p,n)$	GT/SDR strength in ${}^{12}Be$
${}^{33}Al({}^{7}Li,{}^{7}Be\gamma)$	GT strength in the island of inversion

Mass measurement (L_{TOF}~ 100 m)

${}^{52,54}Ca$	Magicity at N=32,34

SHARAQ Collaboration:
Tokyo, RNC, Kyoto, MSU, GANIL, Notre Dame, Niigata. . .

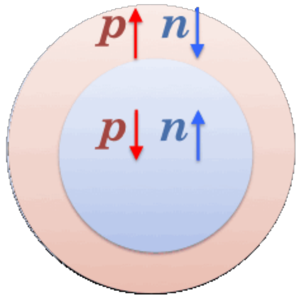
Isovector Spin Monopole Response

Spin-isospin ($\Delta S = \Delta T = 1$) modes with $\Delta L = 0$

Gamow-Teller $0\hbar\omega$ $\sum_k t_\pm(k)\sigma_\mu(k)$

Isovector Spin Monopole $2\hbar\omega$ $\sum_k t_\pm(k)\sigma_\mu(k)r(k)^2$

↑ **Compression mode**



Energy centroid $\bar{E}$, width Γ of IVSMR

→ isovector spin-incompressibility

effective interaction in **spin-isospin channel**

residual interaction, V_{pp}^{IVSM}, V_{ph}^{IVSM} (?)

Sum rule (model-independent)

$$S_- - S_+ = 3\left(N\langle r^4\rangle_n - Z\langle r^4\rangle_p\right)$$

→ neutron skin thickness $\delta_{np} = \sqrt[4]{\langle r^4\rangle_n} - \sqrt[4]{\langle r^4\rangle_p}$

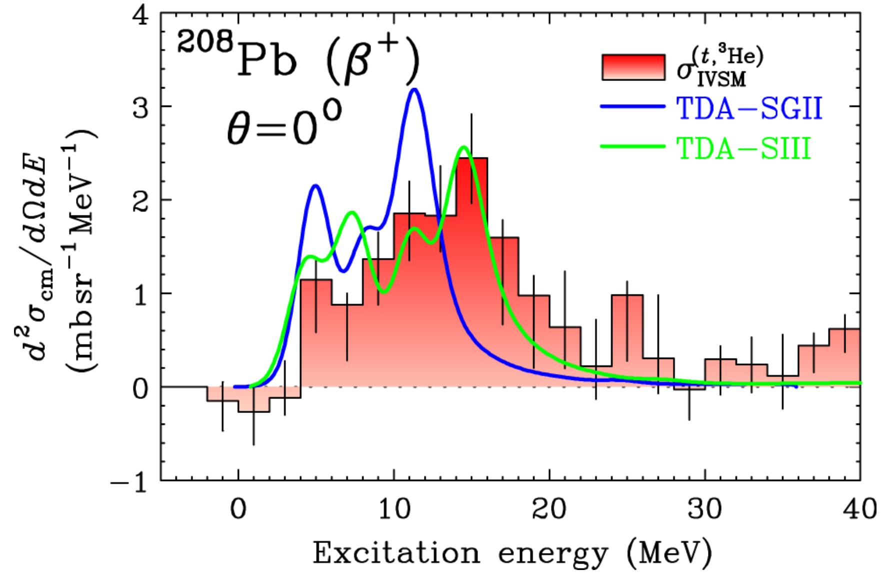
constraint on neutron matter equation of state

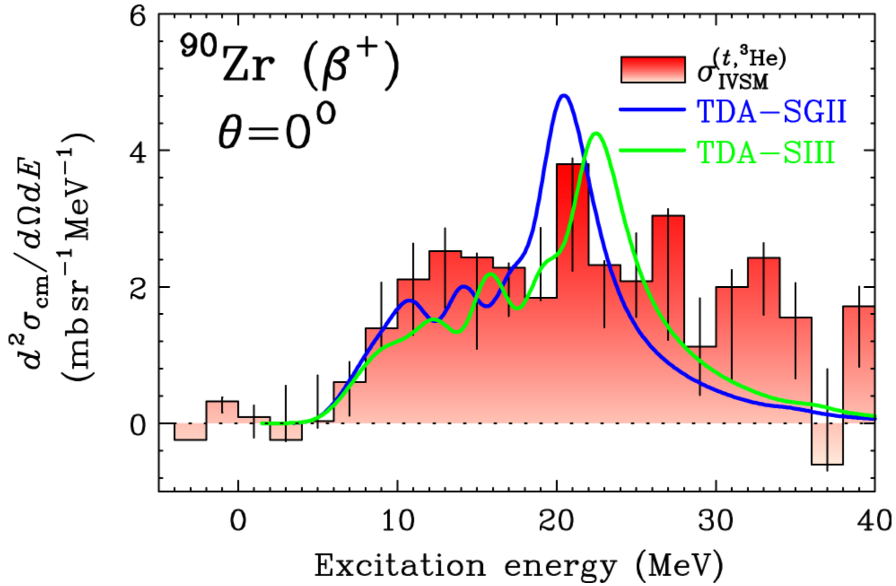
$^{90}Zr, ^{208}Pb\ (t, ^{3}He)$ at 300 MeV/u

K. Miki et al.
PRL

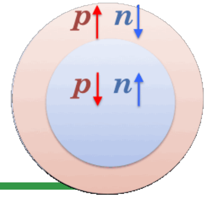
Primary : ^{4}He 320MeV/u 300pnA
Secondary : triton 300MeV/u 10^{7}pps
Purity > 99%

First identification of β^{+}-type isovector spin monopole resonances





High-intensity RI-beam +
high-resolution mag. analysis
→ New probes to nuclei



Exothermic (^{12}N, ^{12}C) Reaction

Advantages

(1) Spin-isospin selectivity

$^{12}N_{gs}(1^+; T = 1) \rightarrow {}^{12}C_{gs}(0^+; T = 0)$

$\rightarrow S_t = 1, \ T_t = 1$

(2) Surface sensitivity

∵ strong absorption of HI reaction

probes only surface of nucleus

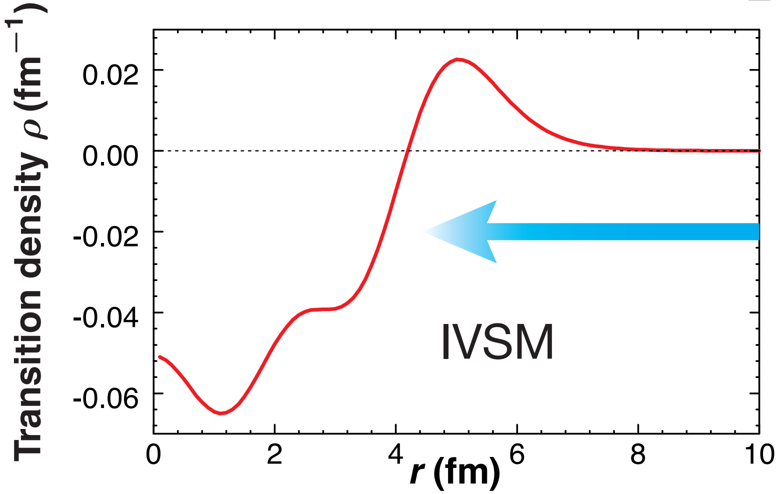
IVSM: transition density has a node at surface

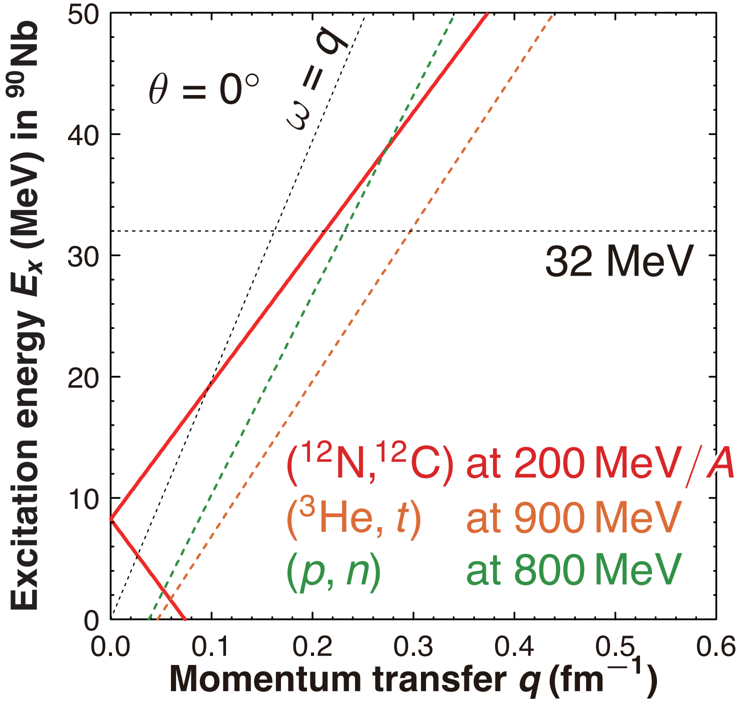
(3) Small q for high E_x

∵ large mass difference of proj. and ejec.

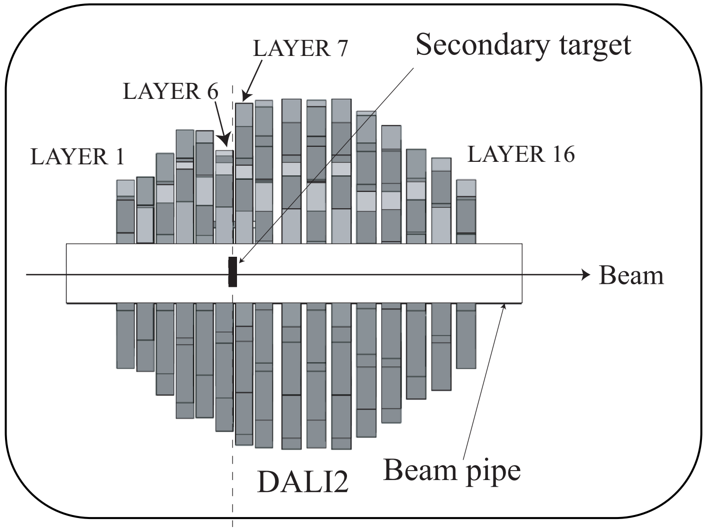
favors $\Delta L = 0$ excitations

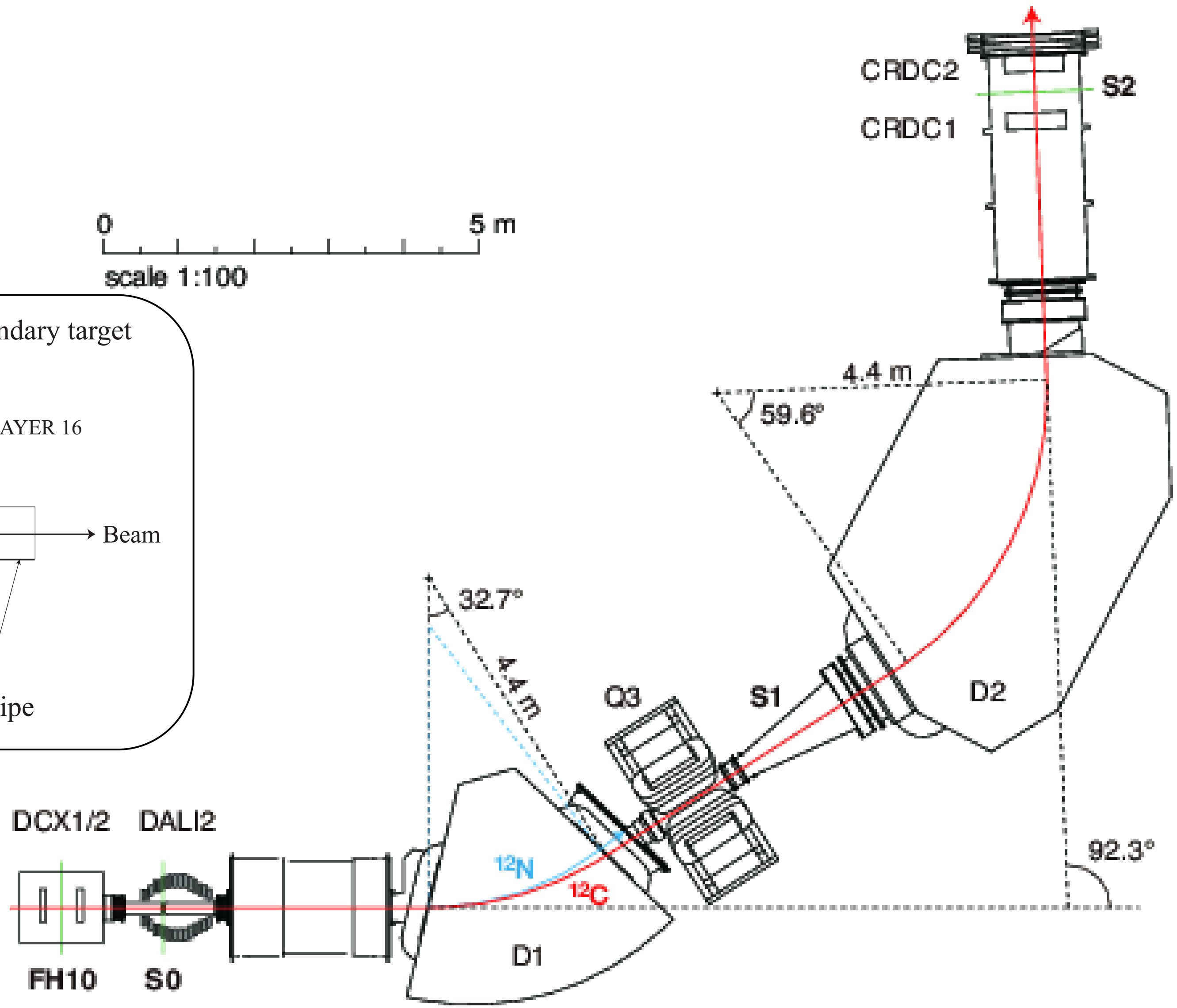
Noji et al.



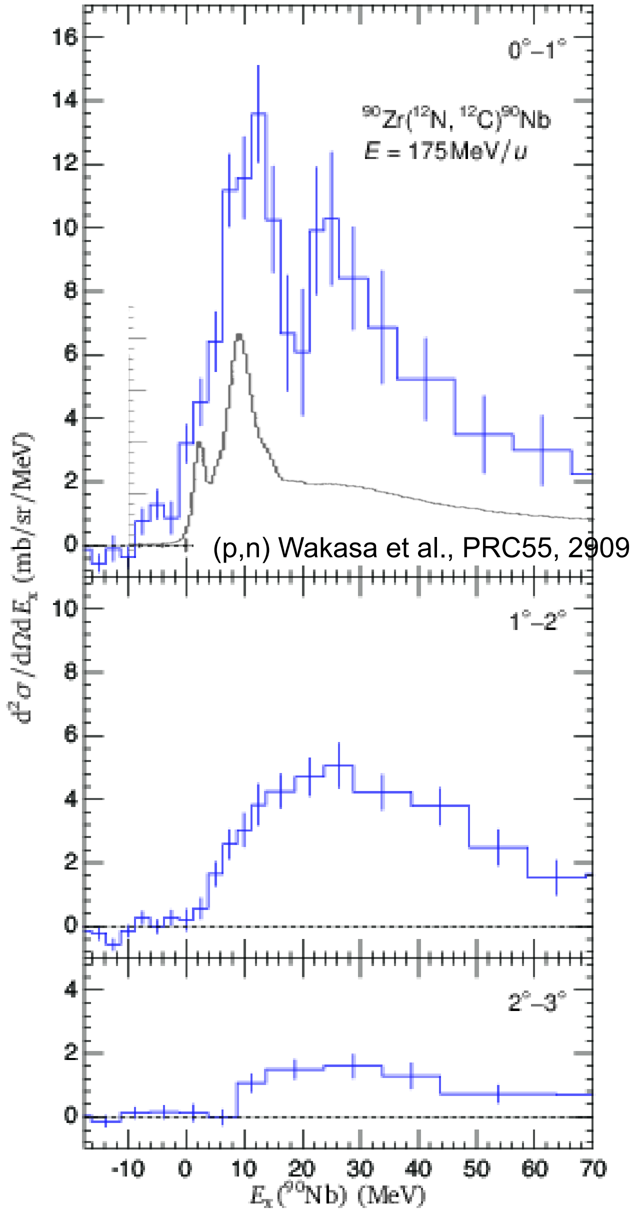


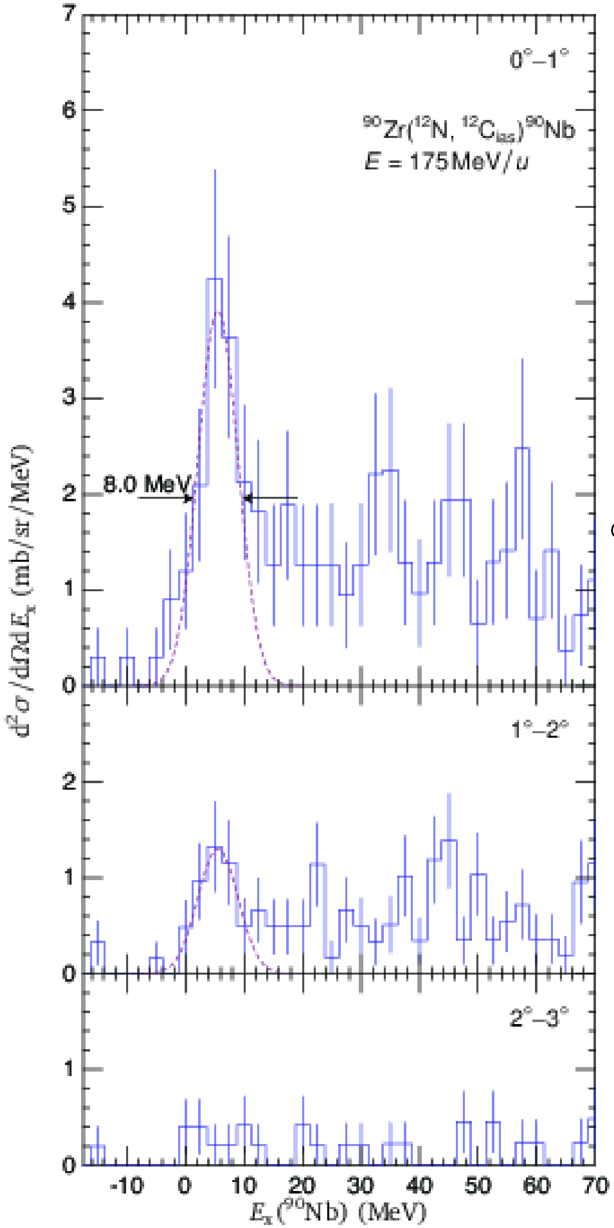
Experimental setup

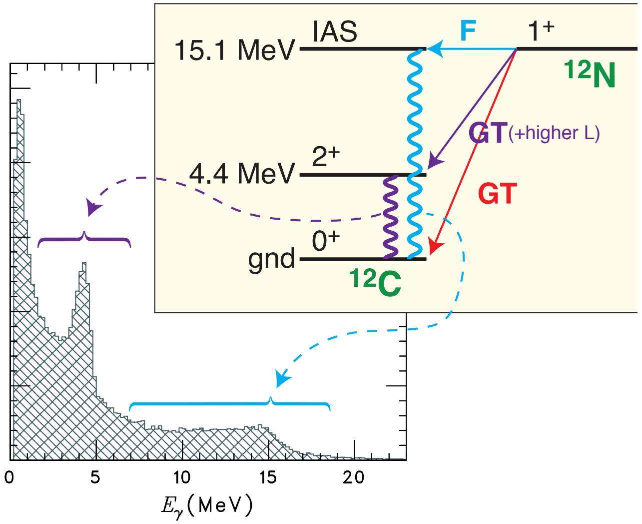




(^{12}N(1$^+$;T=1,^{12}C(0$^+$;T=0): GT) (^{12}N(1$^+$;T=1,^{12}C(1$^+$;T=1): Fermi+GT)







S. Noji et al.

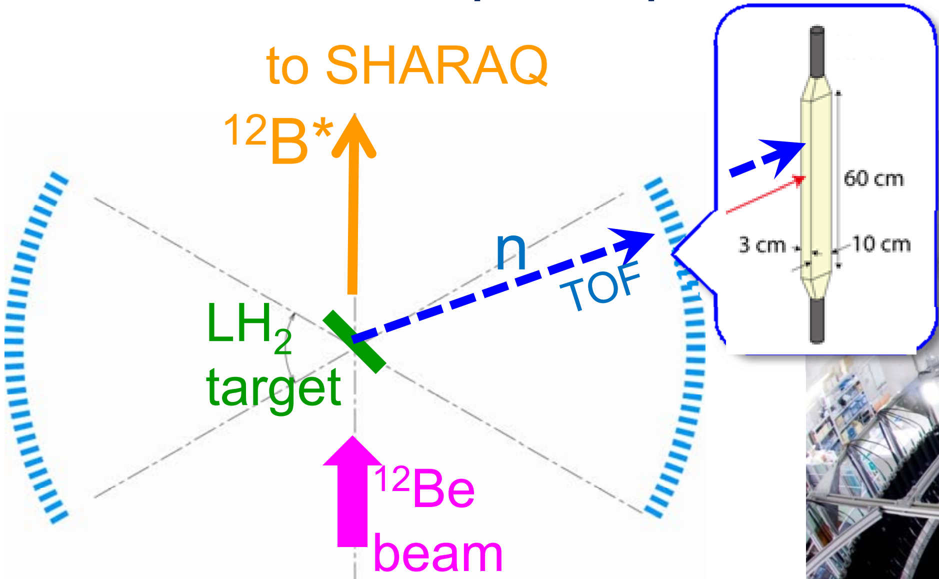
Yako et al.

$^{12}Be(p,n)^{12}B$ Measurement in Inverse Kinematics

Aim:

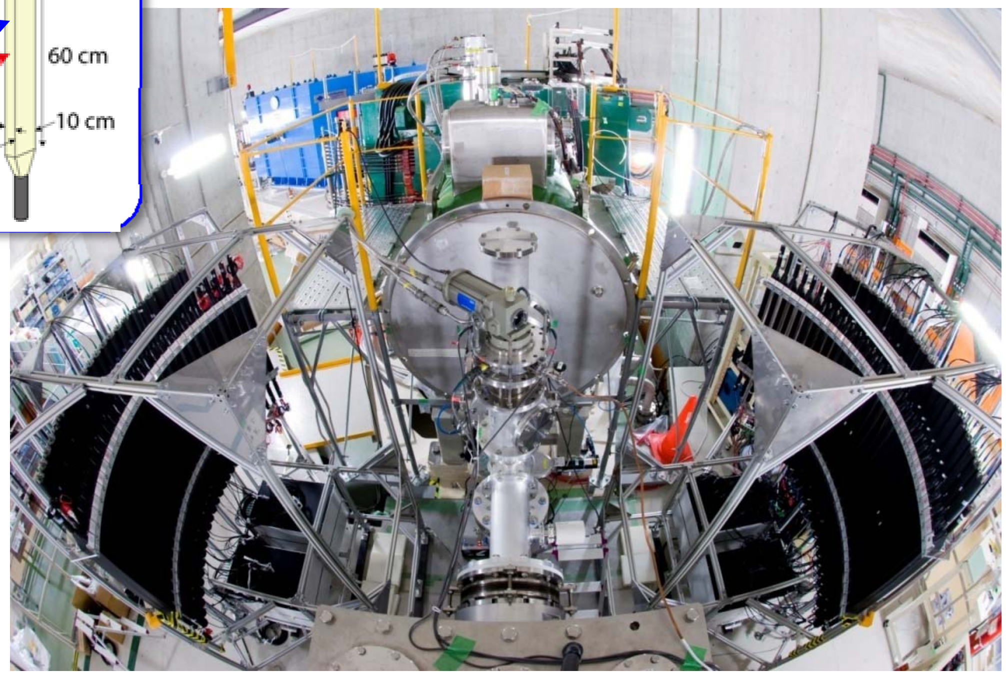
1. Establish the (p,n) measurement in inverse kinematics
2. Gamow-Teller and Spin-Dipole excitations → structure of ^{12}Be

Exp setup : missing mass measurement



Neutron counters

- 119 plastic scintillators (H7195 + BC408, 60 x 10 x 3 cm^3)
- θ = 60-120° , FPL = 180 cm

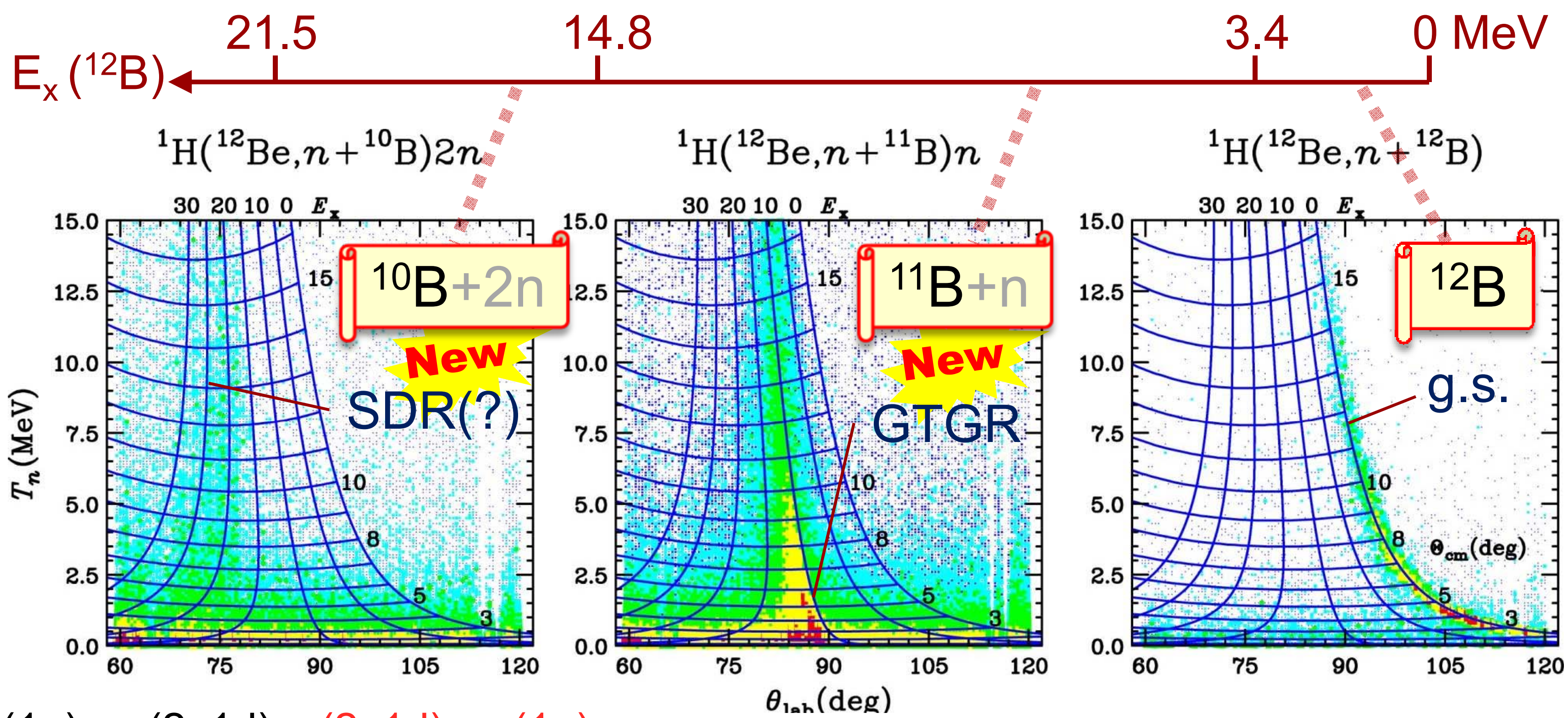


BeamTime [SHARAQ05]

Yako et al.

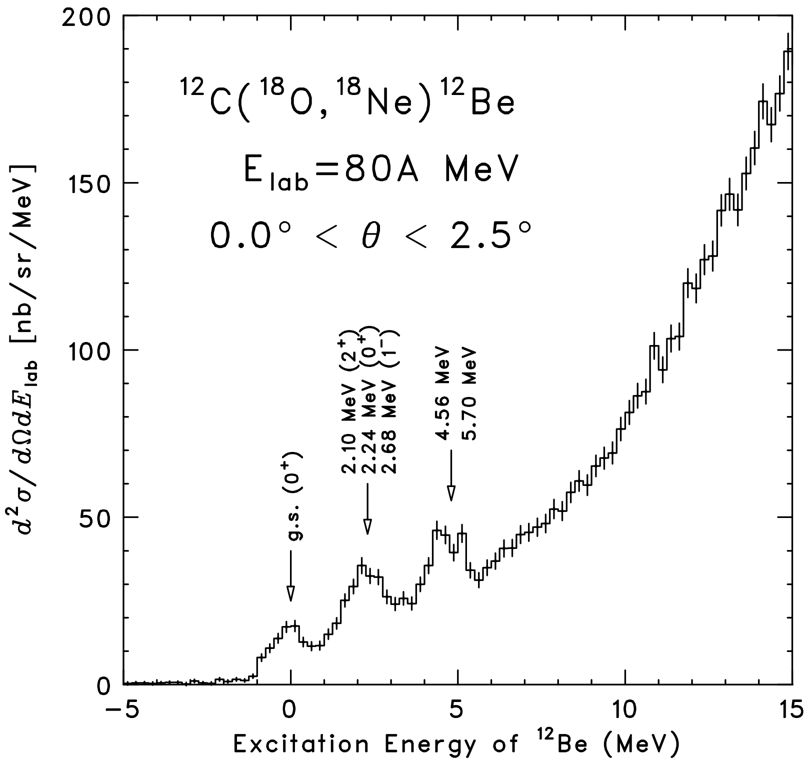
First measurement of B(GT^-) & B(SD^-) distribution in ^{12}Be

- Beam line: BigRIPS + SHARAQ
- Primary beam: ^{18}O 250A MeV, 100-200 pnA
  - ¼ -freq. buncher … pulse separation of 122 ns
- Primary target: Be, 20 mm^t
- Secondary beam: ^{12}Be 200A MeV, 500 kcps on target
- Secondary target: Liq H_2, 14 mm^t



ν(1p)→π(2s1d); ν(2s1d)→π(1p)

Double charge exchange (DCX) reaction of HI

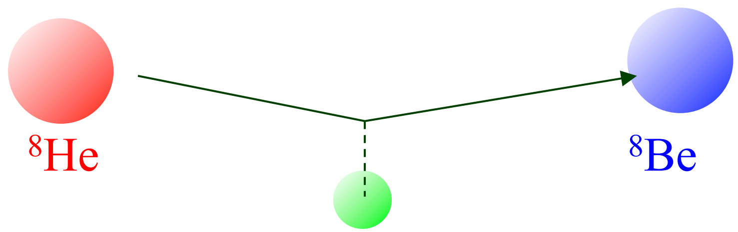


Stable ^{18}O beam @ RCNP
(Takaki, Matsubara et al.)

DCX reaction can be used for spectroscopy for exotic nuclei

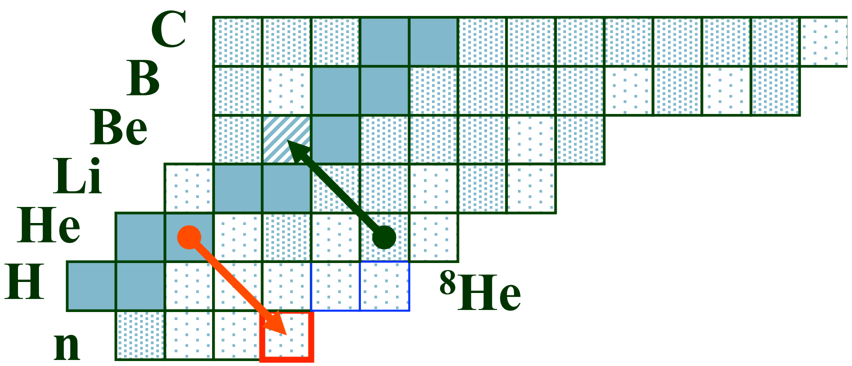
Exp: Apr. 1-15

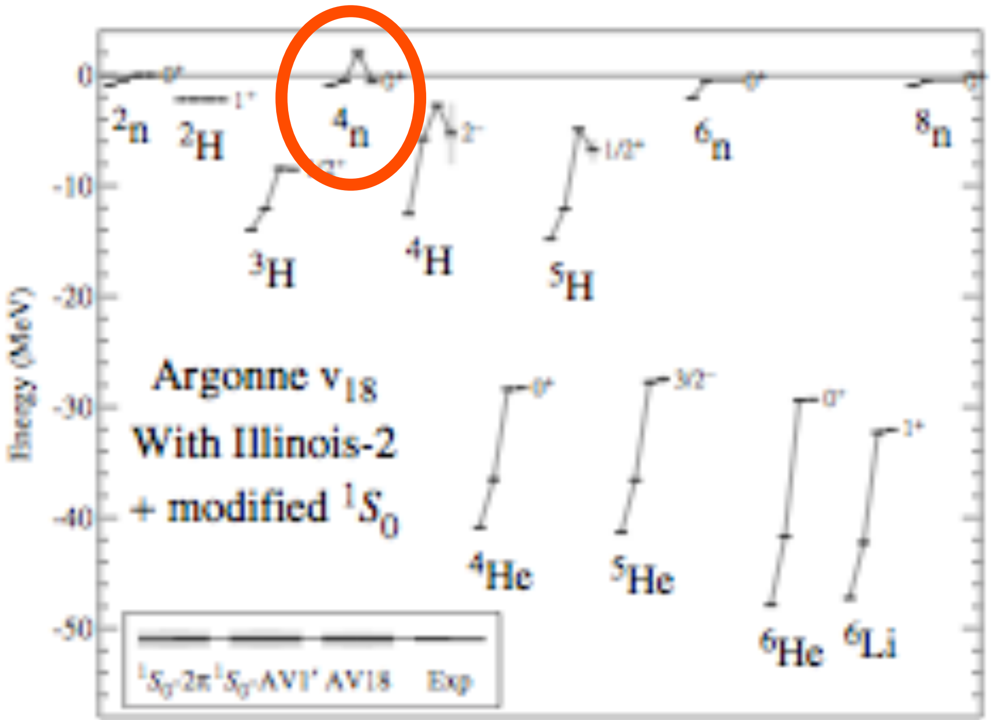
Tetra-neutron system produced by exothermic double-charge exchange reaction (NP1012-SHARAQ06)



Susumu Shimoura
for CNS-RNC-TITech-Kyoto-RCNP-Miyazaki-IPN collaboration

Recoil-less 4n system via DCX using internal energy of ^{8}He

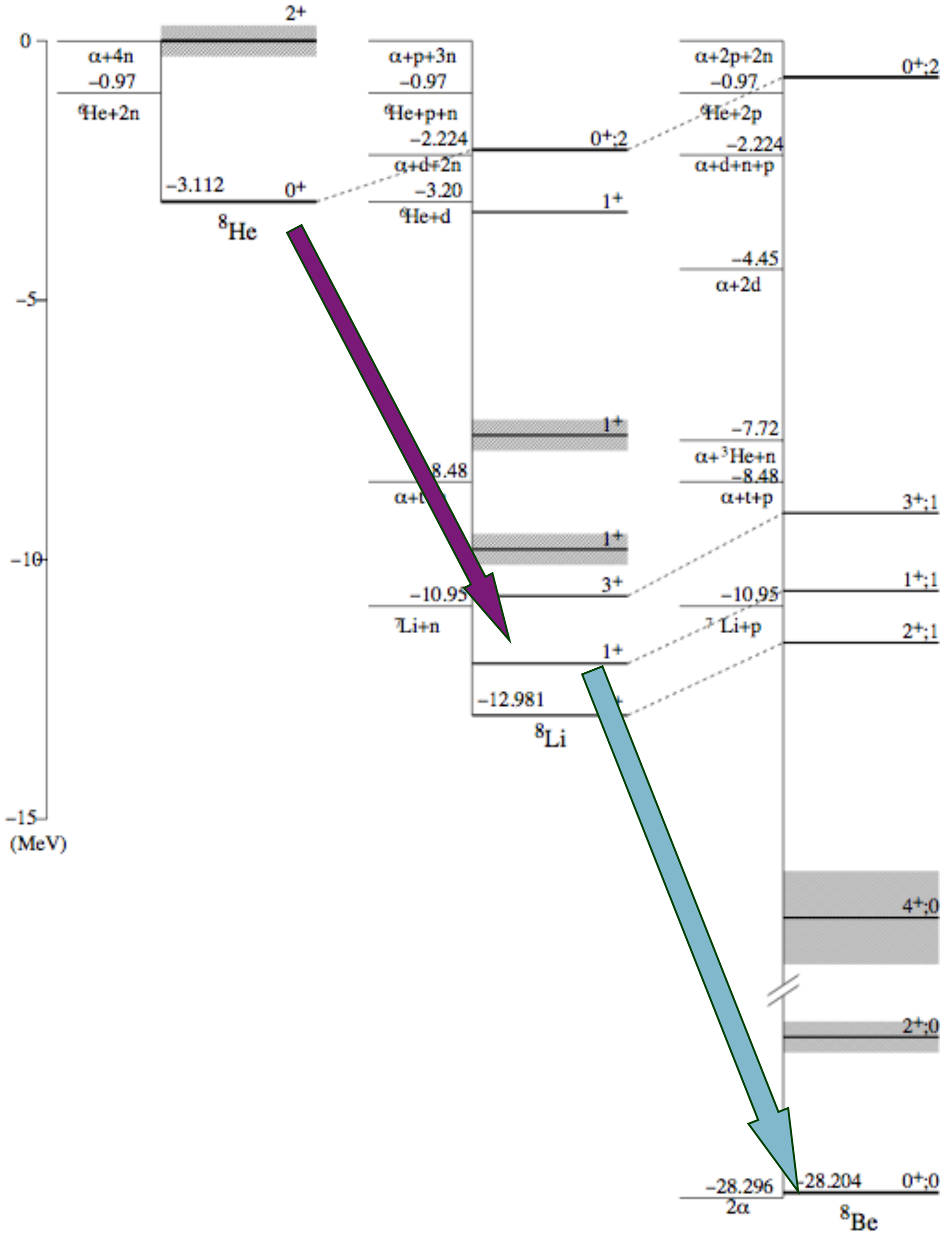


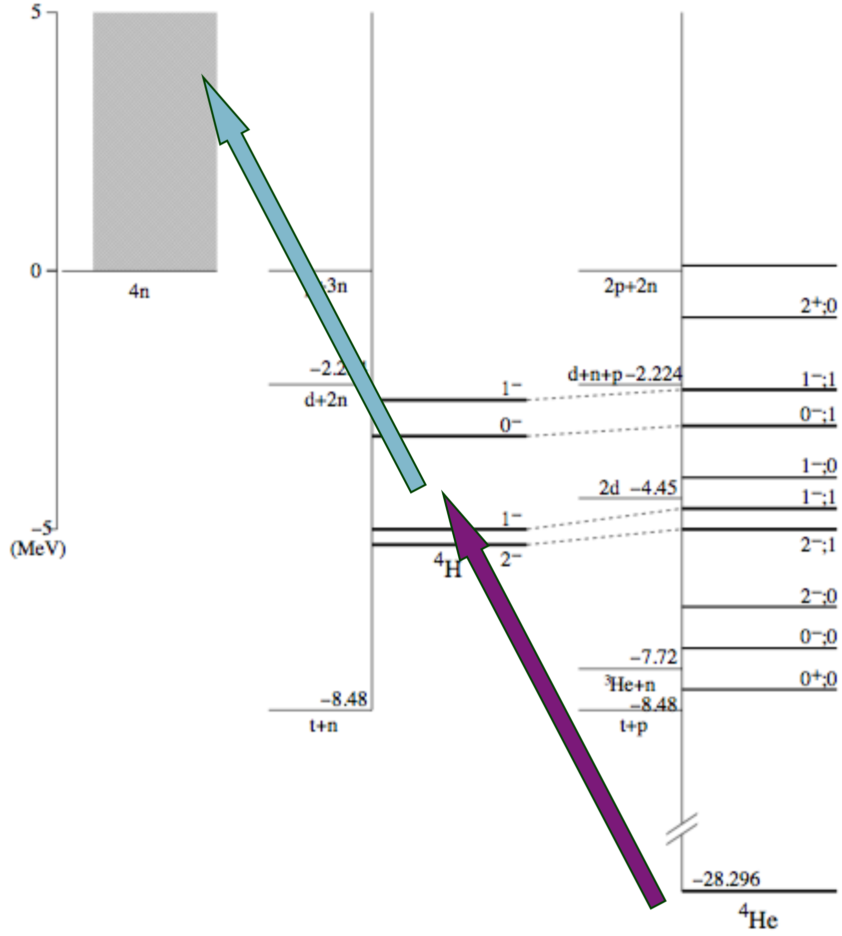


S.C. Pieper et al., PRL 90, 252501 (2003)

4n in breakup of ^{14}Be : Marques et al. PRC 65 (2002) 044006

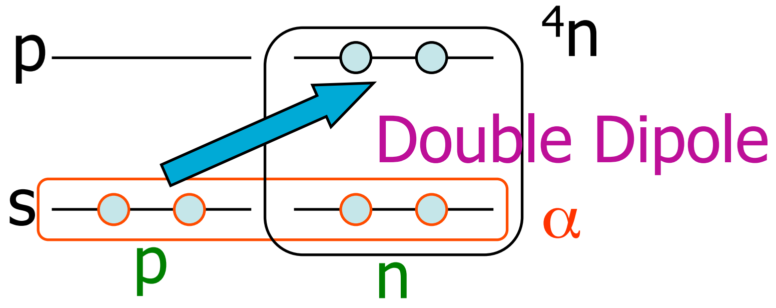
Level diagrams

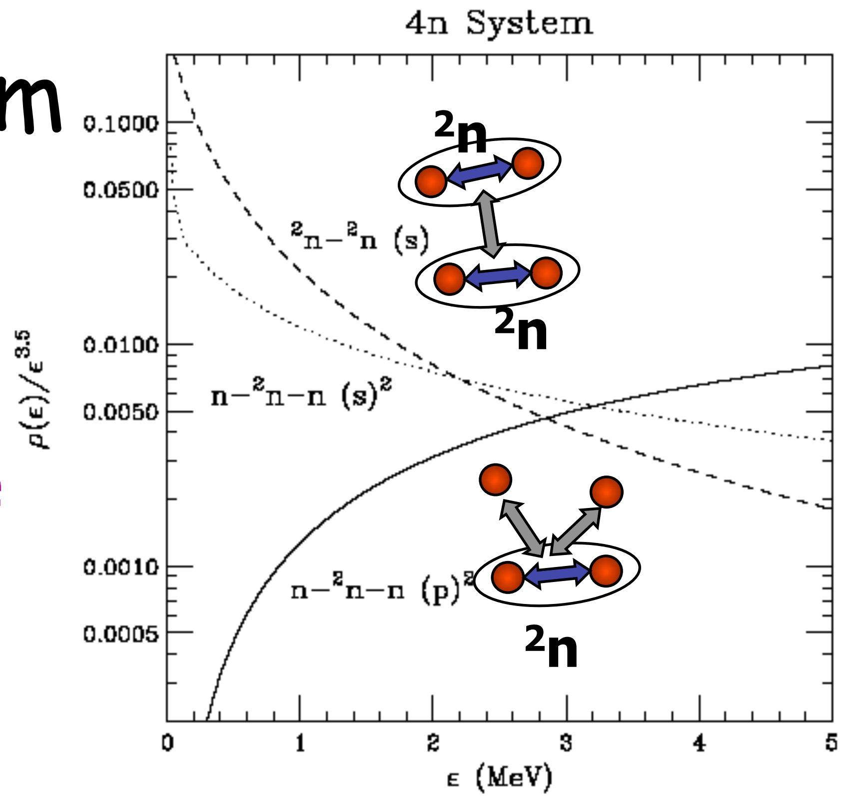




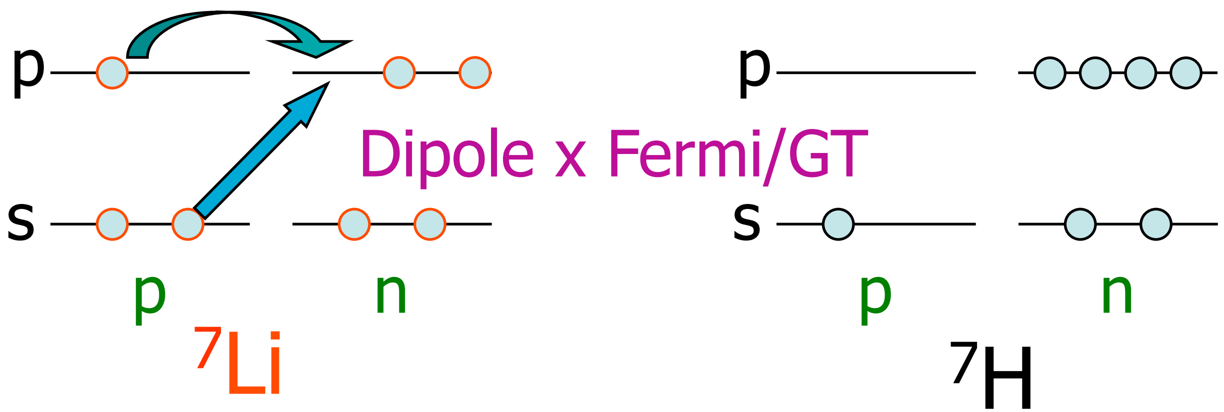
Multi-neutron system

^{4}He(^{8}He,^{8}Be)^{4}n



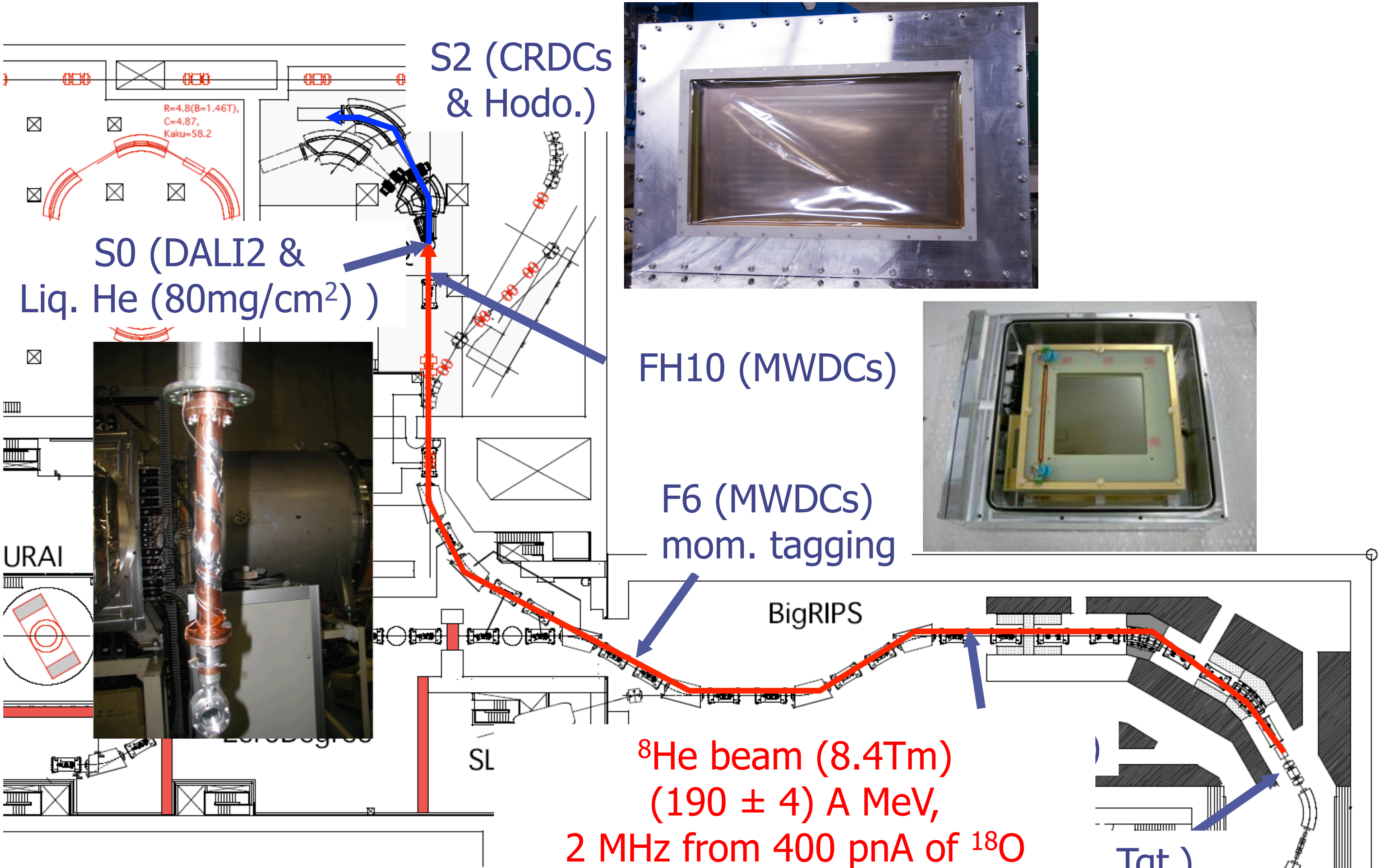


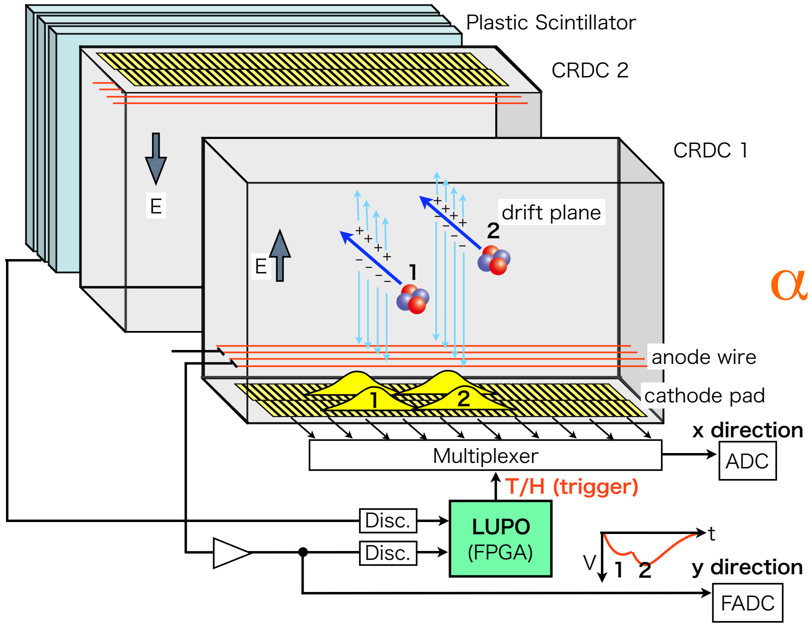
^{7}Li(^{8}He,^{8}Be)^{7}H



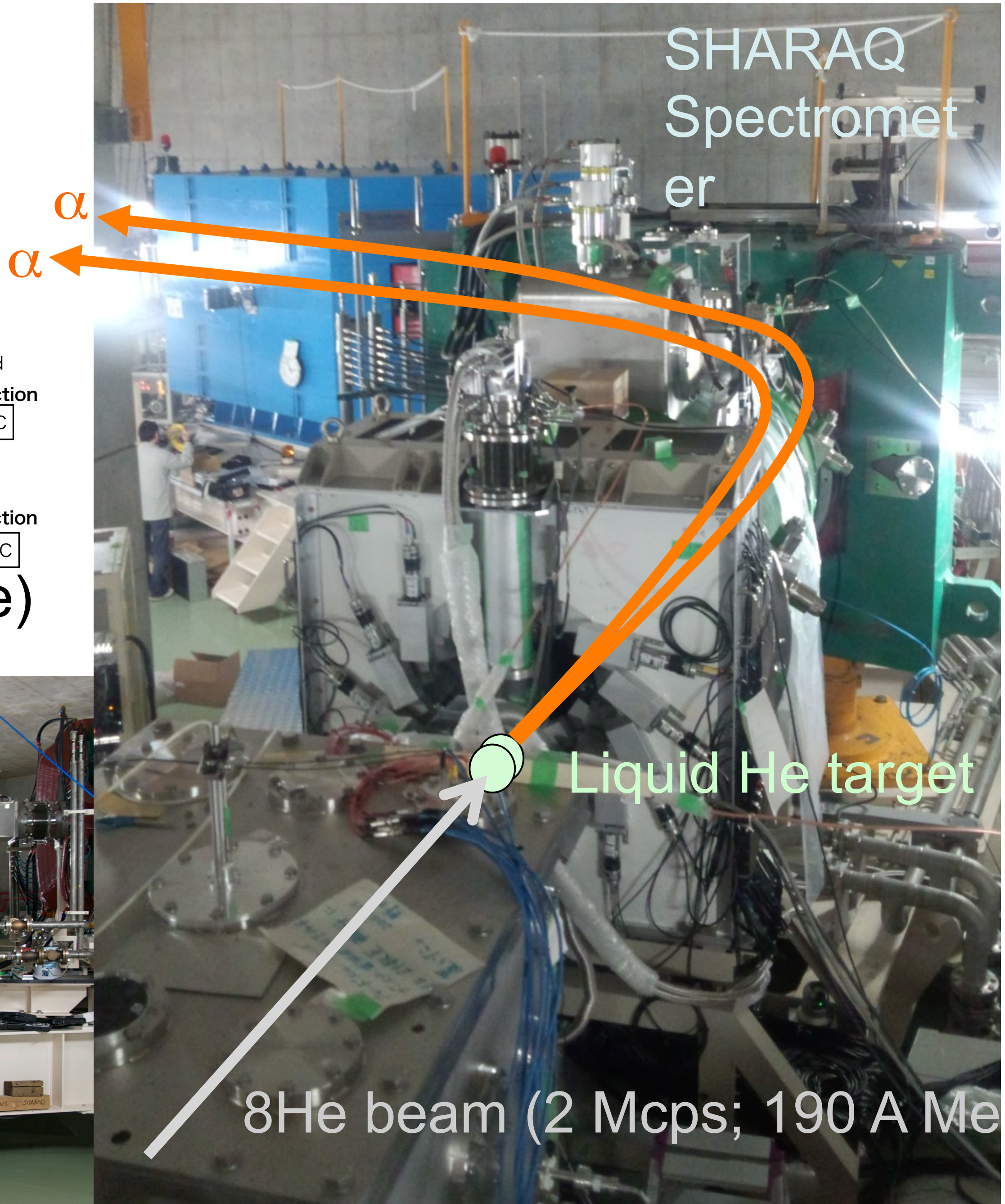
^{4}He(^{8}He,^{8}Be) @ 190A MeV was measured in Apr. 2012

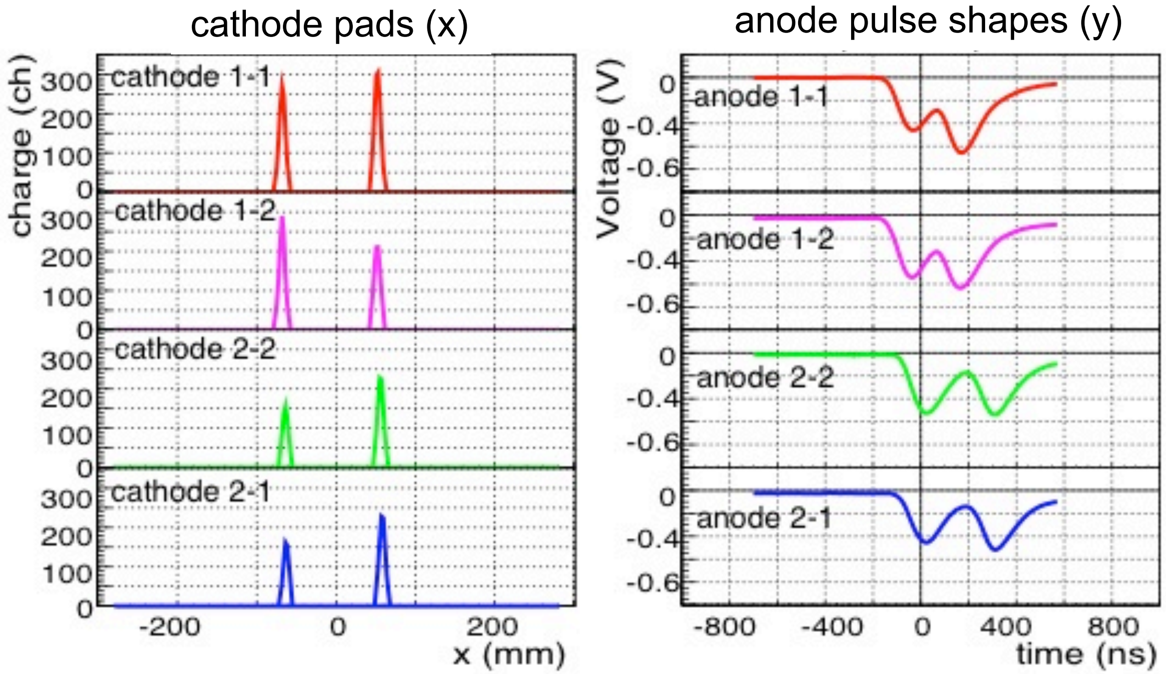
Experimental setup





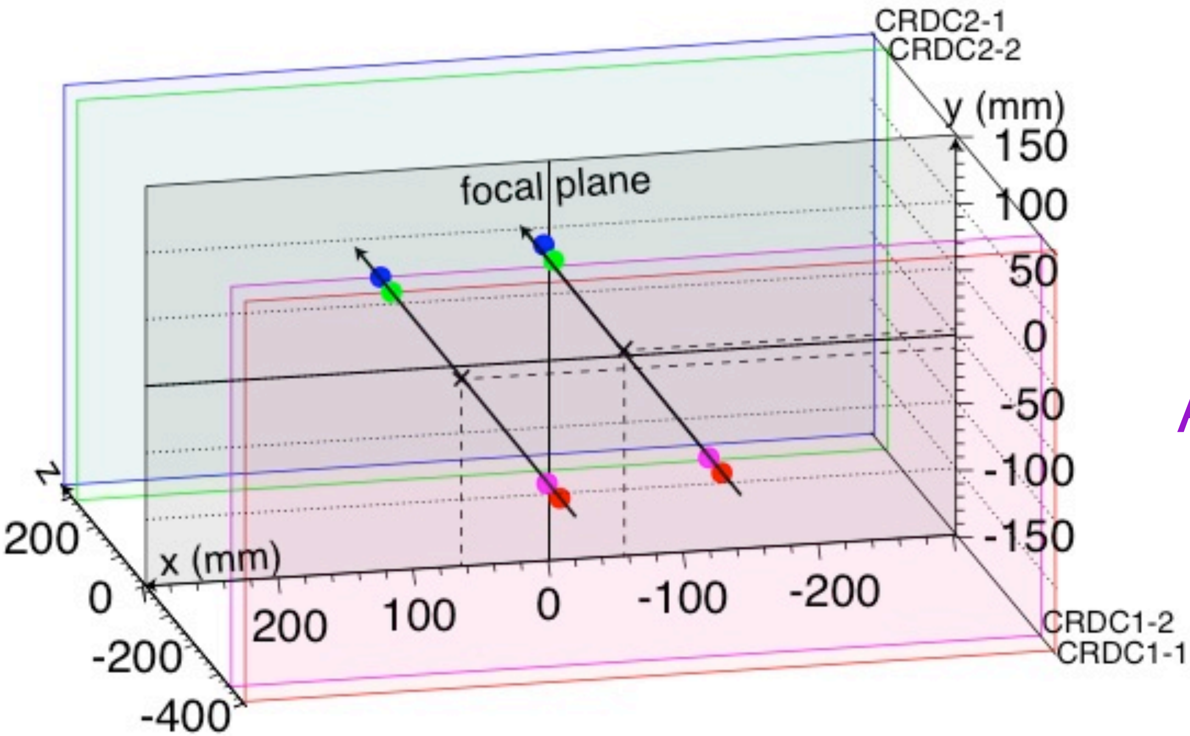
Readout system of 2α (^{8}Be)





Display of 2α event at SHARAQ focal plane (S2)

$^{4}He(^{8}He,^{8}Be(\rightarrow 2\alpha))4n$ @ 190 A MeV



a few hundreds of 2α were accumulated

Analysis is in progress

Opportunities

Missing mass spectroscopy by RI-beam induced reactions (normal kinematics)

(^{10}C,^{10}Be) DGTR

Multi-layer targets to minimize energy-loss difference (^{10}C and ^{10}B)

(^{12}C,^{12m}Be(0^+)) DGTR

Stable beam ; delayed γ at FP

(^{16}O,^{16}F(0^-)), (^{16}O,^{16}N(0^-)) SDR of “pion”-mode

Invariant mass meas. of ^{16}F(0^-)/ β-delayed γ from ^{16}N(0^-) at FP

...

Inverse kinematics

^{52m}Fe(12^+),^{12m}Be(p,n) GT, SDR of isomer (Response of excited state)

High-resolution TOF (Diamond) for event-by-event ID of isomer

(p,p’γ) on heavy and/or odd nuclei spectroscopy more than 1st 2^+

High-rate capability of Focal Plane detector

^{19,17}B, ^{29}F(p,2p) Nuclei beyond drip-line + multi-n correlation

Two-proton spectrometer / neutron tagging etc.

...

High-resolution measurement provides us with
new experimental approaches to physics of exotic nuclei