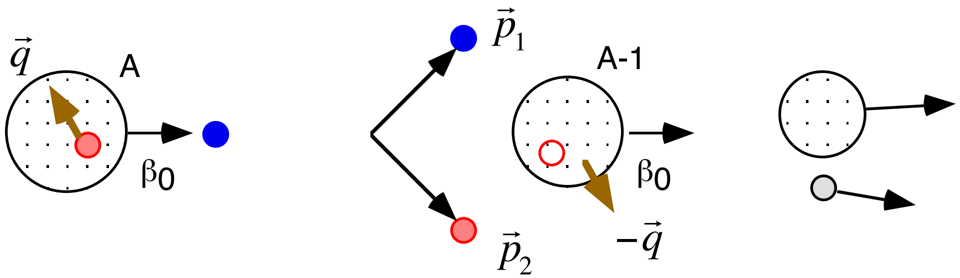
Studies of Exotic Nuclei using (p,2p) Proton Knockout Reactions
and
Construction of a Broad-Range Magnetic Spectrometer

T. Kobayashi (Tohoku Univ.)

participants

T.Kobayashi , K.Ozeki, K.Maeda, T.Tamae, N.Chiga, Y.Matsuda (Tohoku Univ.)
E.Takada (NIRS)
H.Sakaguchi (Miyazaki Univ.)
T.Noro (Kyushu Univ.)
H.Otsu, H.Takeda, S.Terashima (RIKEN)
Y.Sato (Tokyo Inst. Tech.)
R.C.Lemmon, M.Labiche (Daresbury Lab.)
M.Chartier, B.Fernandez-Dominquez (Liverpool Univ.)
W.Catford (Surry Univ.)
T.Aumann, O.Kiselev, P.Egelhof (GSI)
W.Mittig, L.Gaudefroy (GANIL)
N.Orr (LPC-Caen)
A.S.Fomichev, G.M.Ter-Akopian, M.S.Golovkov, S.A.Krupko, A.M.Rodin, S.I.Sidorchuk,
S.V.Stepantsov, R.Wolski (JINR)

(p,2p) proton knockout reaction in Inverse Kinematics

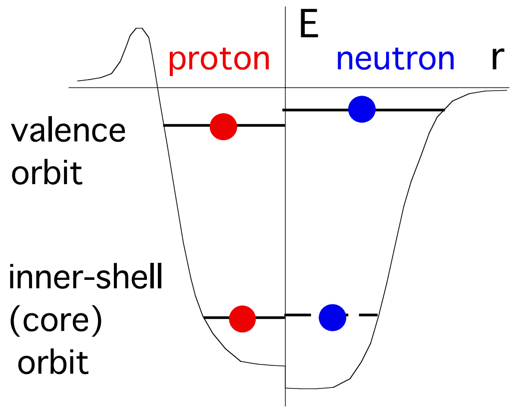


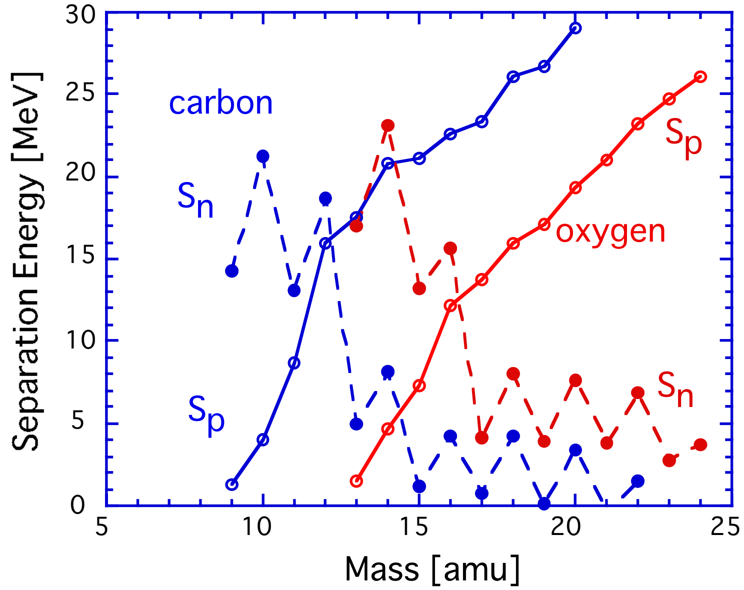
(A-1) system
(hole state)

Coincidence measurements of forward particles

↕

Decay mode of hole state





Nucleon knockout via quasi-free N-N scattering

Beam energy : need to be "high" ➡ suitable for RIBF

Measured Quantities : information on single-particle orbit

Momentum Distribution (**q**)

Angular Momentum (**L**)

$$\vec{q}_{\perp} = \left(\vec{p}_1 + \vec{p}_2\right)_{\perp}$$

$$\vec{q}_{//} = \frac{\left(\vec{p}_1 + \vec{p}_2\right)_{//} - \gamma\beta\left(M_A - M_{A-1}\right)}{\gamma}$$

Separation Energy (E_S, $\mathbf{S_p}$)

$$E_s = T_0 - \gamma\left(T_1 + T_2\right) - 2(\gamma - 1)m_p + \beta\gamma\left(\vec{p}_1 + \vec{p}_2\right)_{//} - \frac{q^2}{2M_{A-1}}$$

S factor

Decay mode of hole states

	(p,2p), (p,pn) on proton target	Knockout reaction by tagging γ-rays on nuclear target @MSU/GSI
E_s resolution	~1 MeV (➡~0.5MeV)	few keV
Final state	unbound/bound	bound
Sensitivity	nuclear interior inner shell	surface(?)
#Valence protons	any	1

(1) Charge radii of inner shell ($\pi 1s_{1/2}$)

momentum distribution

^{3,4,6,8}He

^{6,7,8,9,11}Li

^{14,15,16,17,18}C

^{19,21,23,24,25}F

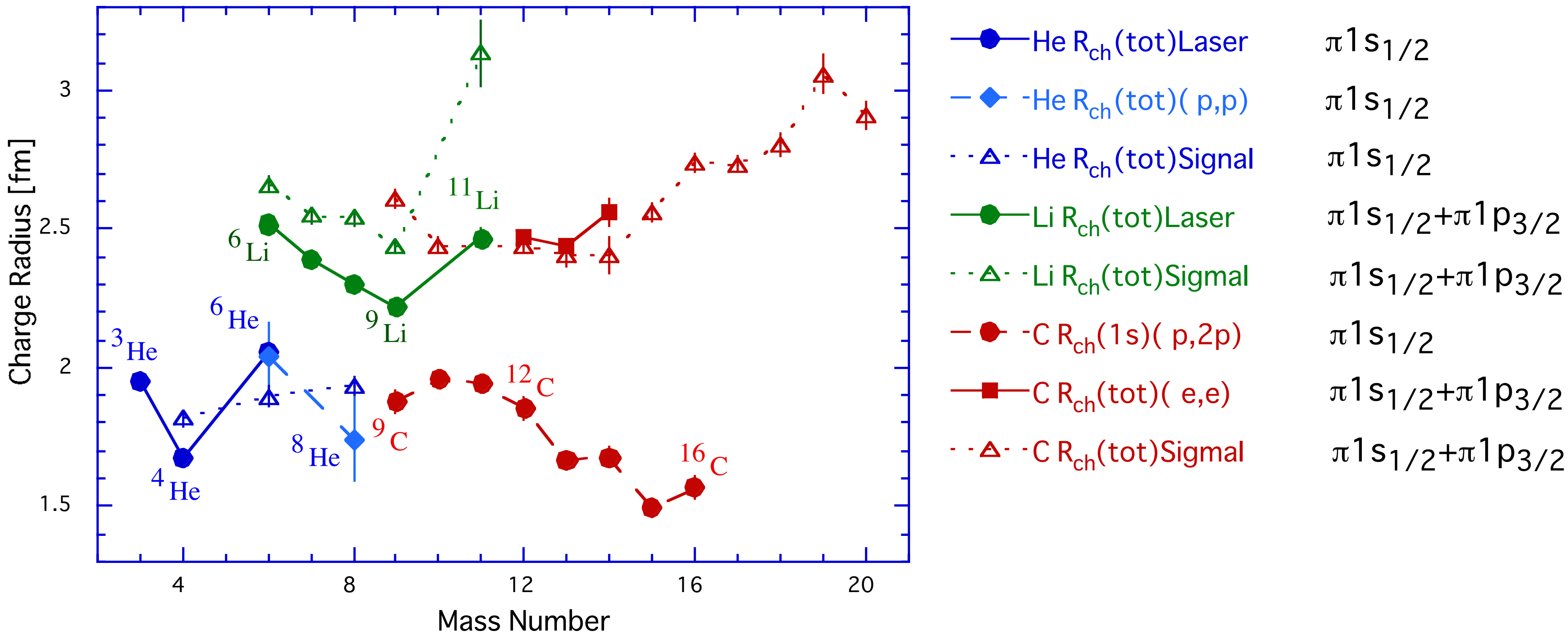
(2) Oxygen isotopes around N=16

$^{18,20,22,\underline{23,24}}$O from ^{19,21,23,24,25}F

(3) Proton-rich nucleus ^{17}Ne

$\underline{^{16}\text{F}}$

(1) Charge radii of inner shell ($\pi 1s_{1/2}$)



$^{9\text{-}16}$C(p,2p)($\pi 1s_{1/2}$)$^{-1}$ momentum distribution ➡ charge rms radius of $\pi 1s_{1/2}$

shirinking, with possible zig-zag pattern, towards neutron-rich side.

binding energy (?) S_p=20-50MeV

excitation effect (?) $\pi 1s_{1/2}$ ➡ $\pi 1p_{1/2}$ Ikeda, Toki

^{3,4,6,8}He(p,2p) comparison with Laser spectroscopy

^{6,7,8,9,11}Li(p,2p) comparison with Laser spectroscopy, additional information on $R_{ch}(\pi 1s_{1/2})$

^{14,15,16,17,18}C(p,2p) cross check of HIMAC exp. by optimizing to s-orbit, towards more neutron-rich side

^{19,21,23,24,25}F(p,2p) $\pi 1p_{1/2}$ orbit filled probably O(p,2p)N reaction will be better/simpler

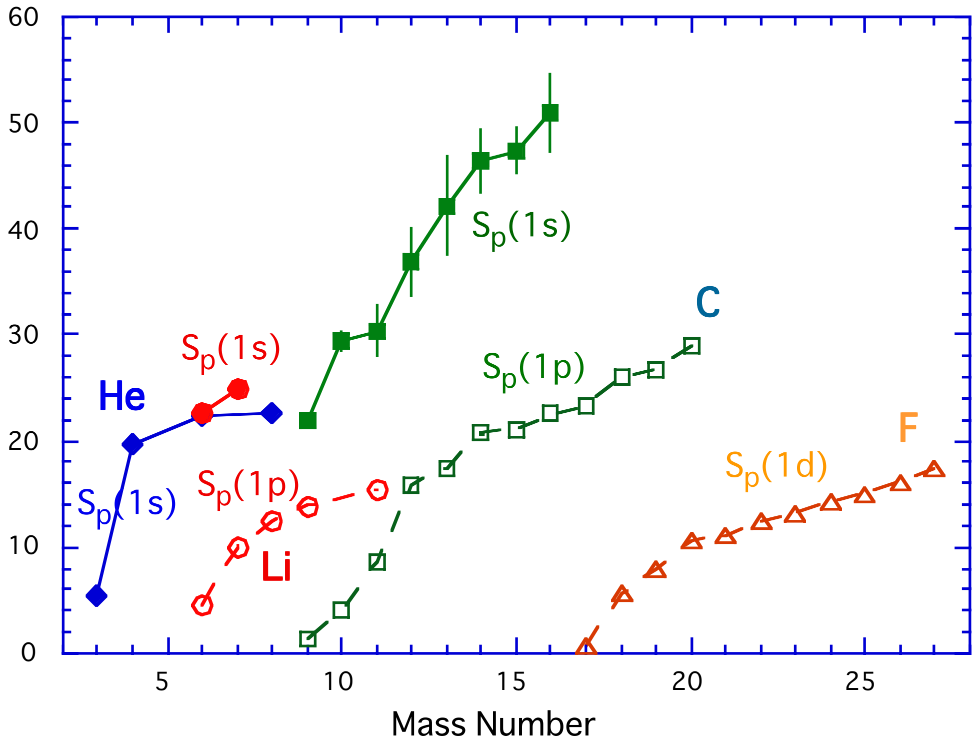
(2) Oxygen Isotopes around N=16

$^{23,24}O$ no particle-stable excited states, ^{24}O=double magic ← $^{24,25,26}F(p,2p)$

^{25}O particle unbound ground state (beam intensity < 7kHz)

∗limited to proton holes : behavior of $\pi 1s_{1/2}$, $\pi 1p_{3/2}$, $\pi 1p_{1/2}$ by adding neutrons
interesting part : $\nu 2s_{1/2}$, $\nu 1d_{3/2}$,

$R_{ch}(\pi 1s_{1/2})$ when $\pi 1p_{1/2}$ orbit is fully occupied (?)



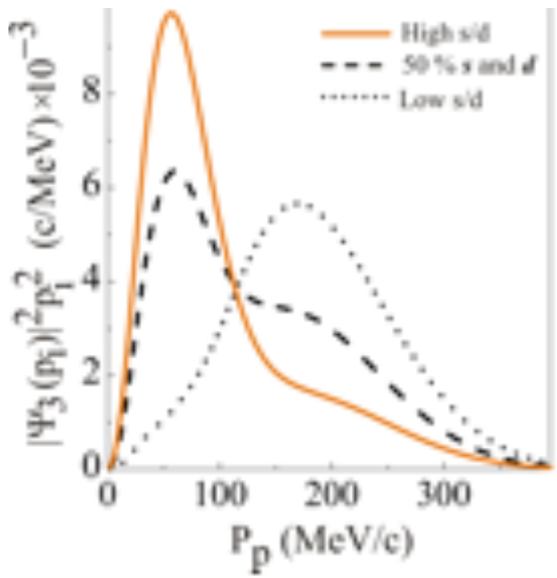
(3) Proton-rich nucleus ^{17}Ne

^{17}Ne(p,2p)^{16}F

Two valence protons in $\pi 2s_{1/2}/\pi 1d_{5/2}$

mixing information from momentum distribution

^{16}F : particle unbound

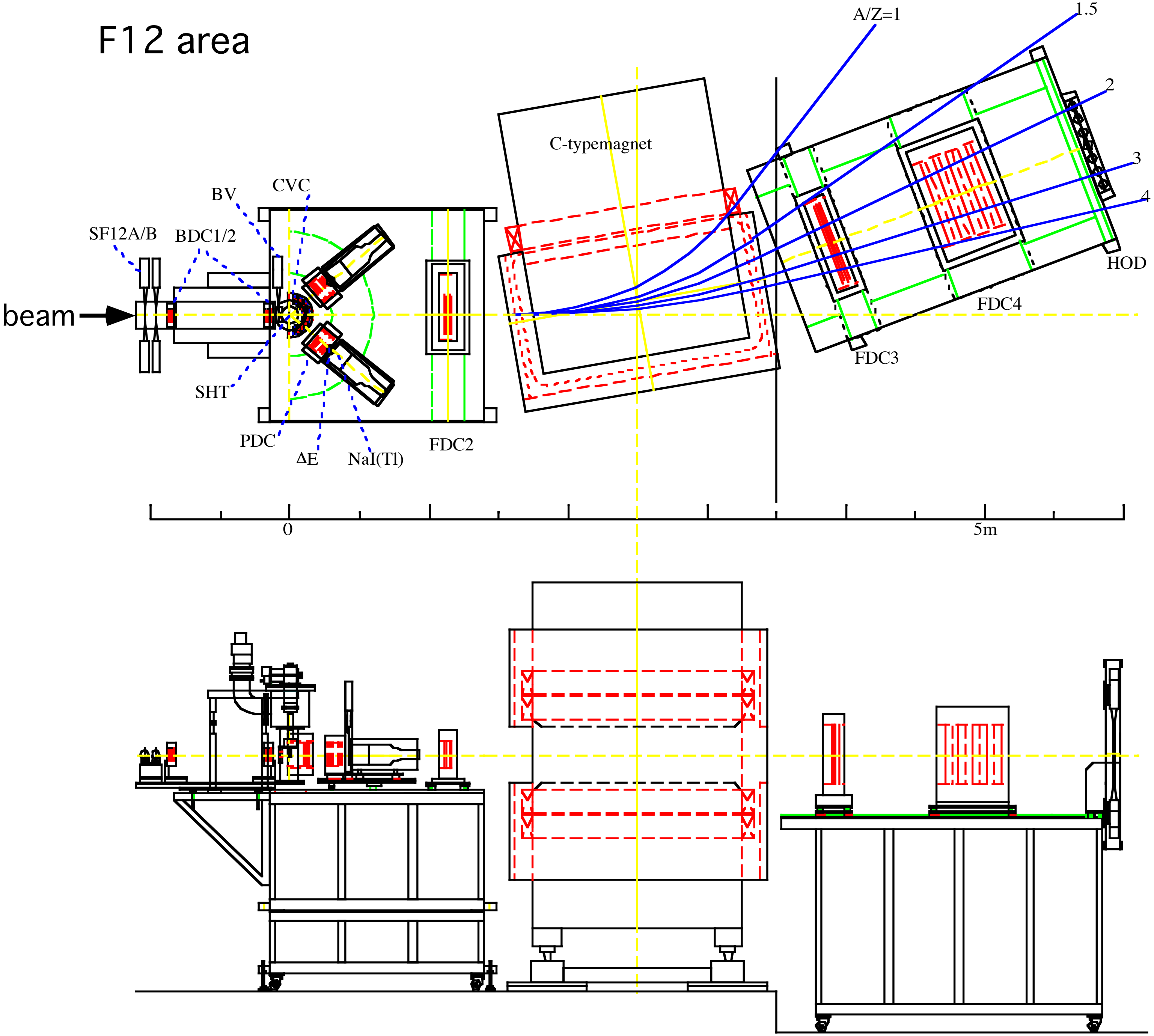


Experimental Setup

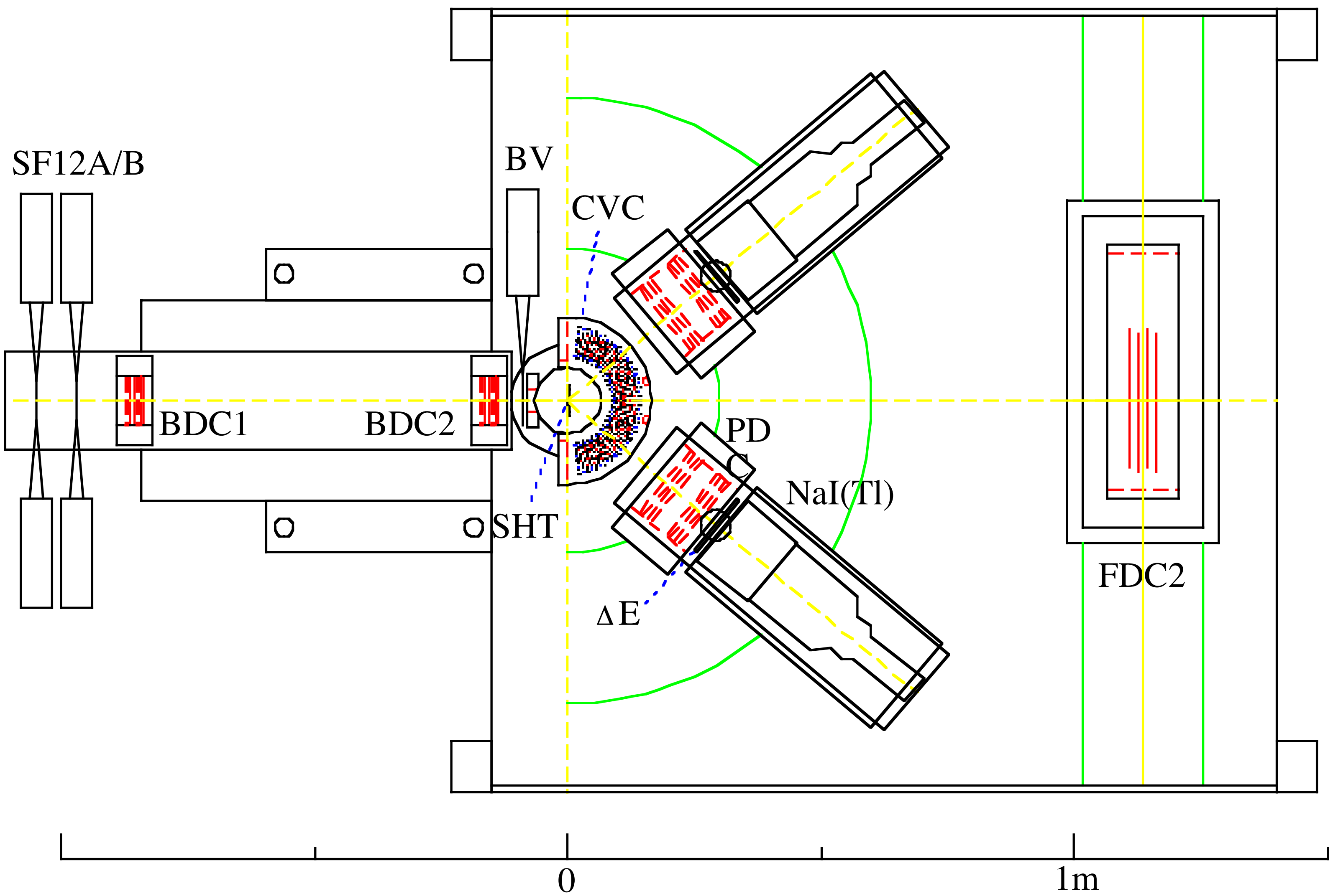
F5: Momentum tag

F8-F12: TOF(17m)

F12 area



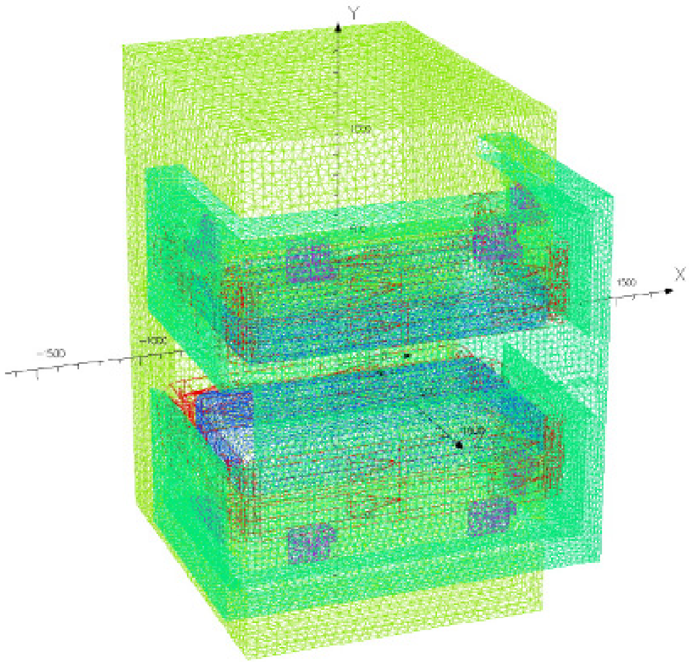
Experimental Setup : (p,2p)

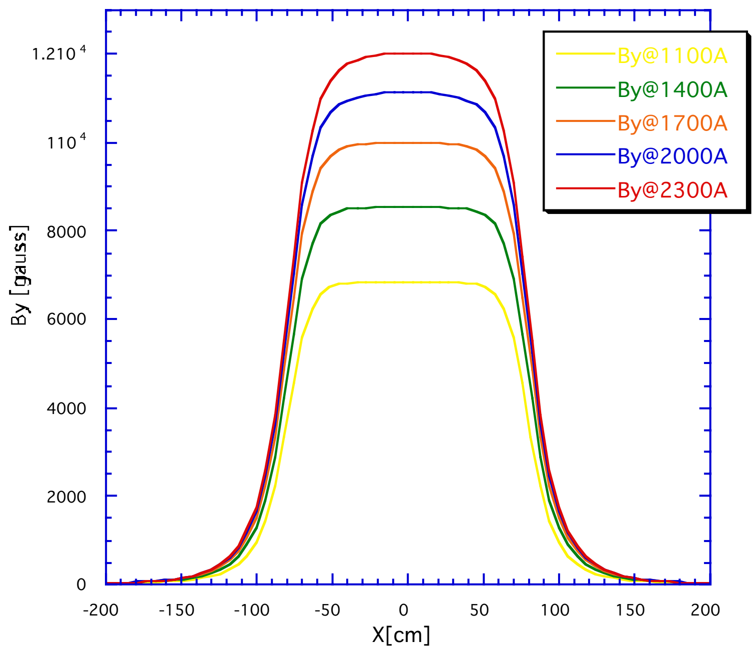


Forward (Broad Range) Magnetic Spectrometer

One on the missing Facility @RIBF

Secondhand C-type Magnet (Kappa) + existing tracking detectors





Gap	0.4 m	#Turns	200
Pole	0.8m x 1.5m	Current	2300 A
Max. Field	1.2 T	Voltage	275 V
Effective length	1.8 m	Motive force	0.45 MAT
Max. BL	2.2 Tm	Power	580 KW
Weight	54 t	Cooling water	10 kg/cm^2, 150 l/min

Power Supply : 2300A/300V

TARN-II PS (2500A/600V)

Secondary Beam Parameters / Measuring time

Intensity > 10^5Hz

measuring time / isotope ∼ 10 hours / $I_b=3\times10^5$Hz

time for beam switching (?)

	Primary beam	Energy [MeV/u]	Secondary beam	Energy [MeV/u]	Prod. Target [g/cm2]	Wedge @F1 [mm]	Wedge @F1 [mrad]	Wedge @F4 [mm]	Wedge @F4 [mrad]	B(D6) [T]	Intensity [/sec/100pnA]	Intensity to be used [/sec]	Measuring time / Isotope [hours]	Measuring time for Isotope chain [hours]	
P	18O	350	p	270								1.0E+06	12	12	12
$^{3-8}$He	18O	350	3He	254	11.03	11	11.6			0.6144	8.83E+07	3.0E+05	10	40	
			4He	252	8.99	42	47.6			0.8129	3.32E+07	3.0E+05	10		
			6He	253	6.93	95	123.7			1.2236	9.01E+06	3.0E+05	10		
			8He	251	8.12	110	144.2			1.6269	2.82E+05	3.0E+05	10		
$^{6-11}$Li	18O	350	6Li	253	9.01	18	20.6			0.8167	1.09E+08	3.0E+05	10	53	
			7Li	254	7.30	36	41.8			0.9528	8.80E+07	3.0E+05	10		
			8LI	253	7.19	43	49.9			1.0879	3.42E+07	3.0E+05	10		
			9LI	252	7.13	50	57.7			1.2221	8.31E+06	3.0E+05	10		
			11Li	252	5.45	86	105.0			1.4944	1.20E+05	2.4E+05	13		
$^{14-18}$C	22Ne	350	14C	246	5.77	14	18.0			0.9359	2.43E+08	3.0E+05	10	50	
			15C	255	5.44	14	16.8			1.0221	6.32E+07	3.0E+05	10		
			16C	256	5.05	14	16.2	7.0	18.6	1.0799	1.23E+07	3.0E+05	10		
			17C	251	5.26	14	16.1	7.0	18.8	1.1484	1.81E+06	3.0E+05	10		
			18C	262	4.56	14	16.0	7.0	18.7	1.2478	2.09E+05	3.0E+05	10		
			19C	267	4.29	14	15.9	7.0	18.7	1.3307	2.13E+03				
$^{19-25}$F	22Ne	350	19F	259	0.90	20.0	24.7			0.8719	4.80E+08	3.0E+05	10	65	
			21F	259	1.60	20.0	22.8			0.9621	5.71E+08	3.0E+05	10		
	48Ca	350	23F	262	2.90	7.0	8.1			1.0611	2.32E+06	3.0E+05	10		
			24F	263	2.90	7.0	8.1			1.1098	3.90E+05	3.0E+05	10		
			25F	264	2.96	7.0	8.1			1.1577	5.96E+04	1.2E+05	25		
			26F	273	2.61	7.0	8.0			1.2276	7.44E+03				
^{17}Ne	20Ne	400	17Ne	253	7.25	7.4	8.9			0.6971	1.75E+07	3.0E+05	10	10	10
											Total measuring time [hours]			230	

Position Detectors

Detector	Half cell [mm]	Cell type	Plane configuration	Effective area [mm]	#Readout channels	L/L_r [x10^{-3}]
WCB	2	MWPC	xx	240 x 150	64 x 2	1.0
BDC1	2.5	Walenta	xx'yy'xx'yy'	80 x 80	16 x 8	0.57
BDC2	2.5	Walenta	xx'yy'xx'yy'	80 x 80	16 x 8	0.57
FDC2	10.5	hexagonal	xx'xx'	242 x 160	12 x 4	0.39
FDC3	10.5	hexagonal	xx'xx'	558 x 400	28 x 4	0.43
FDC4	20	box, field shaping	xyx'y'xyx'y'x	600 x 400	16 x 9	2.7
CVC	~7	hexagonal	xx'xx'	half cylindrical	20 x 4	0.37
PDCL	10	Walenta	xx'yy'xx'yy'	140 x 140	8 x 8	0.67
PDCR	10	Walenta	xx'yy'xx'yy'	140 x 140	8 x 8	0.67
				Total #readout	896	

Electronics: ASD board --->(LVDS) ---> VME 64ch TDC (VME) -->(fiber)--> DAQ PC

Gas: He+50%C_2H_6 or He+60%CH_4

Readiness

(1) Most detectors/targets are from HIMAC exp.

(2) to be constructed

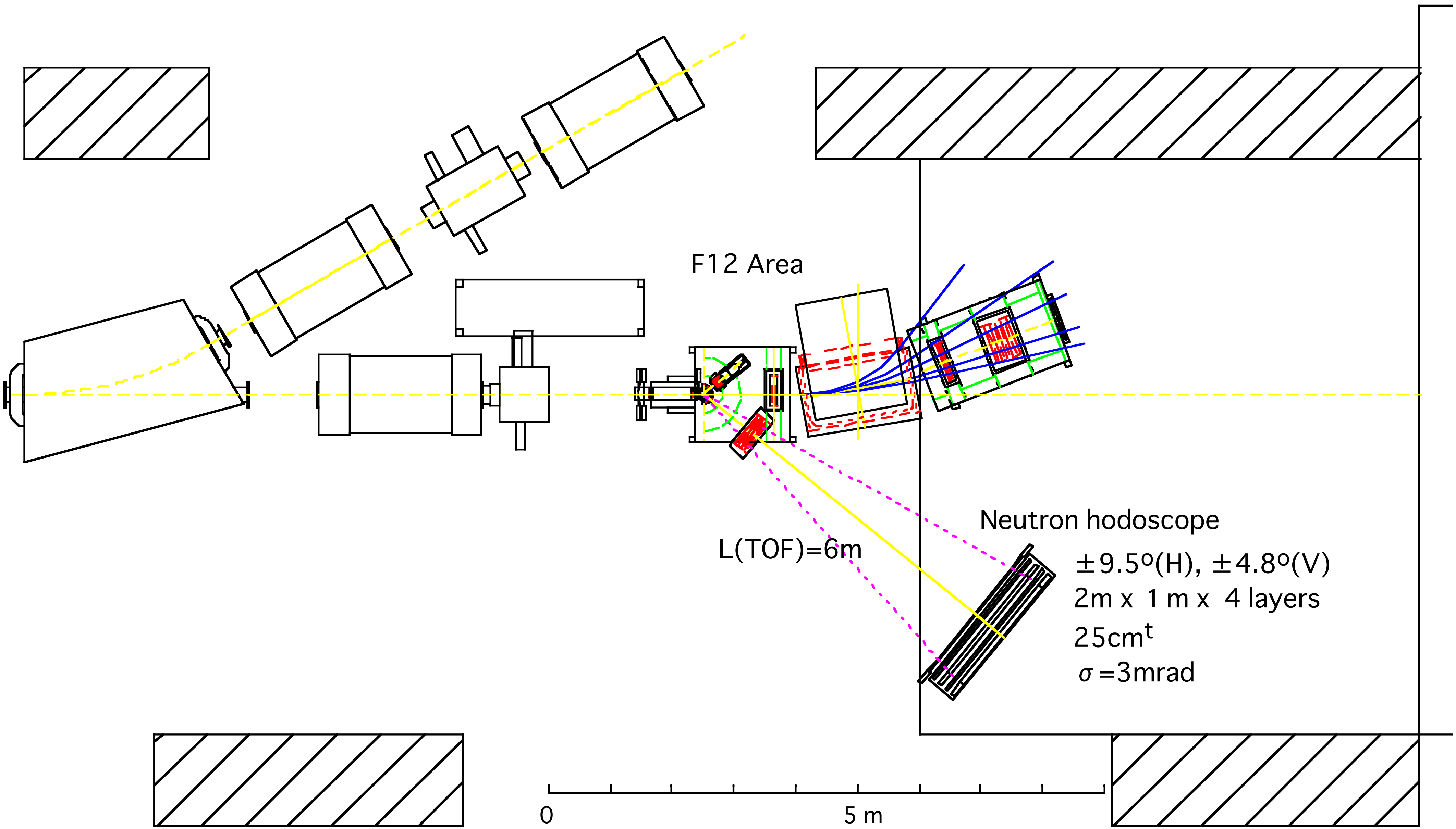
- Detectors
  - Beam MWPC @F5 — momentum tagging in vacuum
  - Vertex chamber around SHT — improve angular resolution
- Detector Stands
  - Spacer stand for (p,2p) stand
  - Downstream tracking detetors (FDC3/FDC4)

(3) Magnetic Spectrometer

- Kappa magnet: transfer from KEK, re-assembly
- Power Supply: transformer (6.6kV → 3.3kV)
  - power line between PS & magnet — need utilities
- Cooling System

(4) Ligth Ion Beam ?

Future Option1: (p,pn) Neutron Knockout Reaction



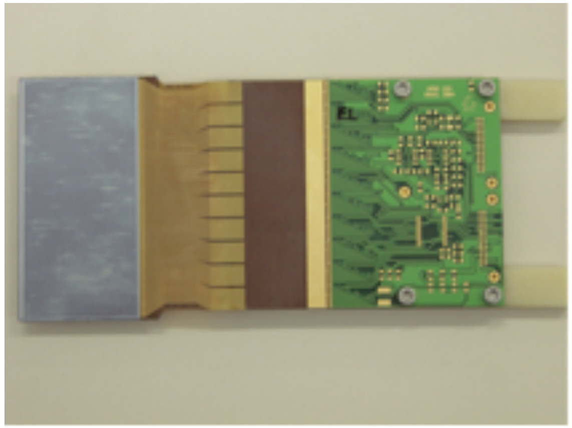
Future Option2 : larger solid angle

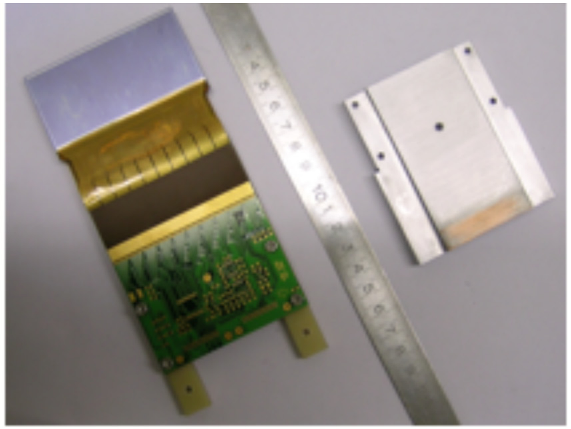
Drift Chamber + NaI(Tl) : Ω～0.1sr/arm

↓ larger angular coverage～weaker beam

(100+300um) DSSM + CsI(Tl)/PD

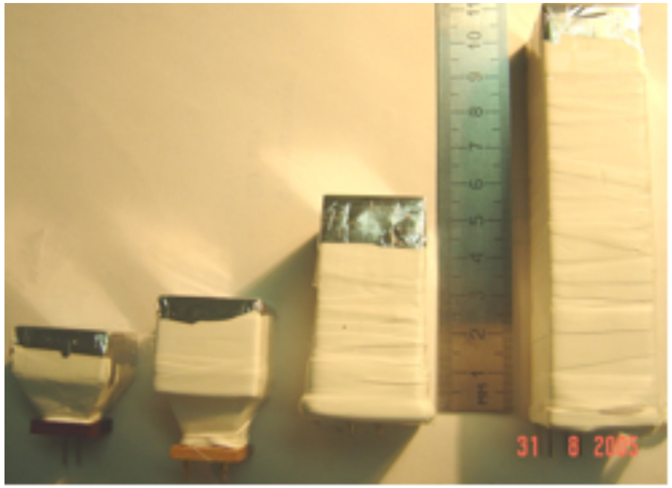
Daresbury / GSI





70mm x 40mm
100um pitch

JINR



50mm x 100mm x 100mm

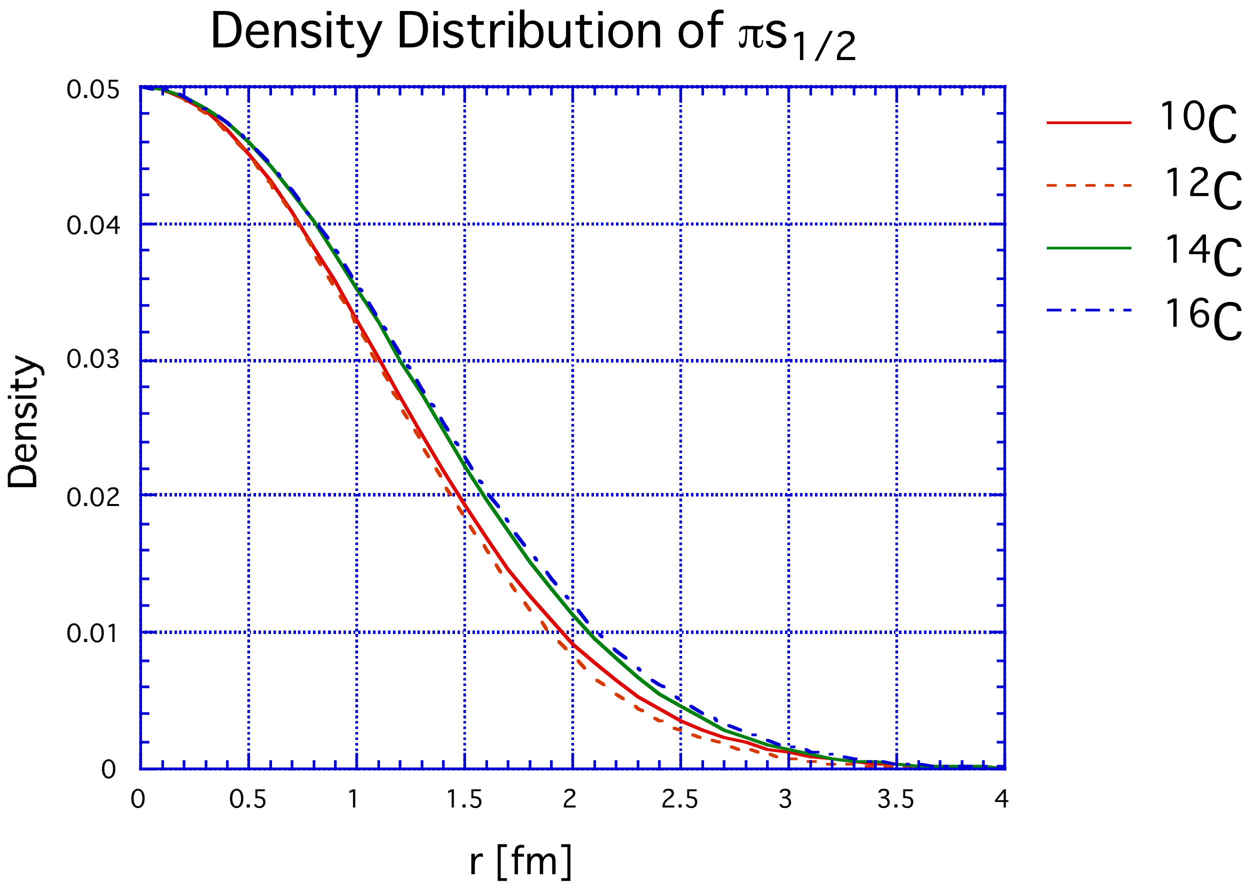
Resolution @250MeV/A (Simulation)

	Separation energy E_s	Momentum $q_{//}$	Momentum $q_{\perp}$
(1) Beam momentum	$\sigma(E_s) \approx 5\frac{\sigma_p}{p}$ MeV		
(2) Scattering angle	$\sigma(E_s) \approx 0.21\sigma_\theta$ MeV/mrad	$\sigma(q_{//}) \approx 0.21\sigma_\theta$	$\sigma(q_{\perp}) \approx 0.45\sigma_\theta$ MeV/c/mrad
(3) Proton energy	$\sigma(E_s) \approx 0.36\frac{\sigma_T}{T}$ MeV/%	$\sigma(q_{//}) \approx 2.6\frac{\sigma_T}{T}$	$\sigma(q_{\perp}) \approx 1.4\frac{\sigma_T}{T}$ MeV/c/%

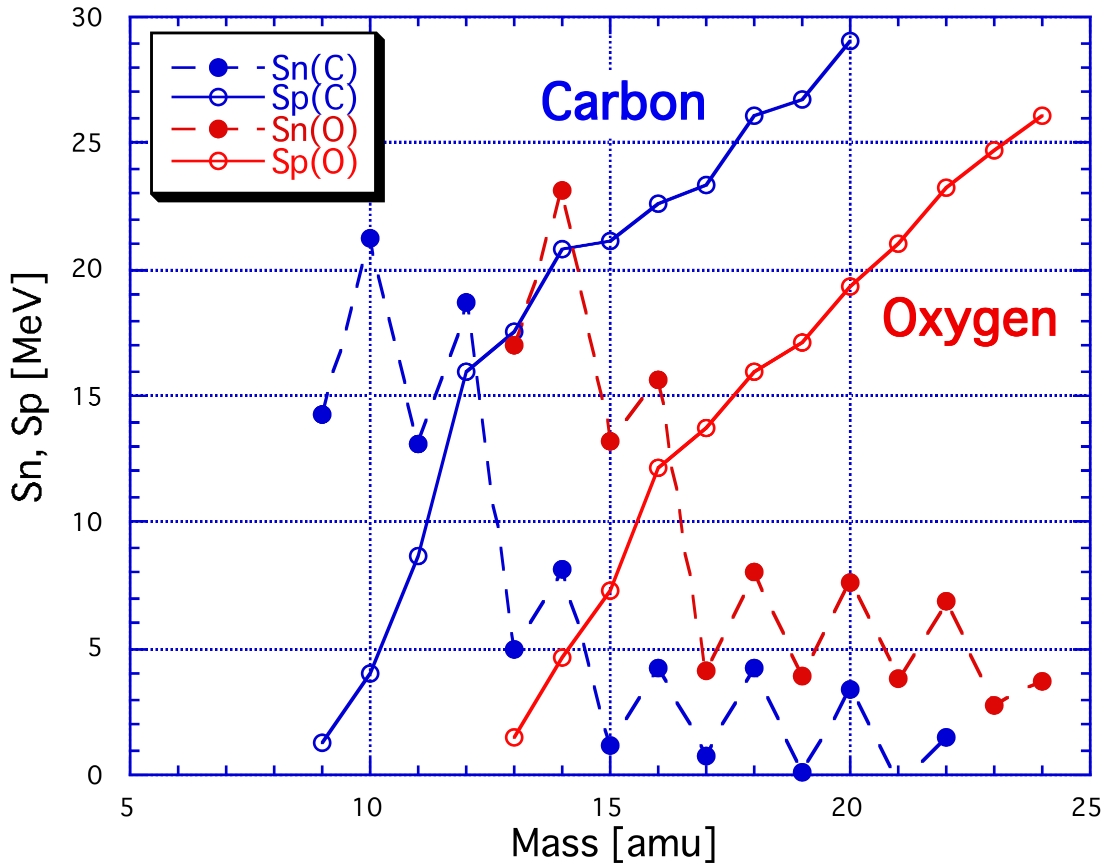
＊SHT target (5mm^t)

$L/L_R(\mathrm{SHT}) \approx 0.46\times10^{-3}$ $\sigma_{\mathrm{MCS}}(T_p = 125MeV) \approx 0.8mrad$

RMF calculation by Lwin

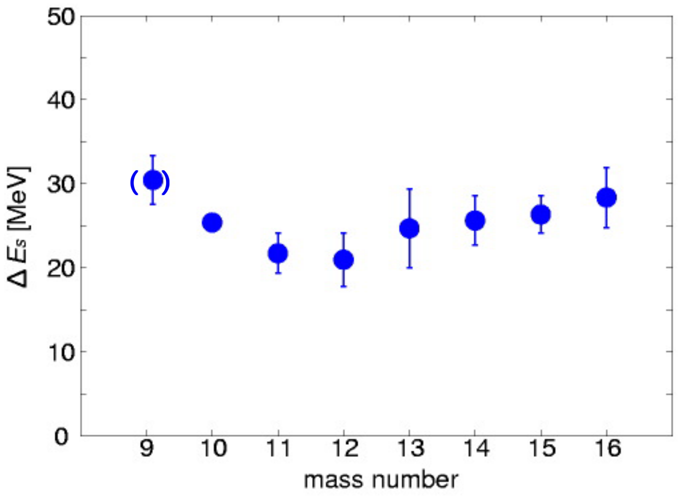


Separation Energy, S_n, S_p, in C / O Isotopes

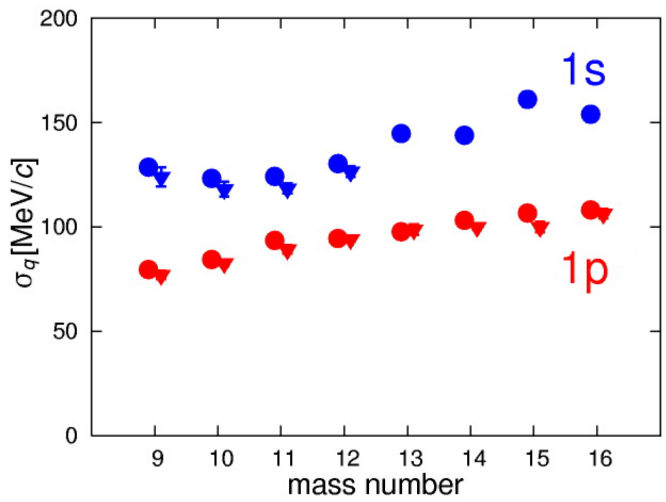


Summary of $^{9\text{-}16}$C(p,2p) @250MeV/A

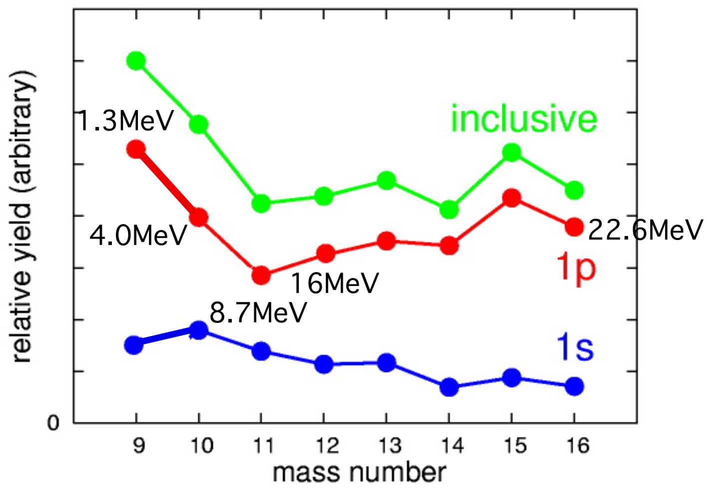
ΔE(1p-1s)



Momentum Width



Total Yield



● Inner-shell ($s_{1/2}$) orbit

∗ s-hole states

systematically observed

∗ ΔE(1p-1s)

wider at proton/neutron-rich side

∗ Momentum distribution

∗ Charge rms radii (1s)

shrinking toward neutron-rich side

● Valenceshell ($p_{3/2}$) orbit

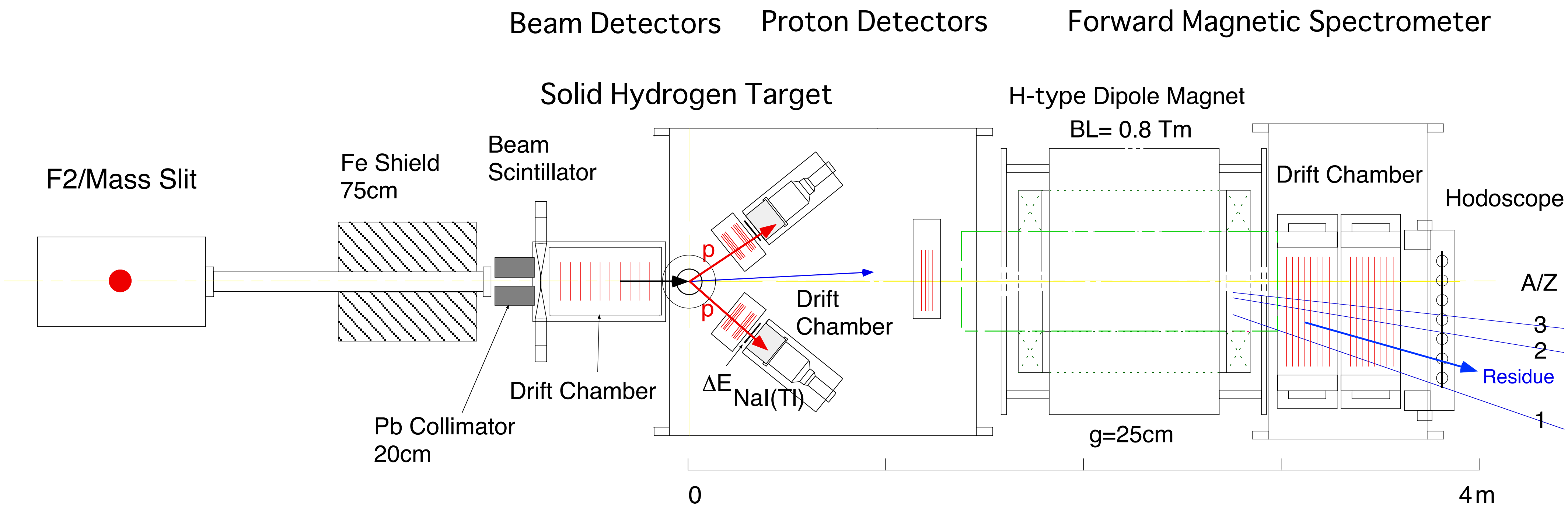
∗ momentum distribution

∗ Total yield

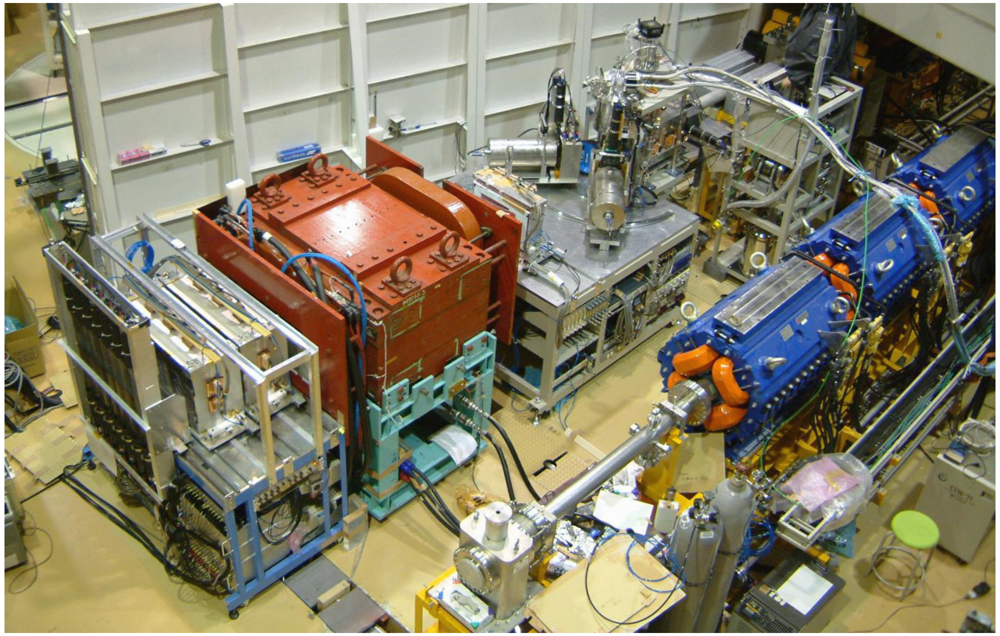
Y(^{12}C)/Y(^{9}C)〜60%

S-factor(?)

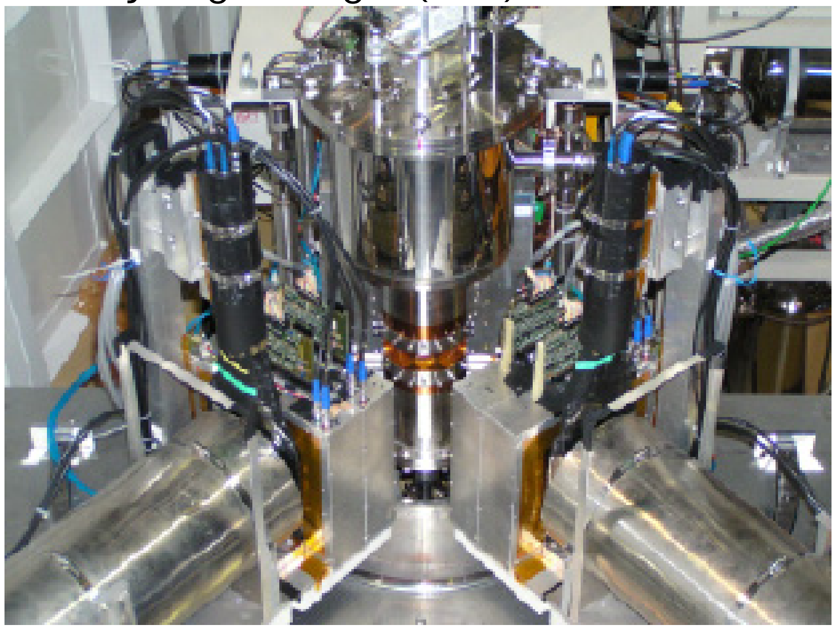
Experimental Setup @HIMAC



Setup from downstream side

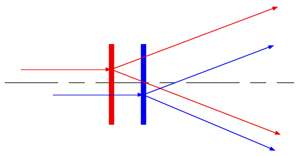


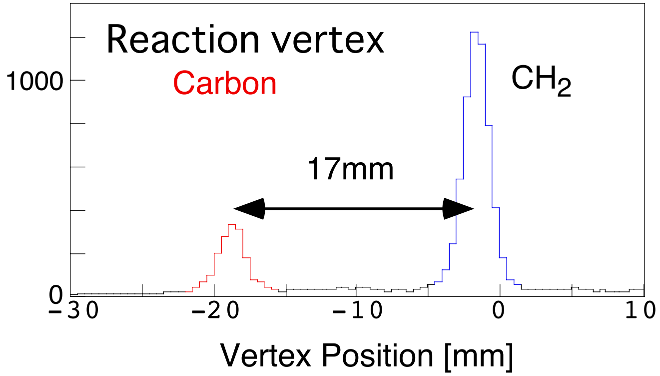
Solid Hydrogen Target (SHT)

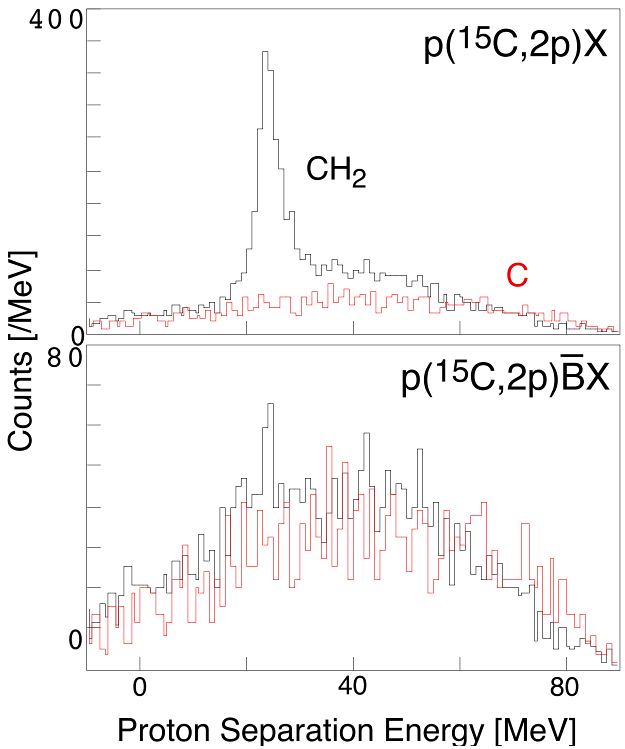


Hydrogen Target

● CH_2(100mg/cm^2)-C(50mg/cm^2)

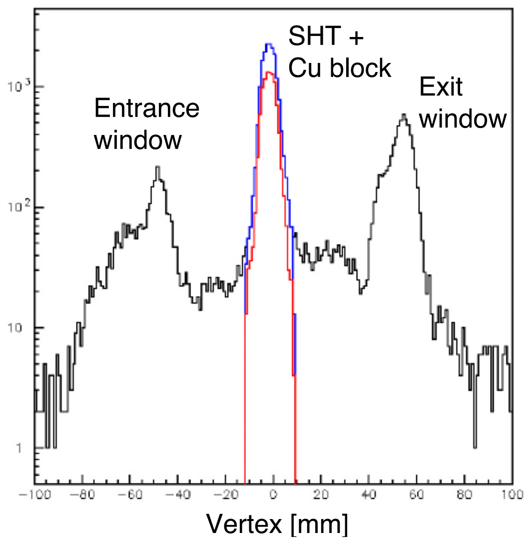


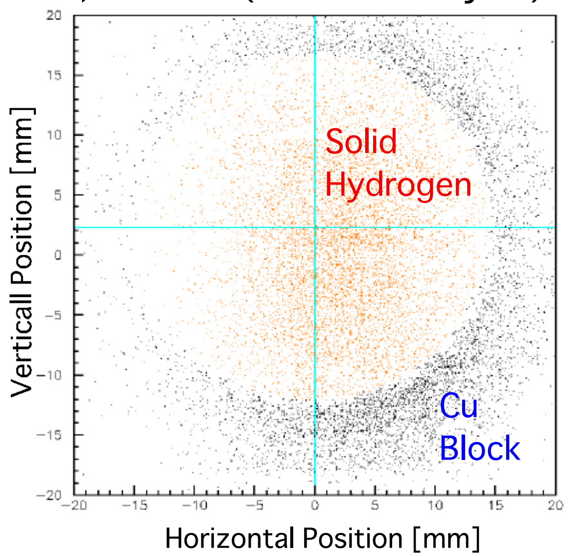


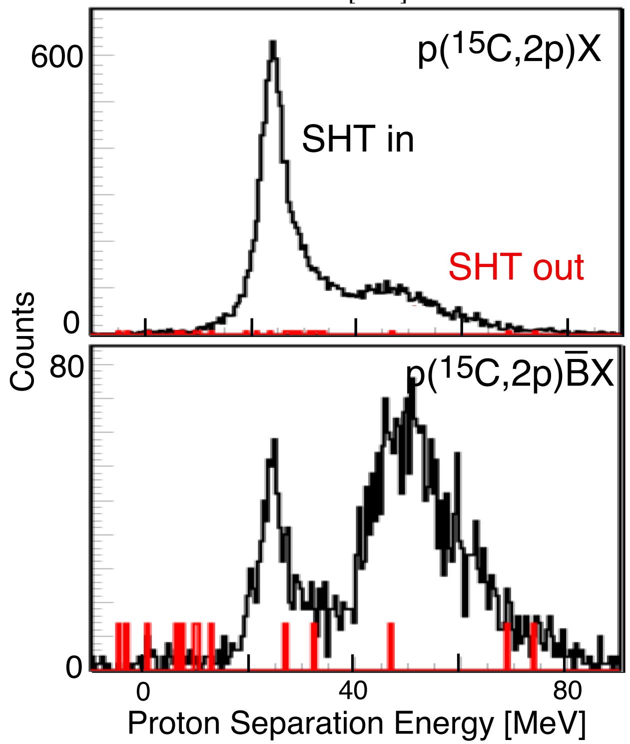


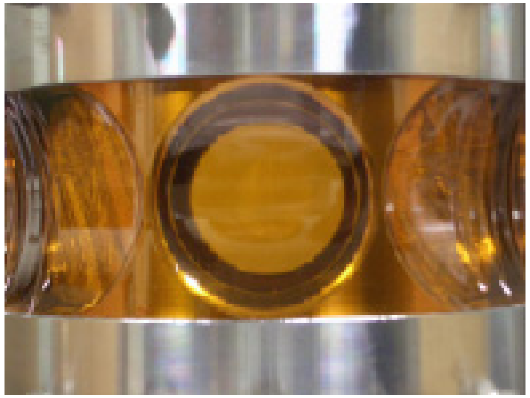
●Solid Hydrogen Target :

30mmϕ, 5mm t (W : 9μm Mylar)





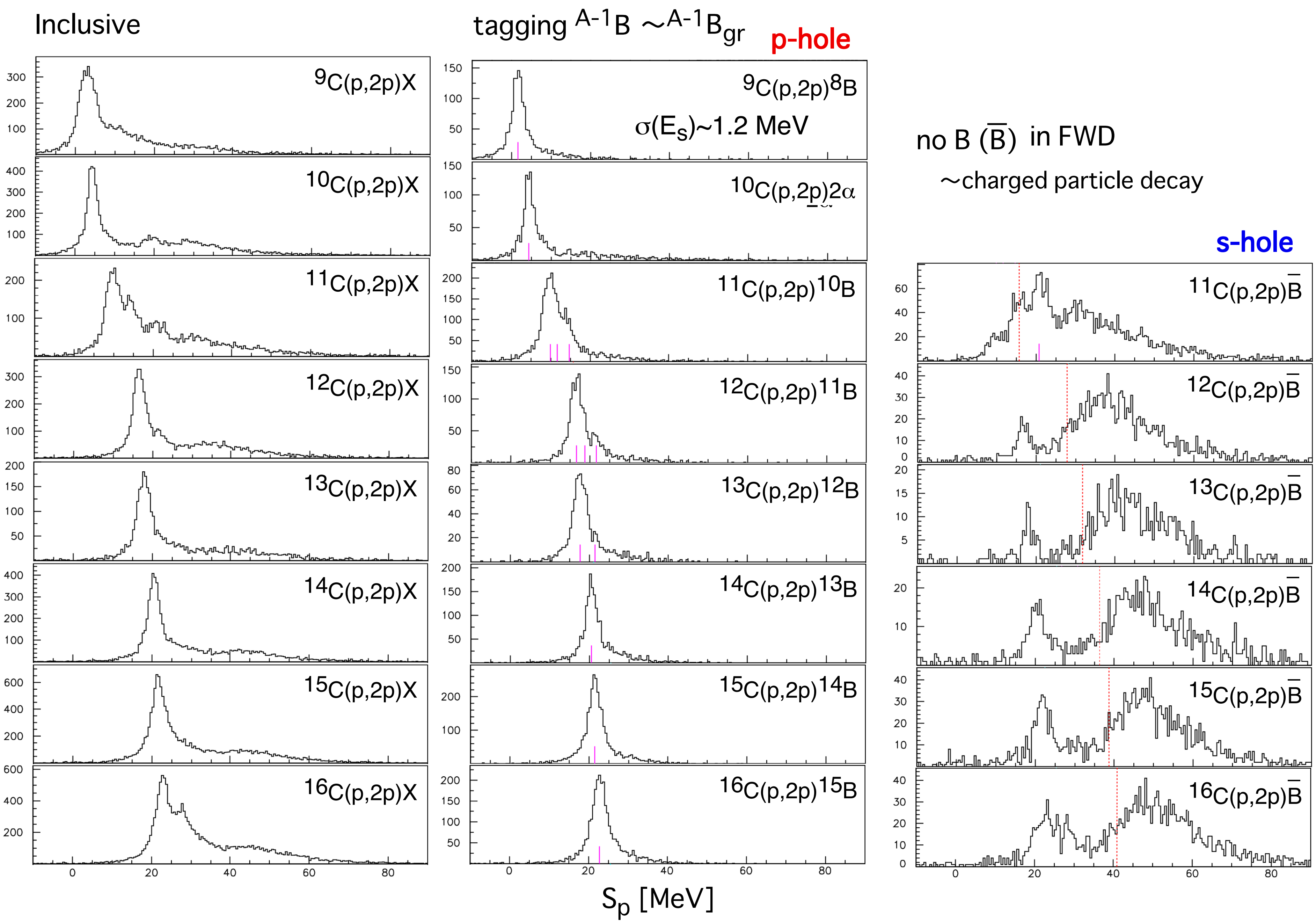




Target : thickness 44 mg/cm^2 ~CH_2 3mmt

Vac window : 50μm kapton

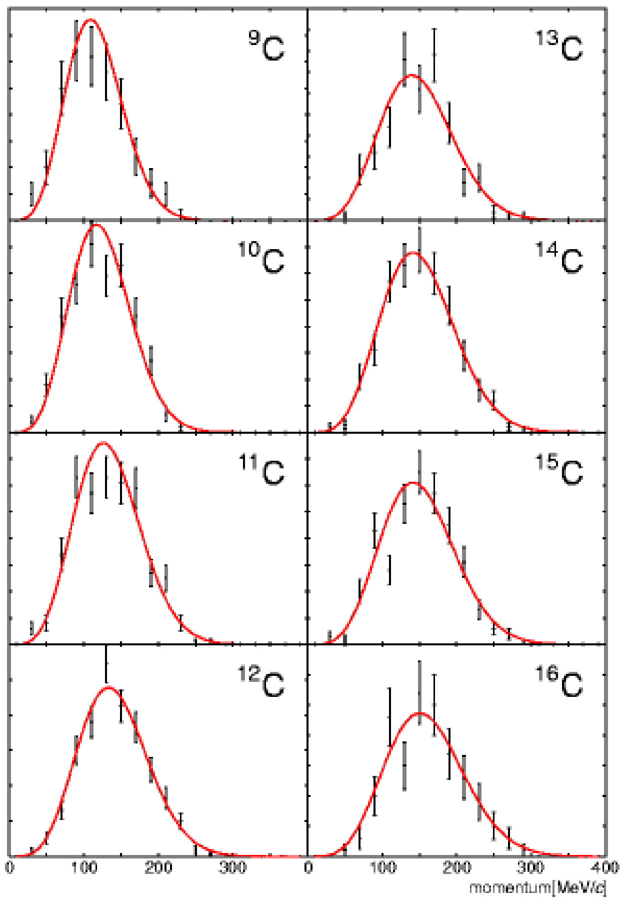
$^{9-16}$C(p,2p) S_p Distribution



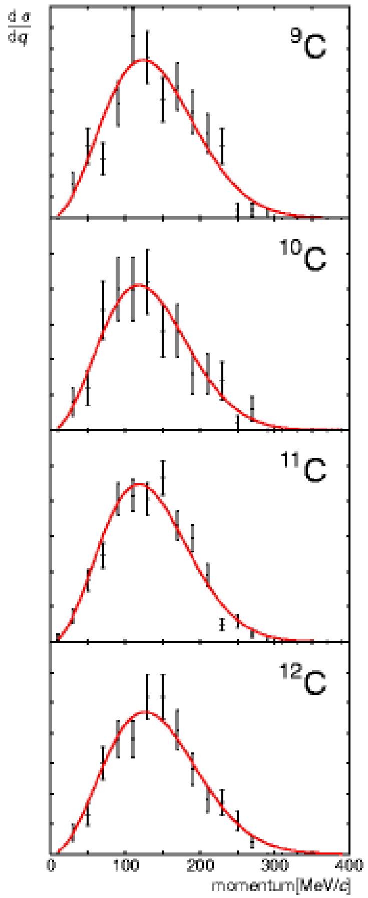
Momentum distribution

$$\frac{d\sigma}{dq}$$

$1p_{1/2}$

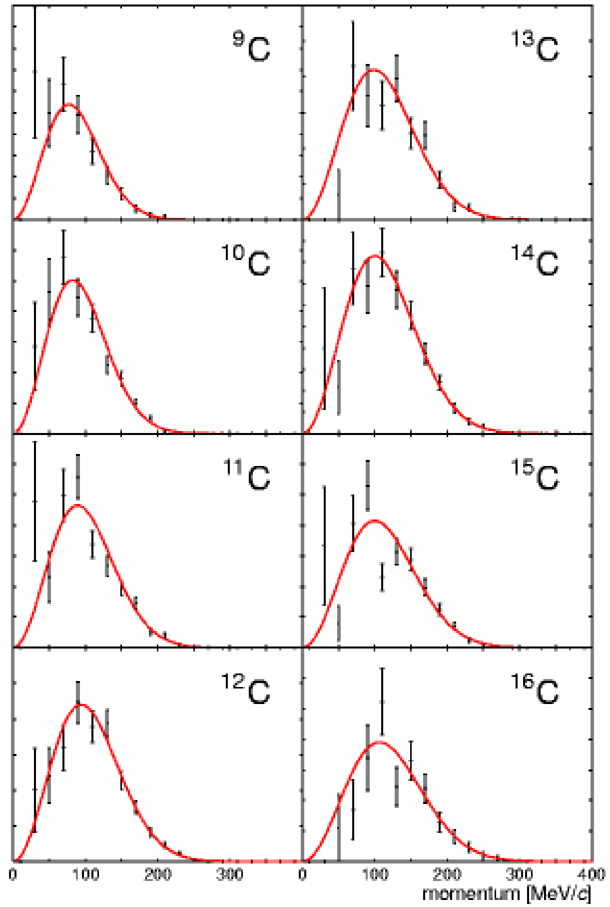


$1s_{1/2}$

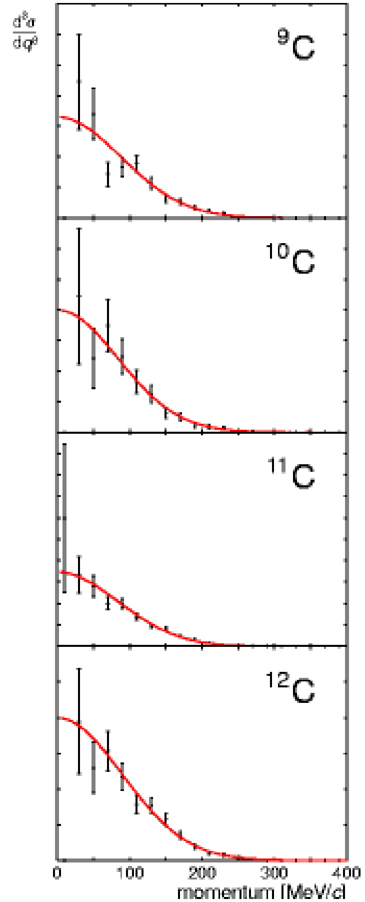


$$\frac{d^3\sigma}{d\vec{q}^3}$$

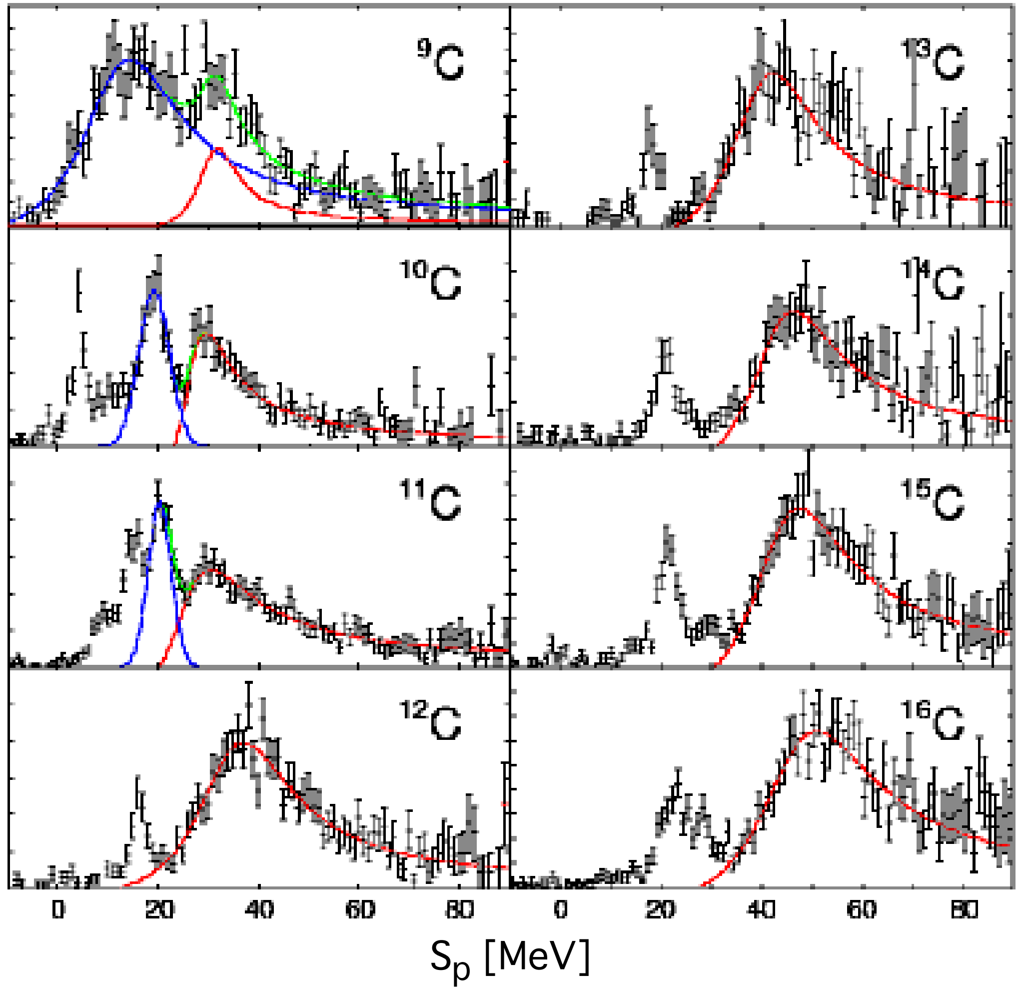
$1p_{1/2}$

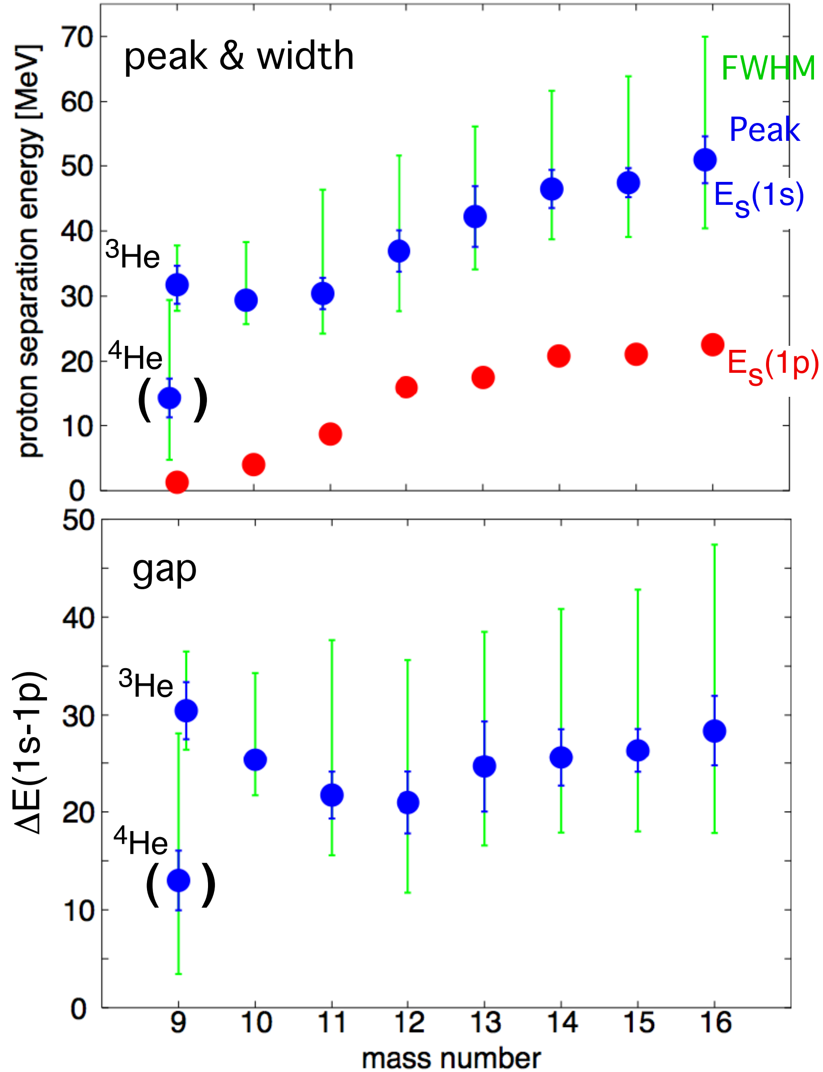


$1s_{1/2}$

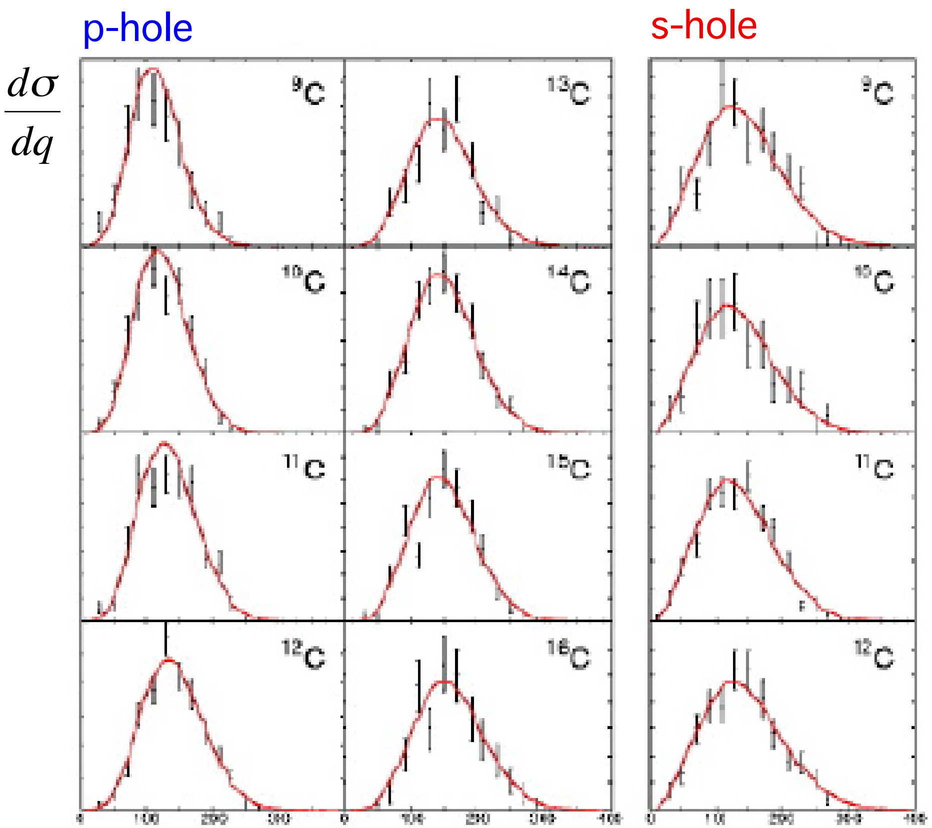


$^{9-16}C(p,2p)$ s-hole states



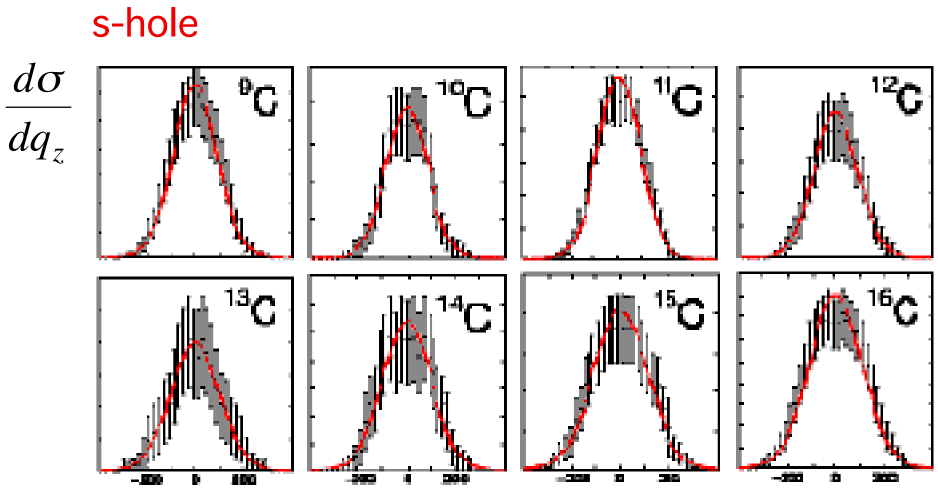


$^{9-16}C(p,2p)$ Momentum Distribution

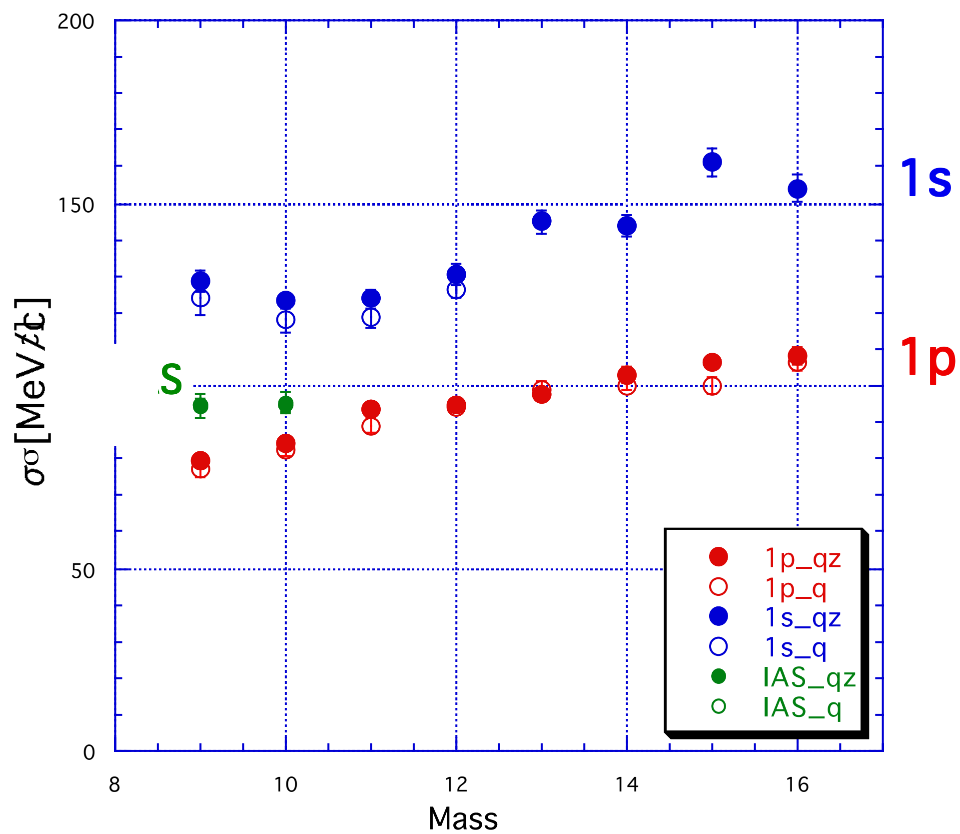


Assume : Harmonic Oscillator

$$\frac{d^3\sigma_l}{d\vec{q}^3} \propto \frac{d\sigma_l}{q^2 dq} \propto q^{2l} \exp\left(-\frac{q^2}{\sigma_l^2}\right)$$



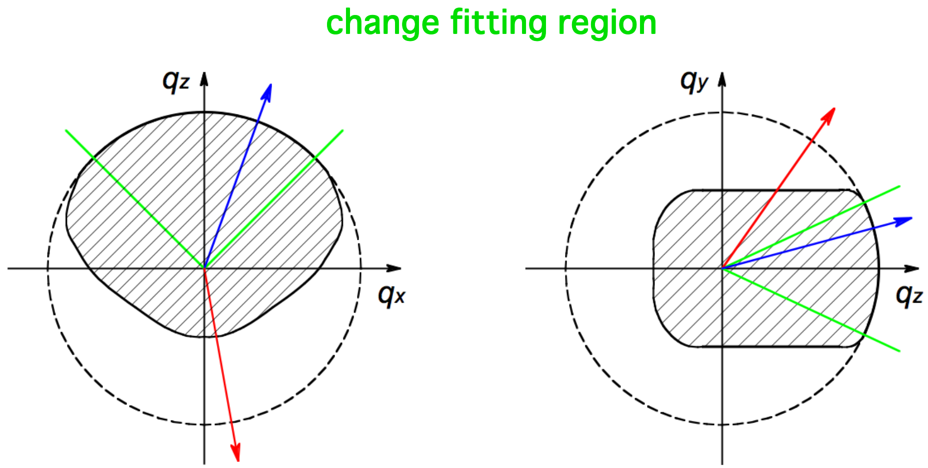
Momentum Width



Acceptance Correction by 2 methods

(1) Radial (q) distribution

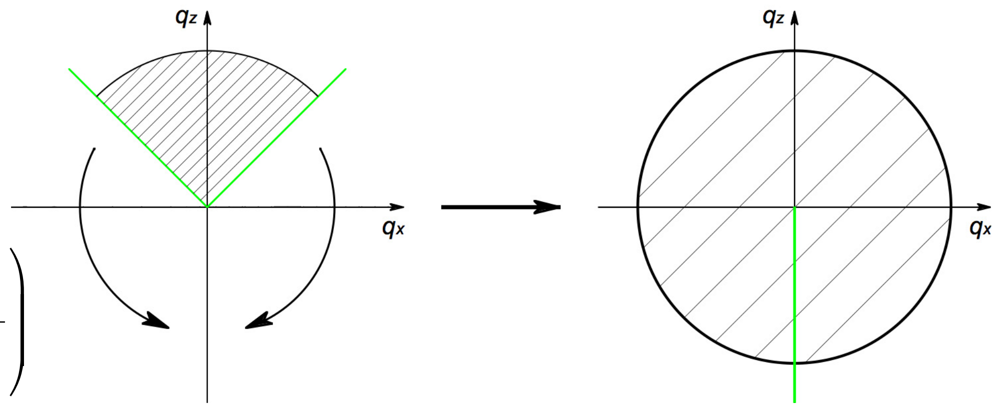
$$\frac{d\sigma_l}{dq} \propto q^{2l+2} \exp\left(-\frac{q^2}{\sigma_l^2}\right)$$



(2) q_z distribution

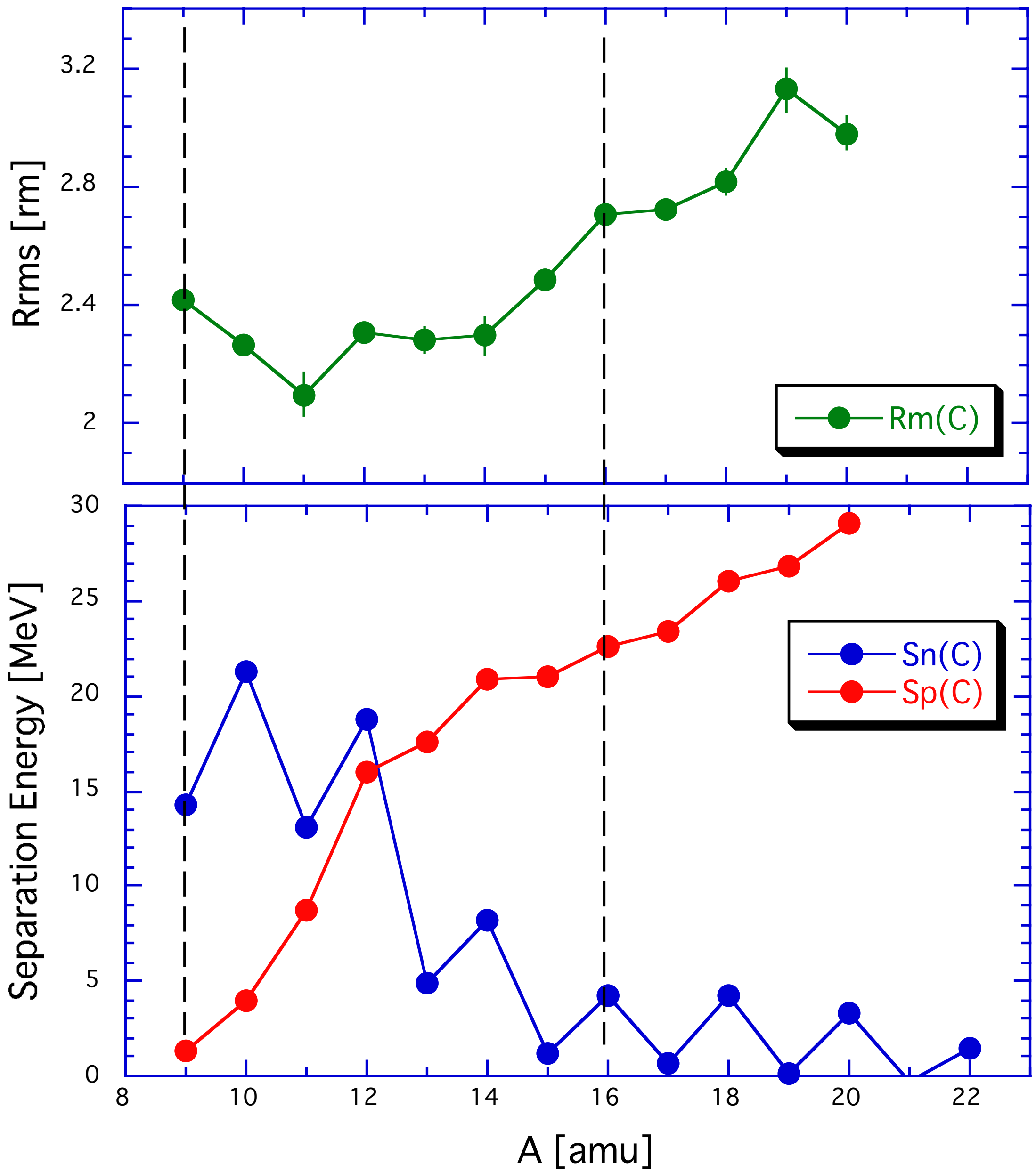
$$\frac{d\sigma_s}{dq_z} \propto \exp\left(-\frac{q^2}{\sigma_s^2}\right)$$

$$\frac{d\sigma_p}{dq_z} \propto \left(q_z^2 + a\sigma_p^2\right)\exp\left(-\frac{q^2}{\sigma_p^2}\right)$$

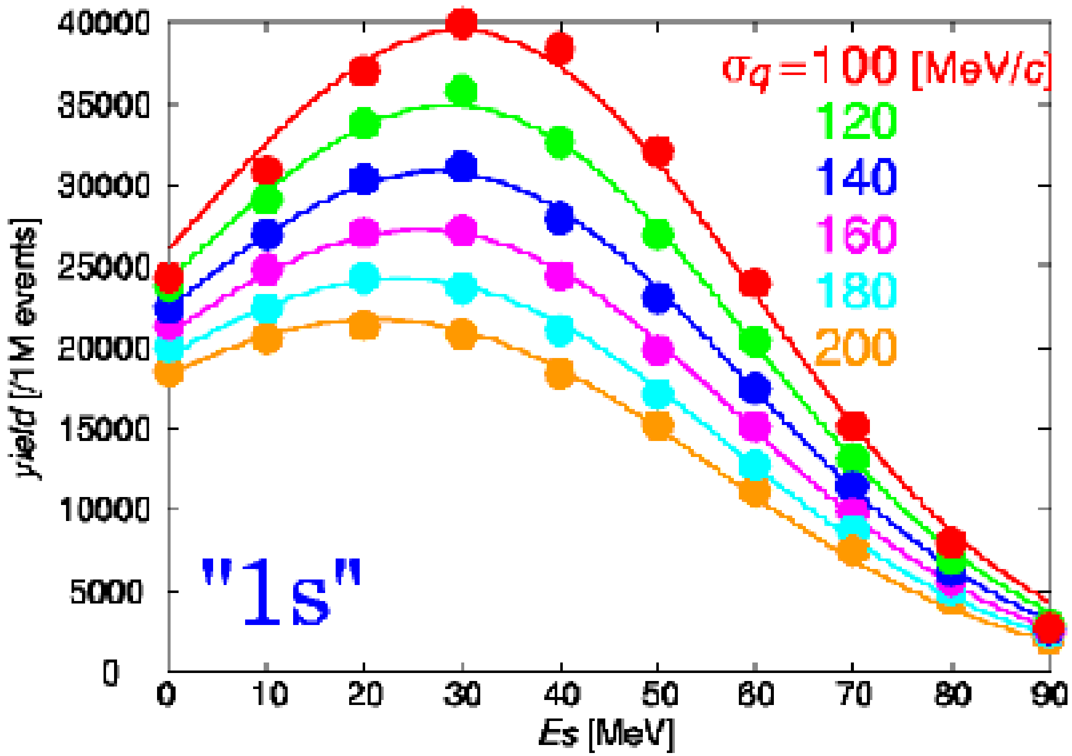


cf $\frac{d\sigma_p}{dq_z} = \int \frac{d^3\sigma_p}{d\vec{q}^{\,3}} dq_x dq_y \propto \left(q_z^2 + \sigma_p^2\right)\exp\left(-\frac{q_z^2}{\sigma_p^2}\right)$

Carbon Isotopes



Acceptance

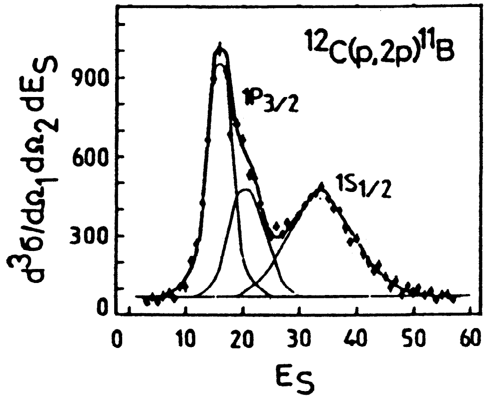


σ_q=100 [MeV/c]
120
140
160
180
200
"1s"
yield [/1M events]
Es [MeV]
40000
35000
30000
25000
20000
15000
10000
5000
0
0 10 20 30 40 50 60 70 80 90

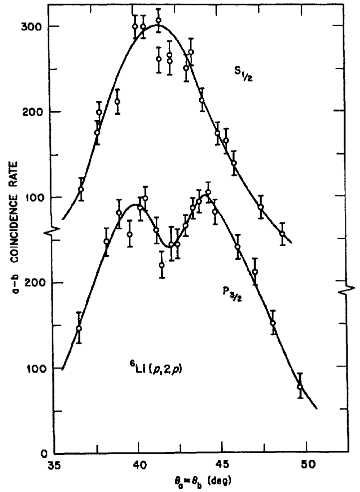
Proton-induced (p,pN) Reaction

- (p,pp) in 60's-70's
  Beam energy : 150-1000 MeV @synchro-cyclotrons
  Resolution : ~4 MeV FWHM each orbits roughly separated

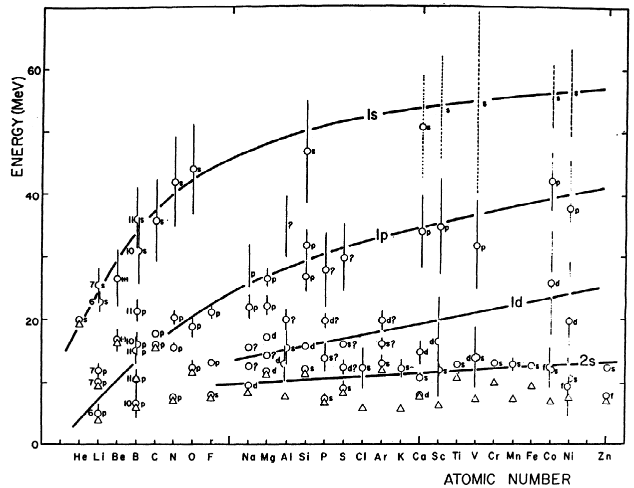
Separation Energy



Momentum Distribution

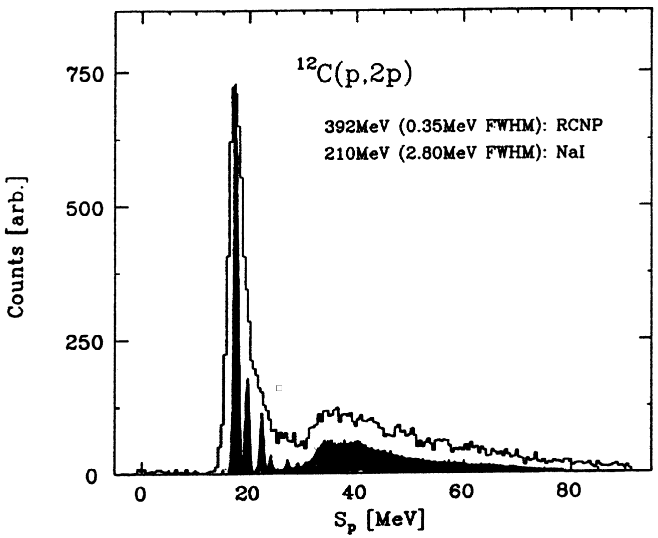


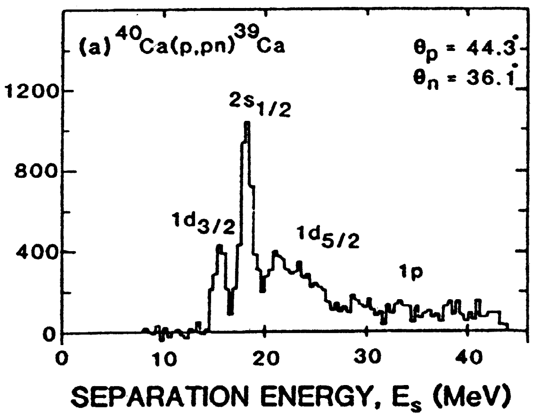
Binding Energy



R. of Mod. Phys. 1973

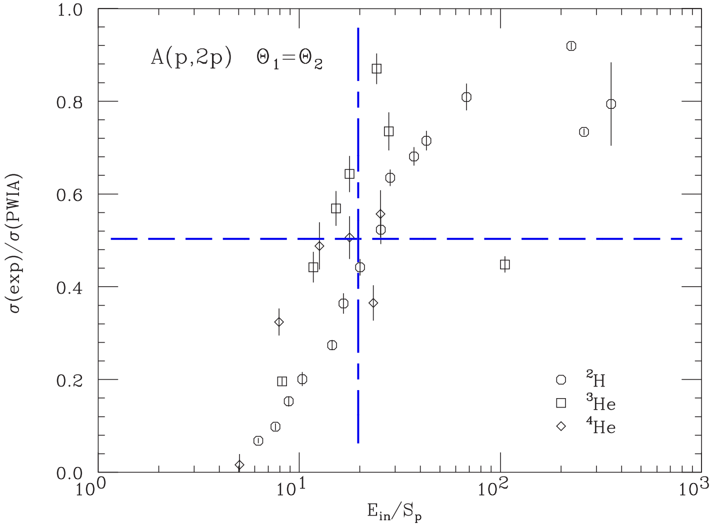
- High-Resolution Mesasurement (p,pp) & (p,pn)
  @RCNP(400MeV), IUCF(150MeV),





Beam energy-1

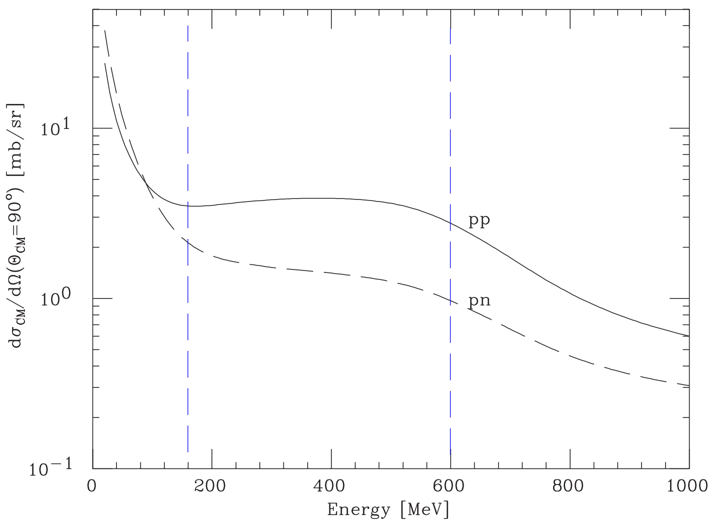
(1) Knockout cross section : Energy dependence



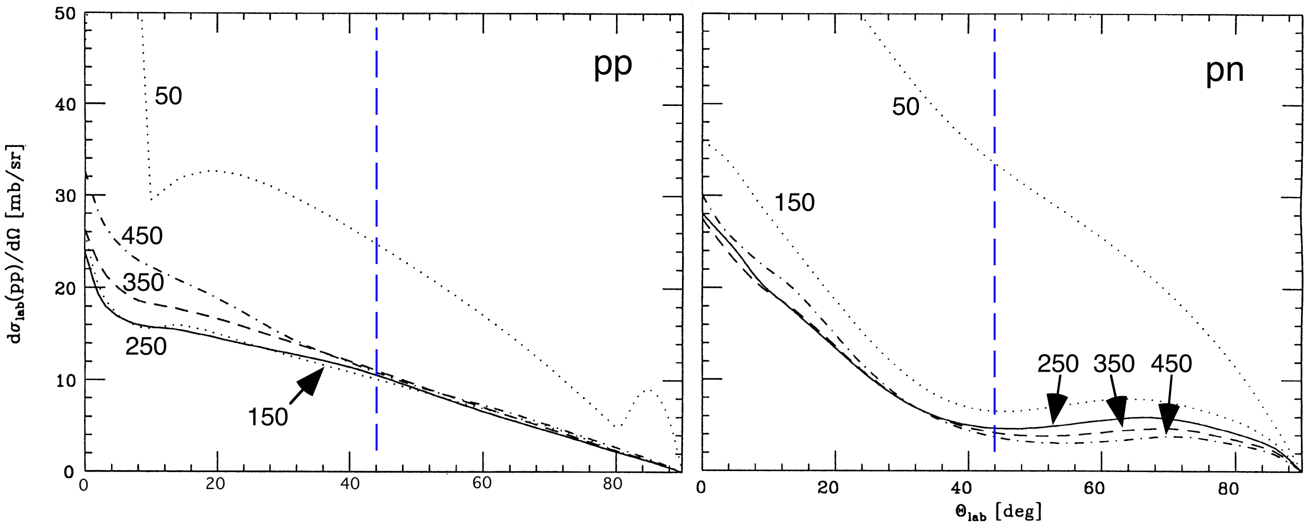
d, ^{3,4}He(p,2p) S_p= 2.2, 5.5, 20.0 MeV

$N_{eff} ≒ 0.5xN_{real}$ @$E_{in} ≒ 20xS_p$

(2) N-N cross section @Θ_{cm} 90^o

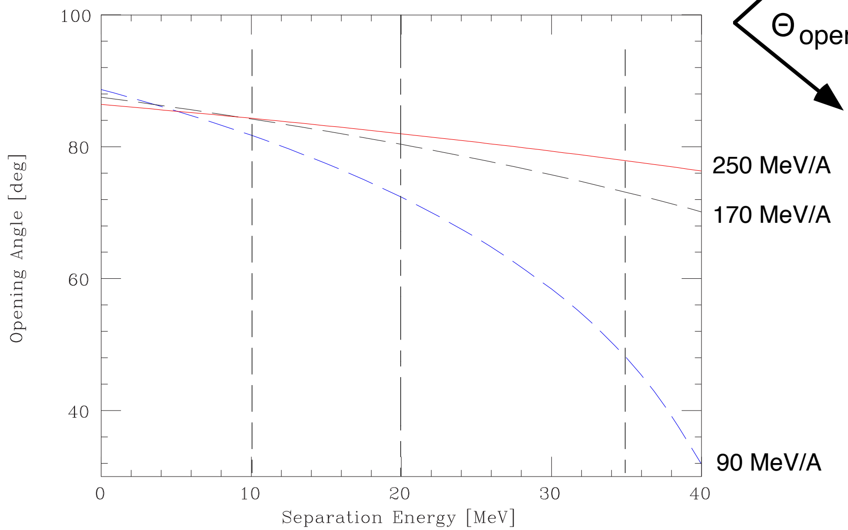


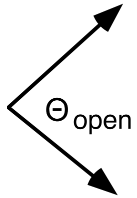
Angular distribution of N-N (lab)

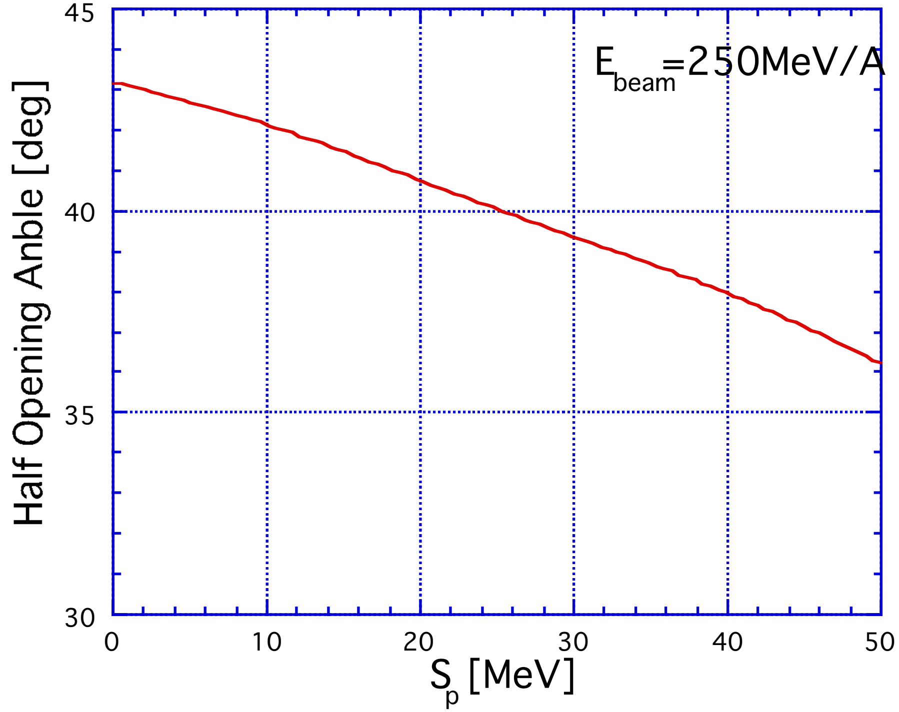


Beam energy-2

(4) Opening Angle of N-N







(5) Proton detection

$\langle E_p \rangle$ ≒ $E_{beam}/2$, E_{p_max} ≒ E_{beam} ~30% reaction loss @E_p~200MeV

$p(^6He,pn)^5He$, $p(^{11}Li,pn)^{10}Li$ Experimental Setup

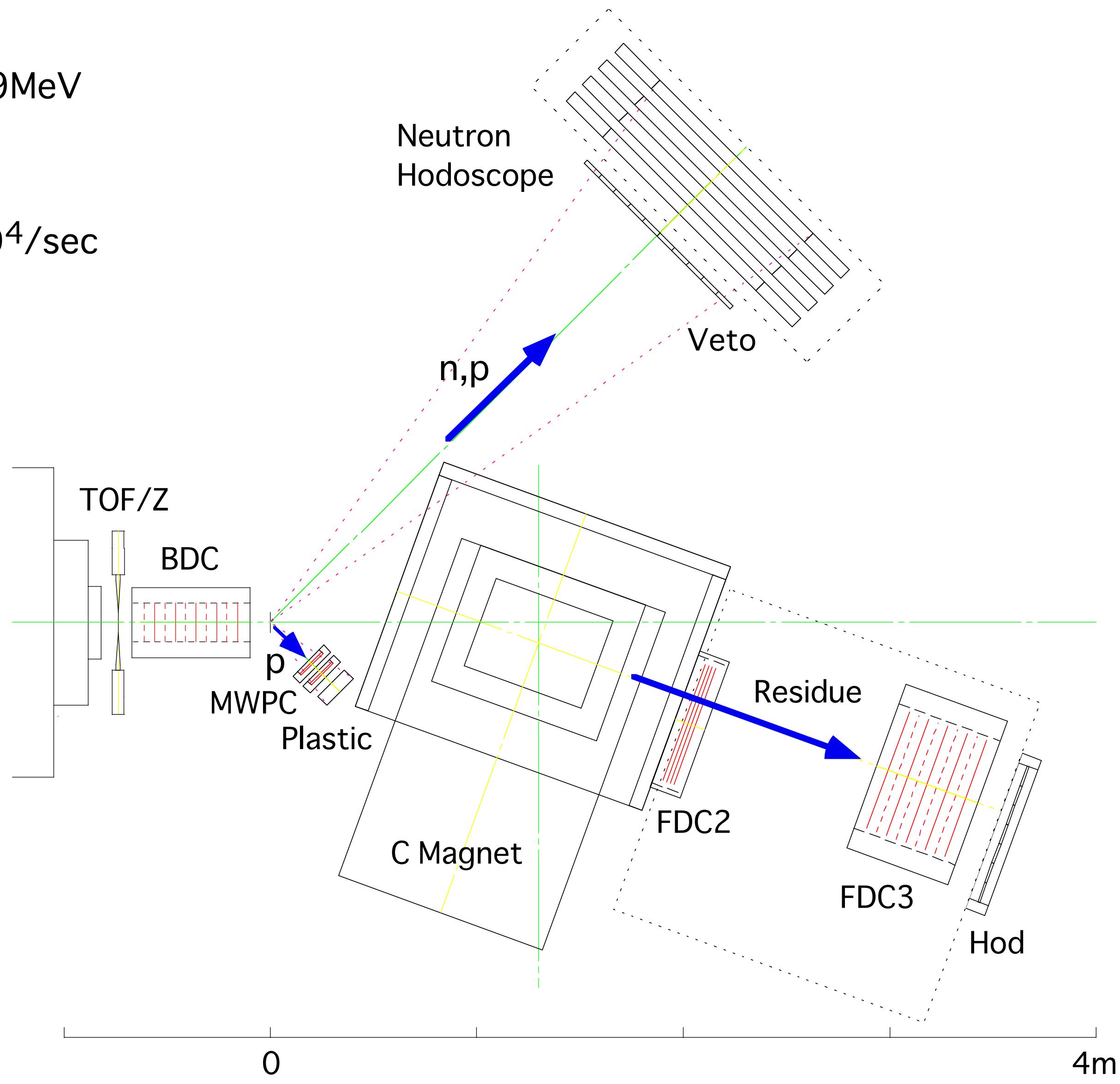
2 weakly-bound valence neutrons

$S_n(^{11}Li) \sim 0.7$MeV , $S_n(^6He) \sim 1.9$MeV

RIKEN / RIPS

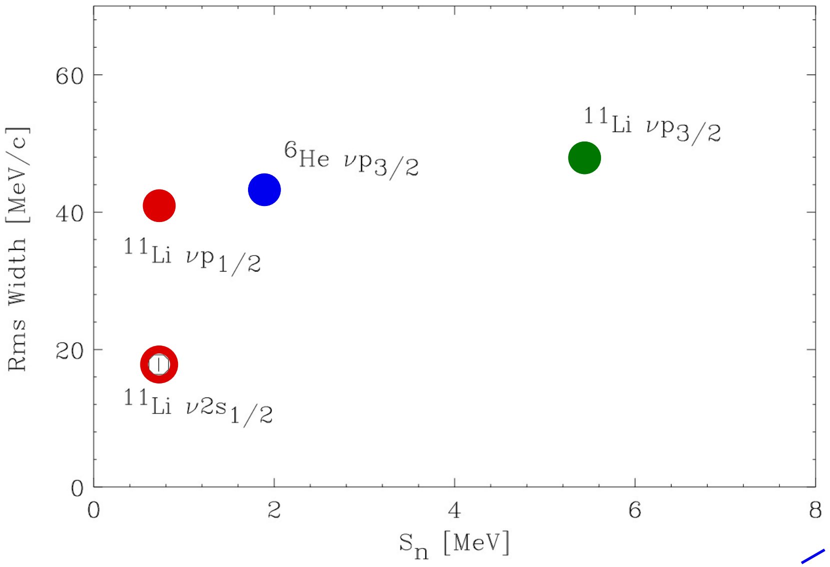
beam: E_B= 85MeV/A, $I_B \sim 10^4$/sec

target: 0.1-0.2g/cm^2 CH_2

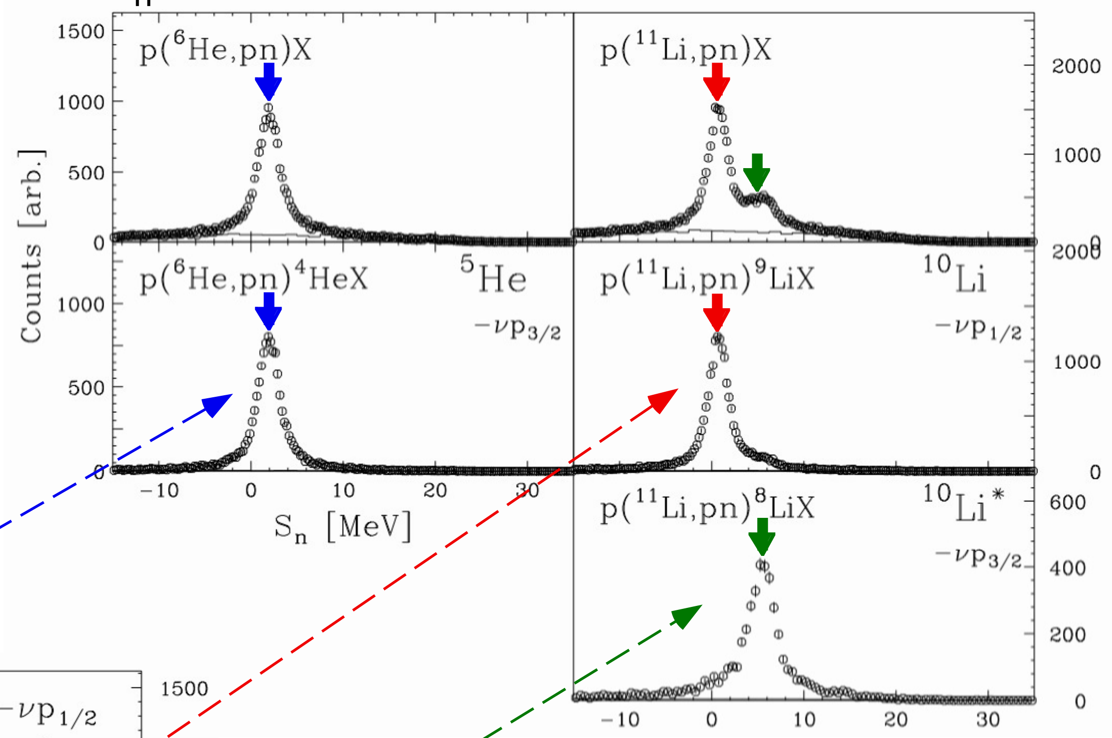


$p(^6He,pn)^5He$, $p(^{11}Li,pn)^{10}Li$ Summary

Momentum Width

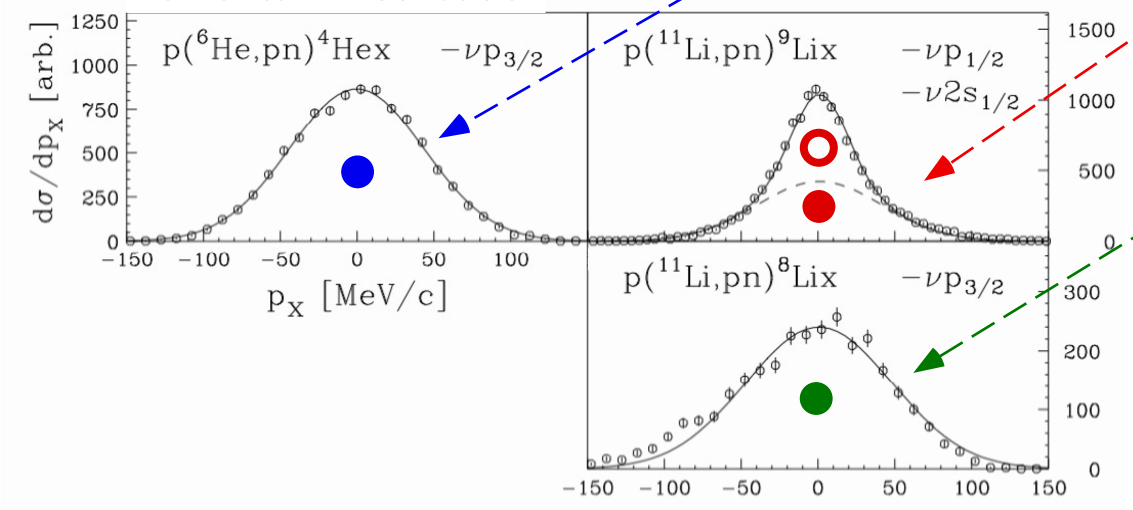


S_n Distribution



$\sigma(S_n) \sim 1.1$MeV

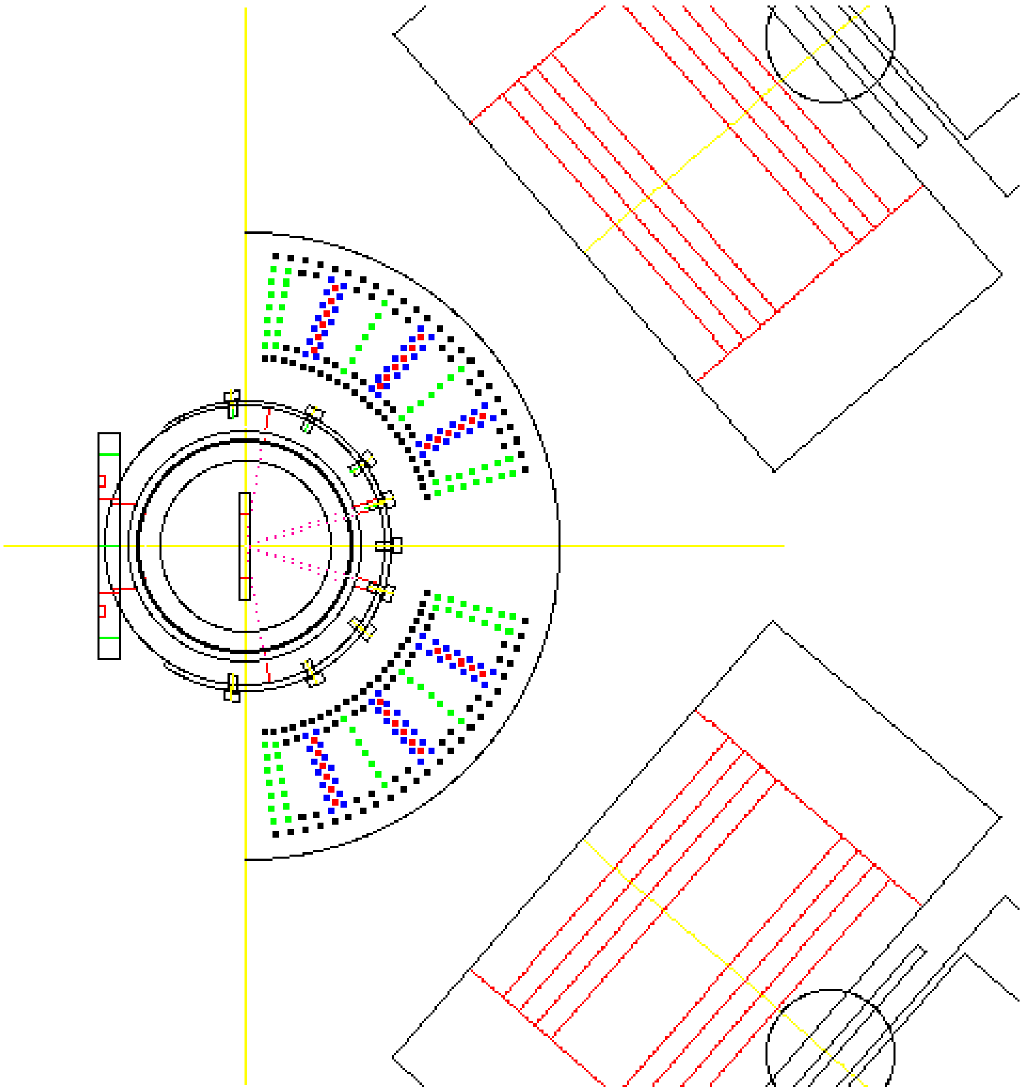
Momentum Distribution



$\sigma(q) \sim 8$ MeV/c

* Momentum distribution
  of single valence neutron
  w/o exclusive mes.
* Width
  $\nu p_{1/2}(^{11}Li) \sim \nu p_{3/2}(^{11}Li) \sim \nu p_{3/2}(^6He)$
  $>> \nu 2s_{1/2}(^{11}Li)$

Vertex Chamber



Hexagonal structure
or
Jet-type