(p,2p) Reactions on $^{9\text{-}16}C$ at 250 MeV/A

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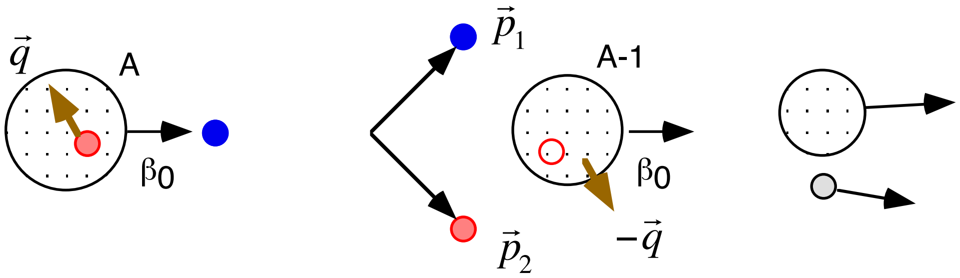
Single-Particle Motion in Unstable Nuclei

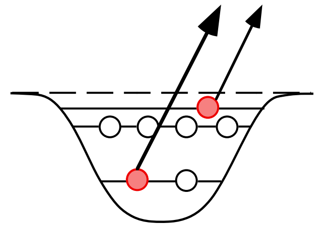
e beam: (e,e'p)
p beam: (p,2p), (p,pn)

Nucleon knockout Reactions, (p,2p) & (p,pn), in Inverse Kinematics



(A-1) System
(Hole State)

Decay of
Hole State



Coincidence Measurements of forward particles

Decay Mode of Hole State with high efficiency

Nucleon knockout via quasi-free N-N scattering

Beam energy : need to be "high"

Measured Quantities

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, $\mathbf{S_p}$)

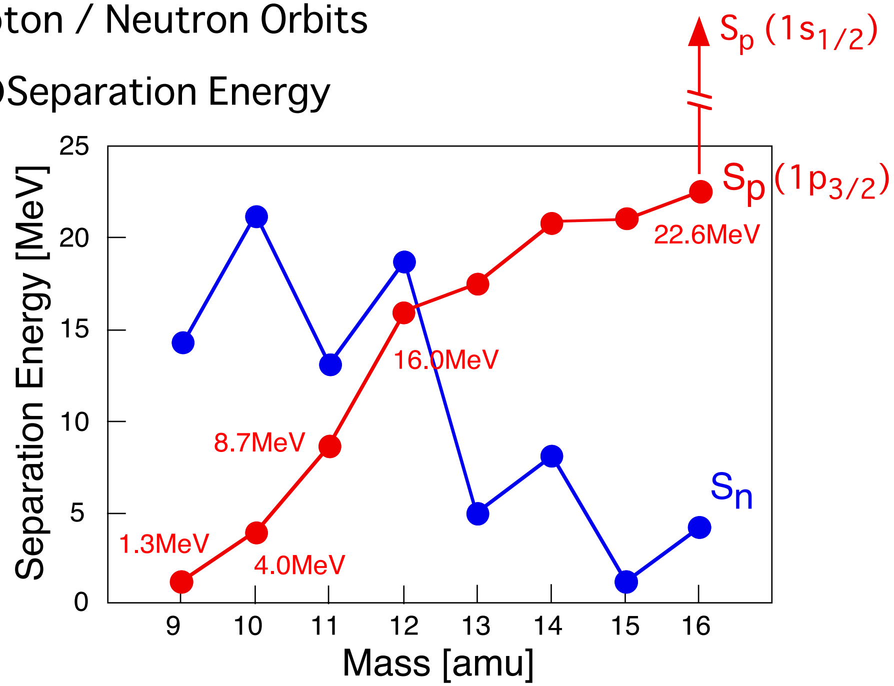
$$E_s = T_0 - \gamma\left(T_1 + T_2\right) - 2(\gamma - 1)m_p + \beta\gamma\left(\vec{p}_1 + \vec{p}_2\right)_{//} - \frac{q^2}{2M_{A-1}}$$

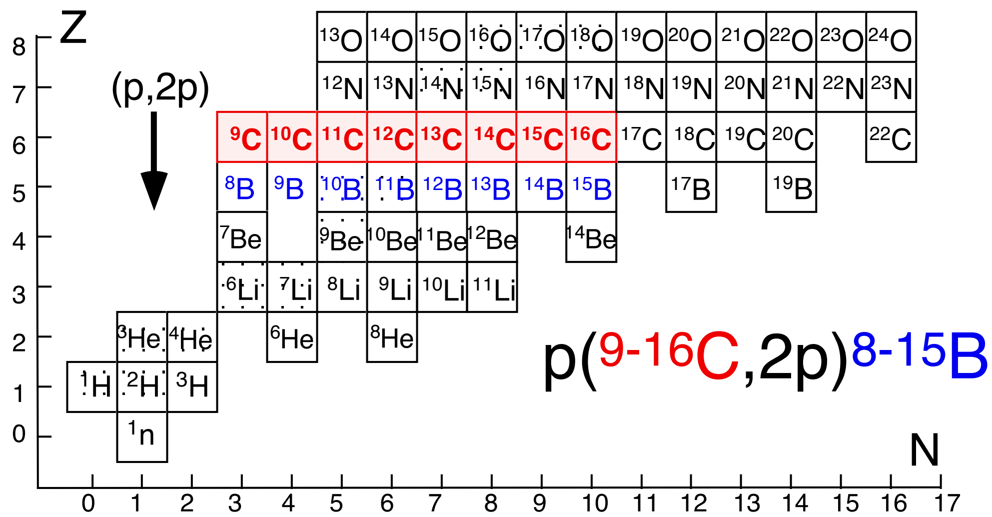
Decay Mode of Hole States

"Target" : Carbon Isotopes $^{9,10,11,12,13,14,15,16}C$

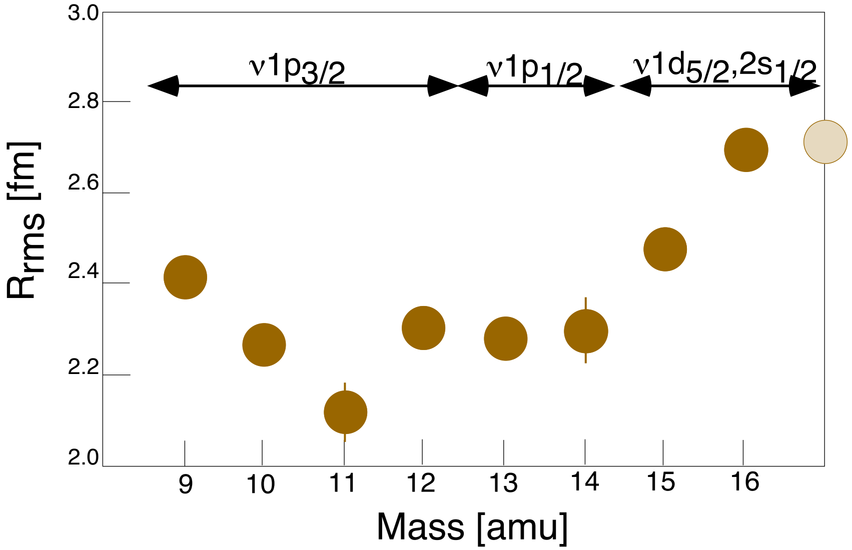
Proton / Neutron Orbits

● Separation Energy





● Root Mean Square (rms) Radii



○ Proton "p"-orbit (L=1) valence shell

Separation Energy : Weakly-bound: $S_p(^9C)$= 1.3 MeV
to
Strongly-bound: $S_p(^{16}C)$= 22.6 MeV

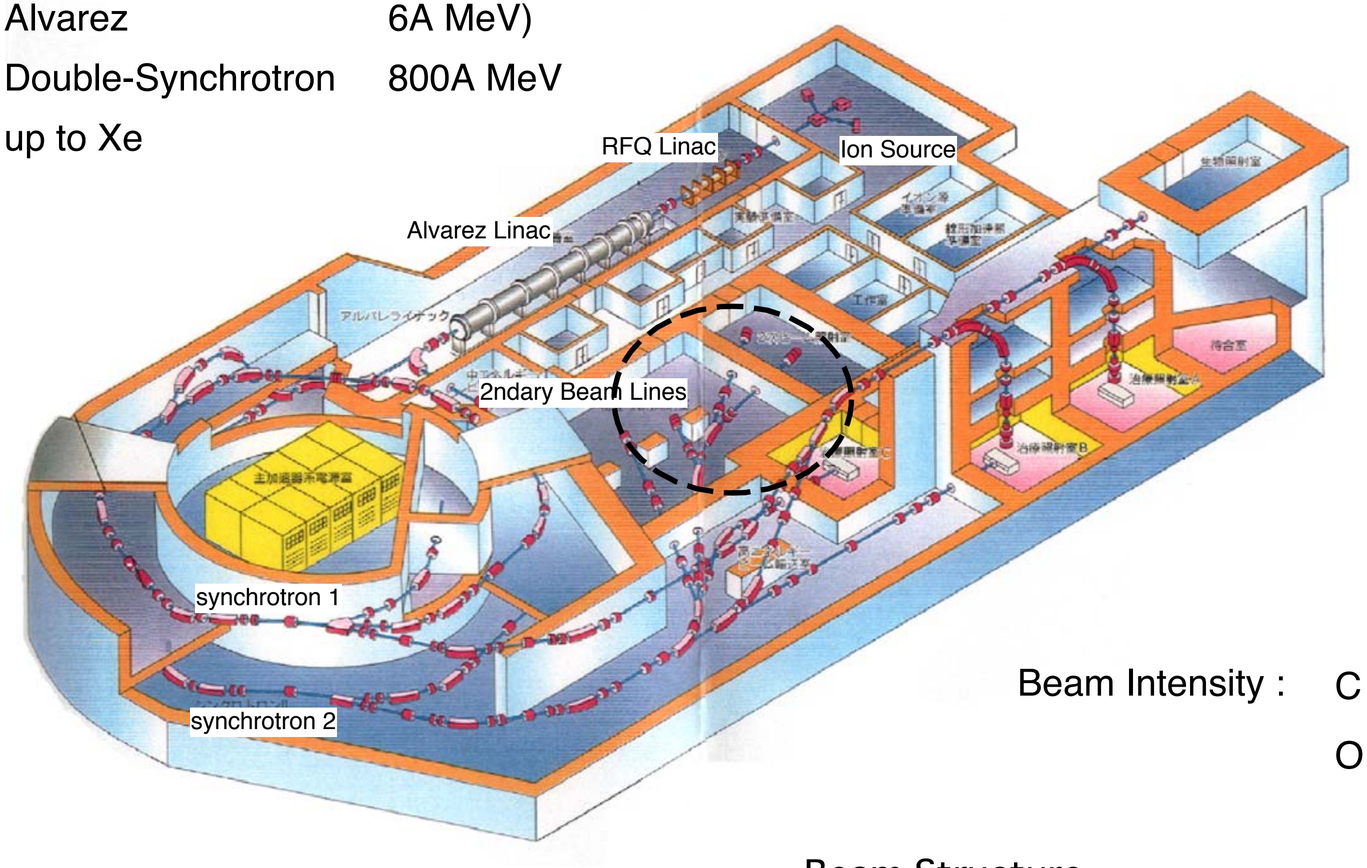
○ Proton "s"-orbit (L=0) inner-shell

deeply-bound (S_p= 30-50 MeV)

HIMAC (Heavy Ion Medical Accelerator in Chiba)   at NIRS (National Institute for Radiological Sciences)

Accelerator Facility for Cancer Therapy

RFQ	0.8A MeV
Alvarez	6A MeV)
Double-Synchrotron	800A MeV
up to Xe	



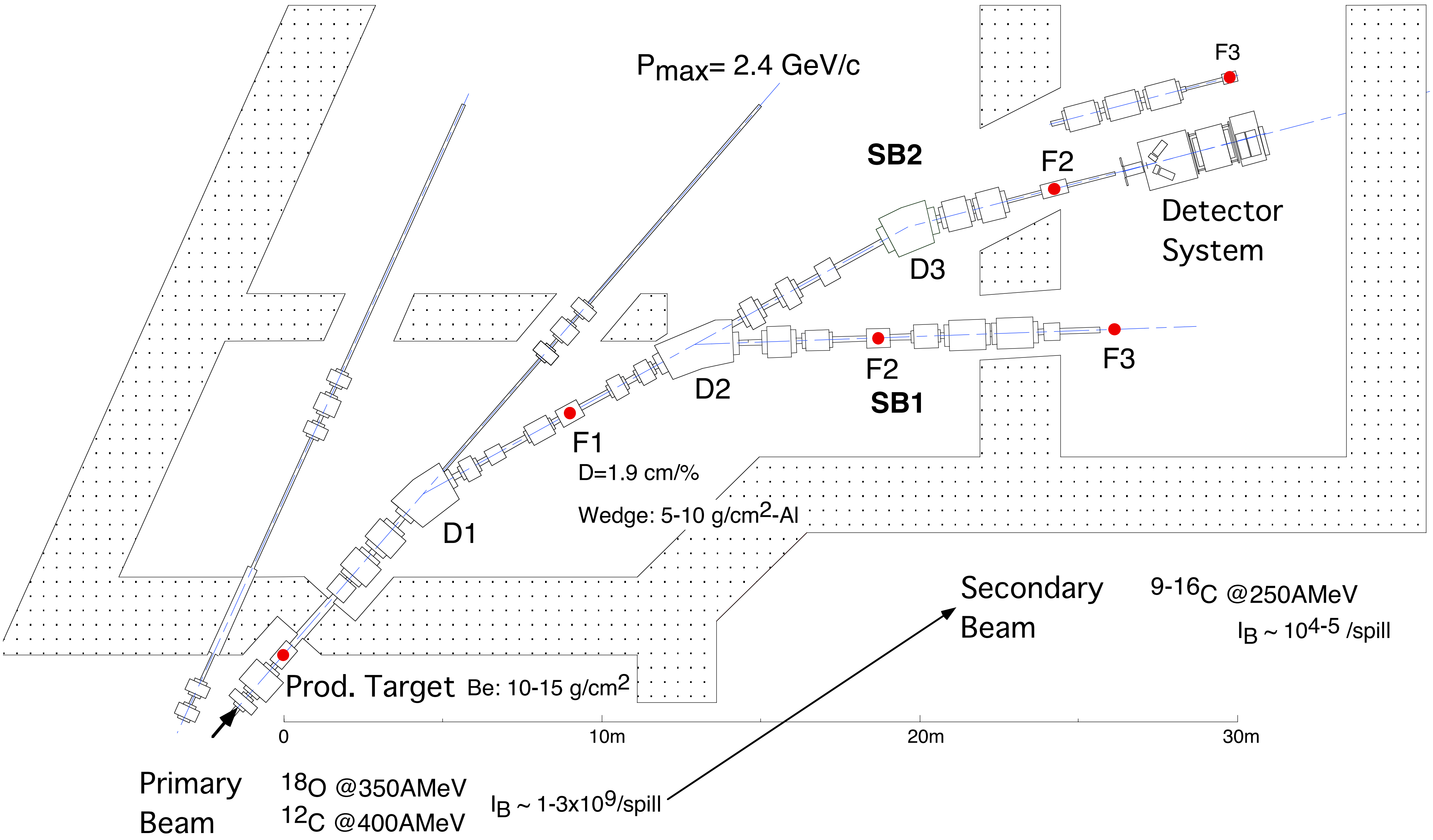
Beam Intensity : C : 1.8×10^9 /sec

O : 1.1×10^9 /sec

Beam Structure

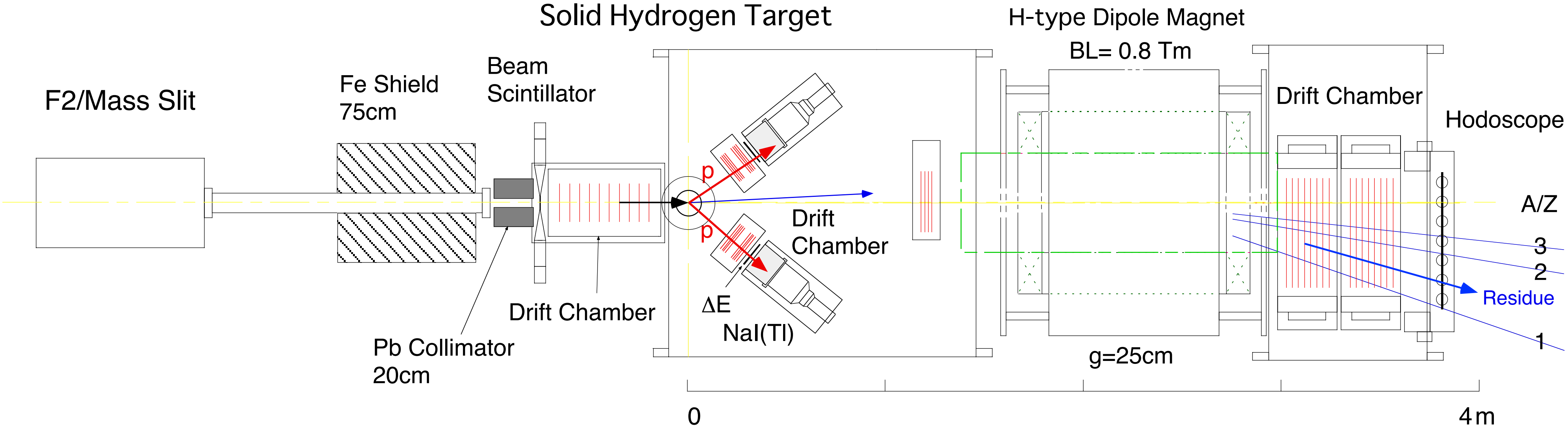
Repetition Rate :	$(3.3\ \mathrm{sec})^{-1}$
Duty factor :	30-50 %
Slow Extraction :	debunched beam:

Secondary Beam Lines @HIMAC

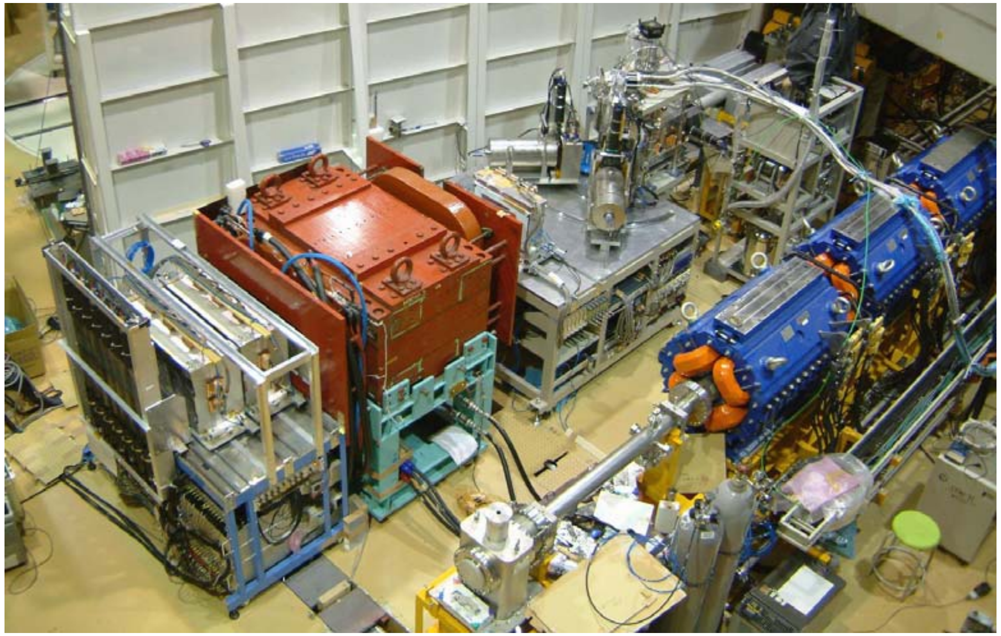


Experimental Setup @F3

Beam Detectors   Proton Detectors   Forward Magnetic Spectrometer



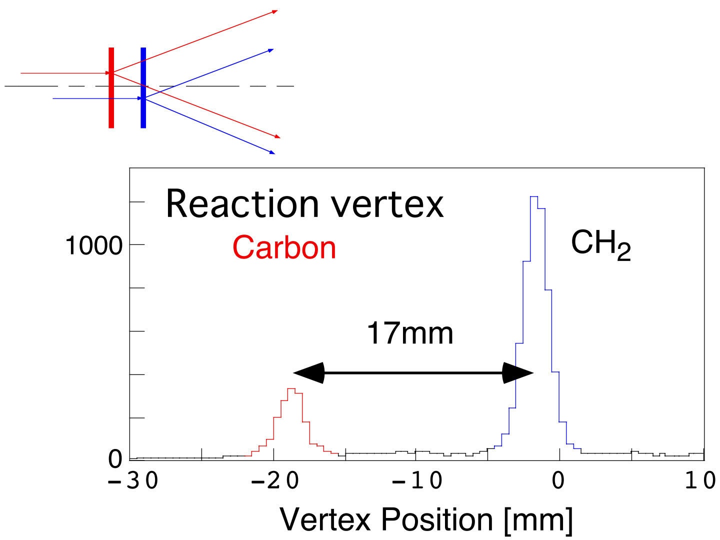
Setup seen from downstream side

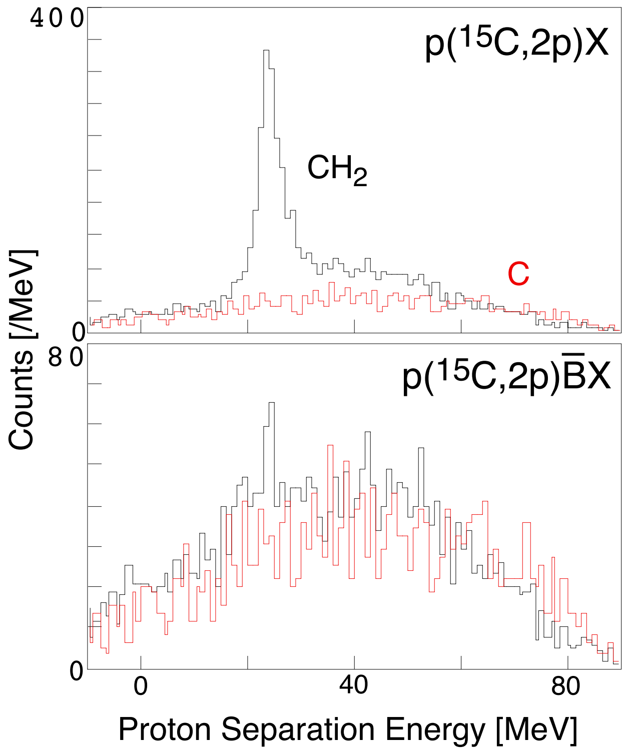


Solid Hydrogen Target (SHT)

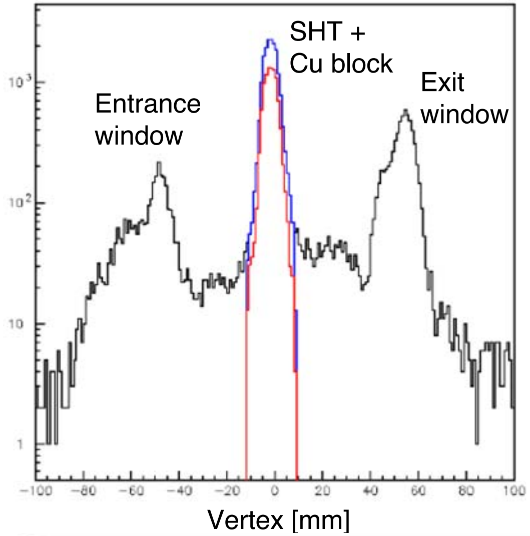
"Hydrogen" Target

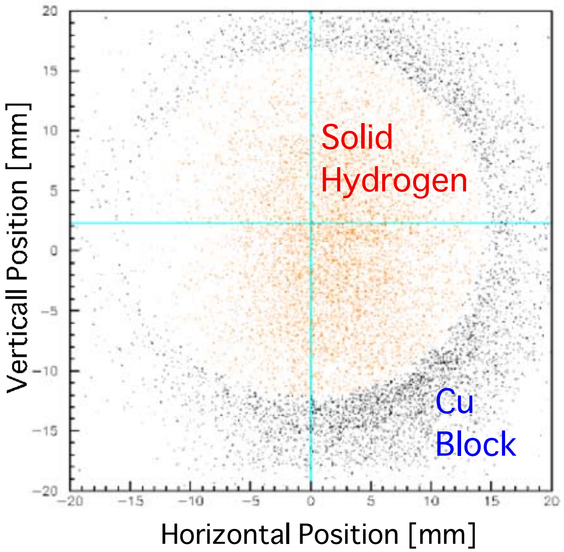
● CH_2(100mg/cm^2)-C(50mg/cm^2)

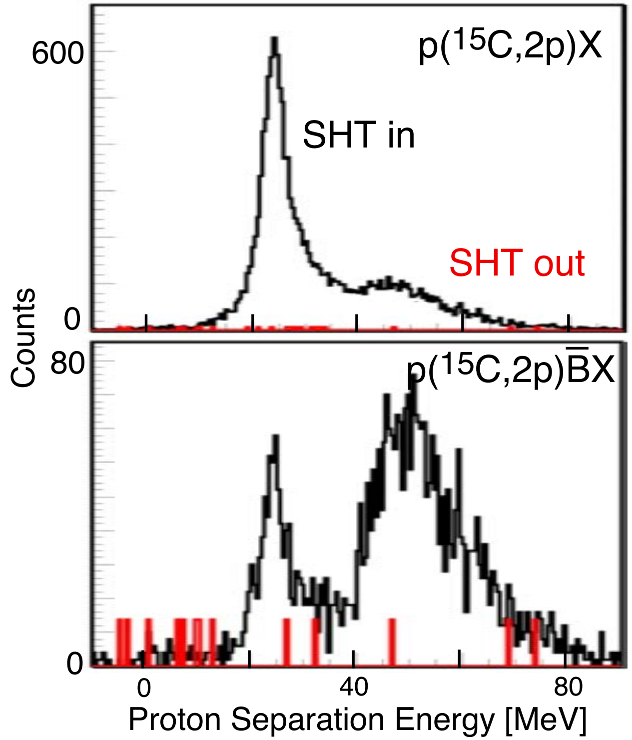


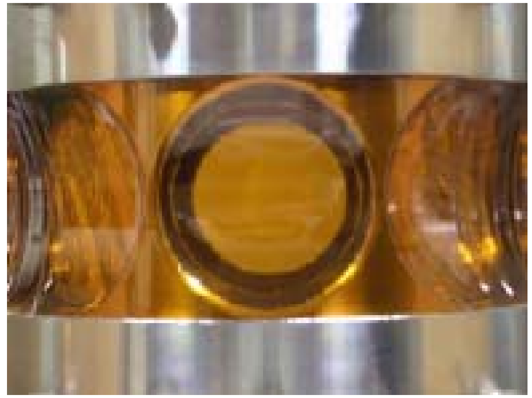


● Solid Hydrogen : 30mmϕ, 5mm t (W : 9μm Mylar)
Target (SHT)









Target : thickness	44 mg/cm^2 ~CH_2 3mmt
Vac window :	50μm kapton

Measured Quantities

beam :

velocity (β) : $\sigma_\beta / \beta \approx 1.2\times10^{-3}$

phase space : $\sigma \approx 1\mathrm{mrad}$

"Symmetric" Geometry $\theta_{CM}(pp) \approx 90°$

two protons :

Angle : $\theta_{Lab} = \pm 39° \pm 9°(\mathrm{H,V})$ $\sigma \approx 3$ mrad

Energy : $T_P = 20-210$ MeV $\sigma_T / T \approx 1\%$ $@T_P = 115MeV$

forward particles :

(Z,A) identified: $\sigma_A \approx 0.25$

momentum ($\vec{q}$) :

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

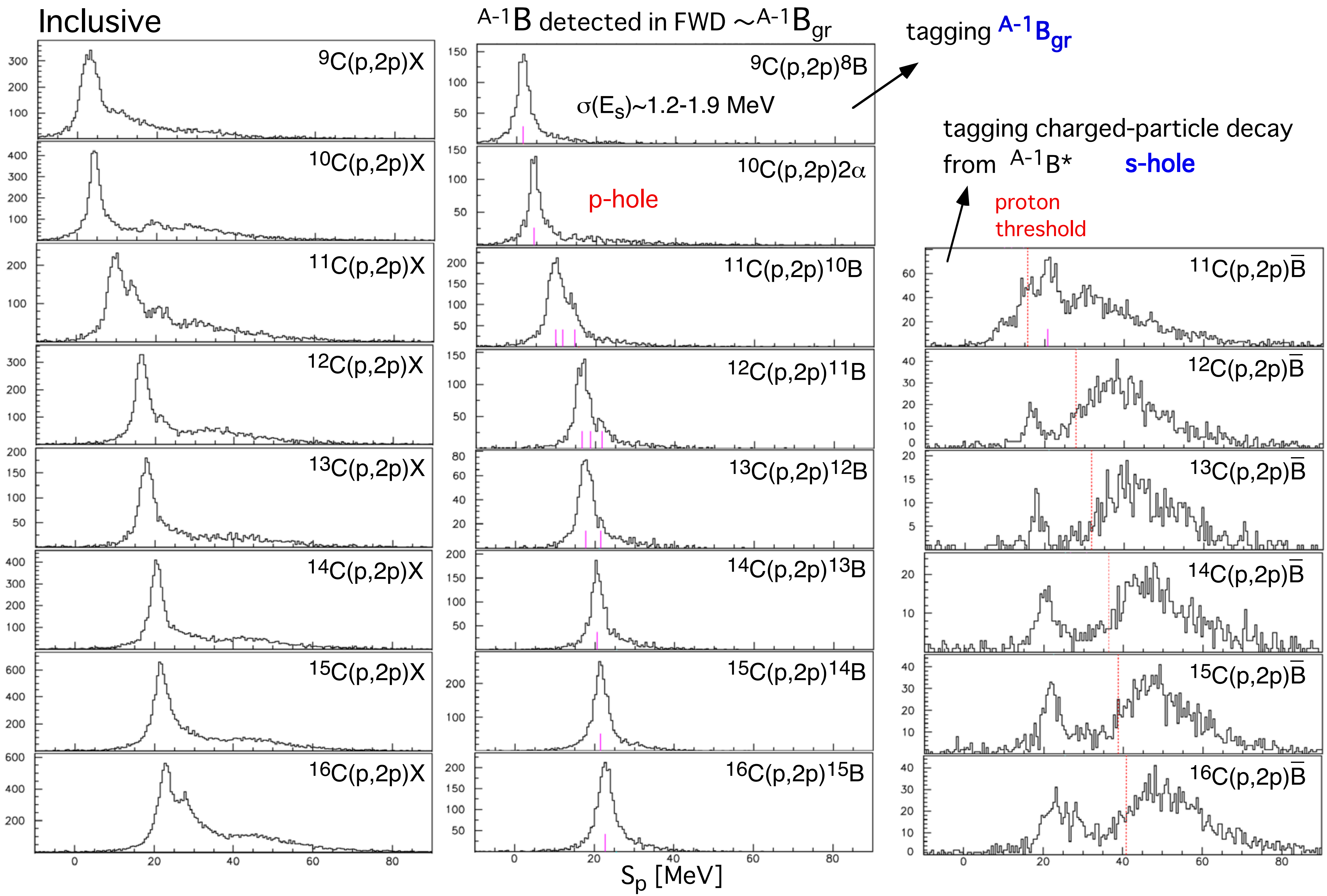
$$\vec{q}_{//} = \frac{\left(\vec{p}_1 + \vec{p}_2\right)_{//}}{\gamma} - \beta\left(M_A - M_{A-1} - \frac{q^2}{2M_{A-1}}\right)$$

separation energy (S_p) :

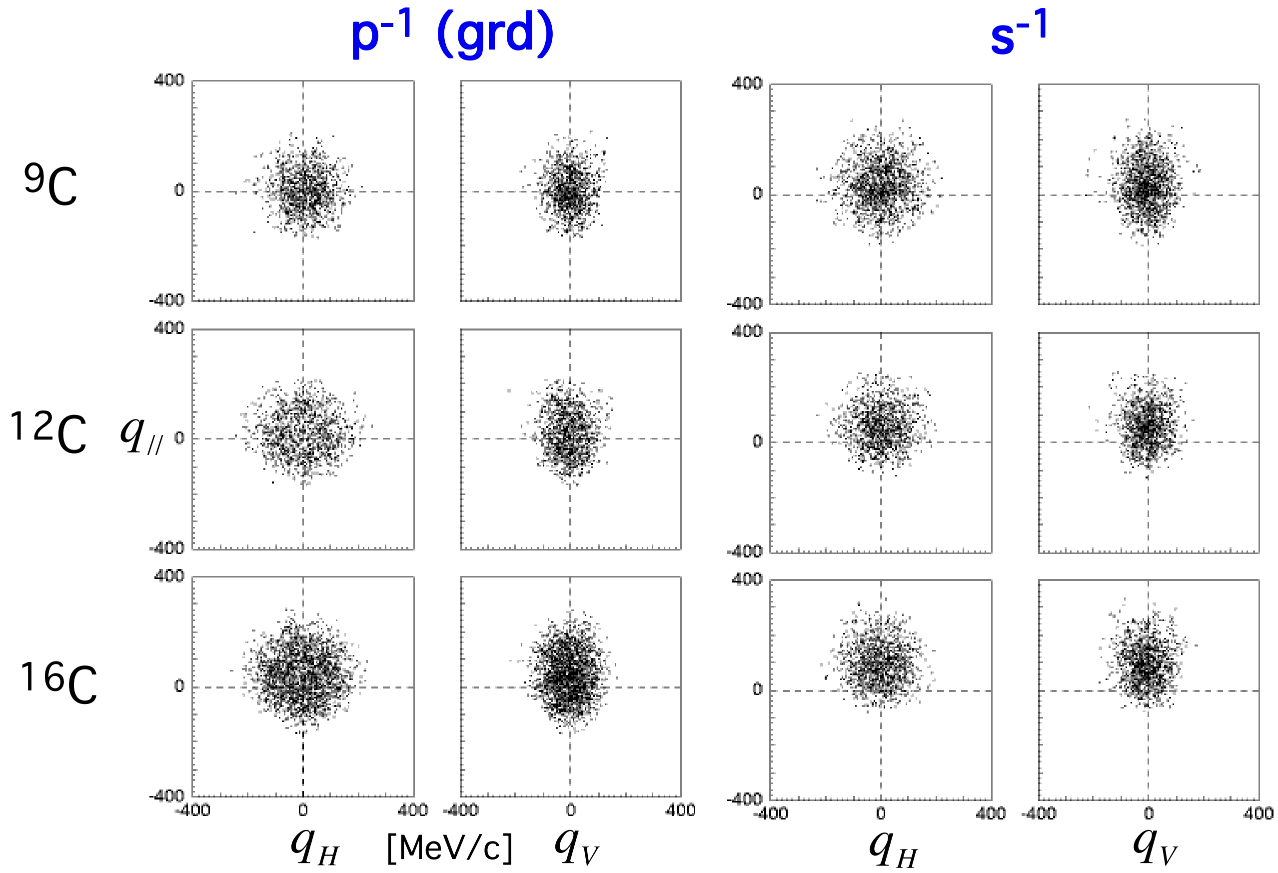
$$S_p = \beta\gamma\left(\vec{p}_1 + \vec{p}_2\right)_{//} - (\gamma-1)m_p - \gamma\left(T_1 + T_2\right) - \frac{q^2}{2M_{A-1}}$$

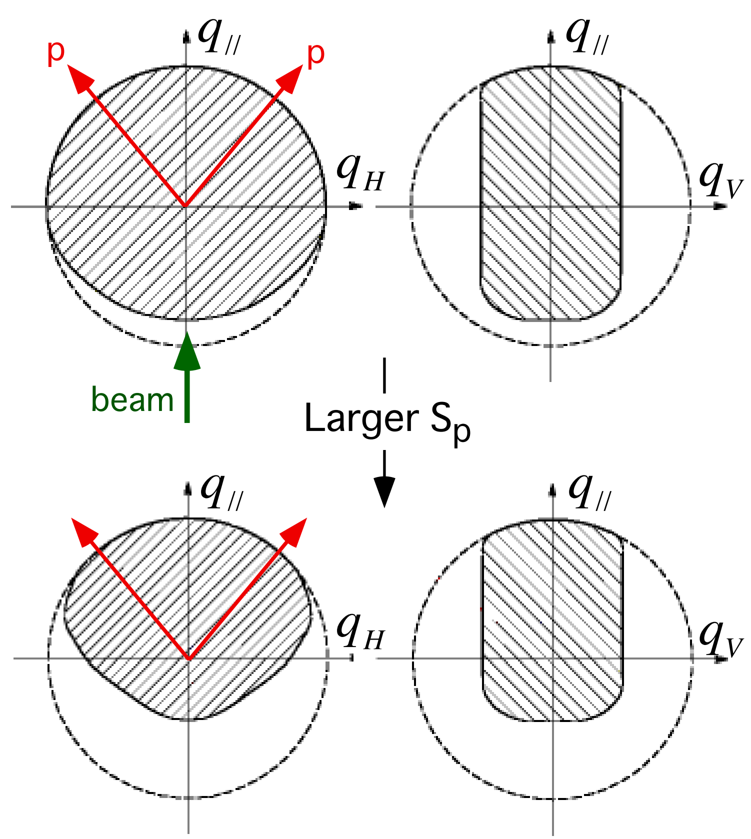
+ acceptance correction

Proton-Separation-Energy (S_p) Distribution

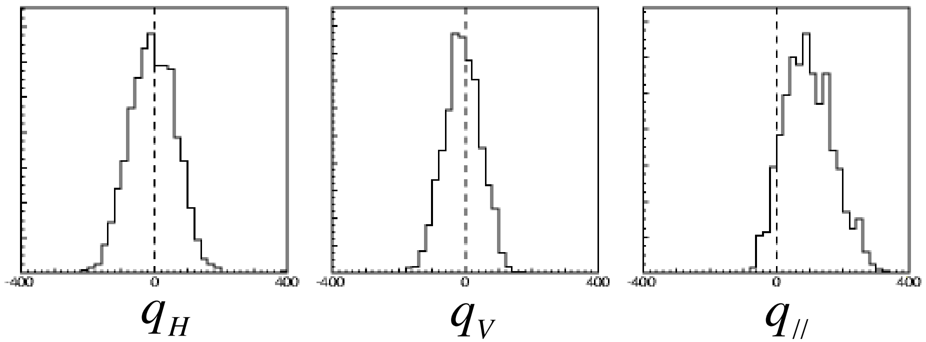


Effect of Angular Acceptance

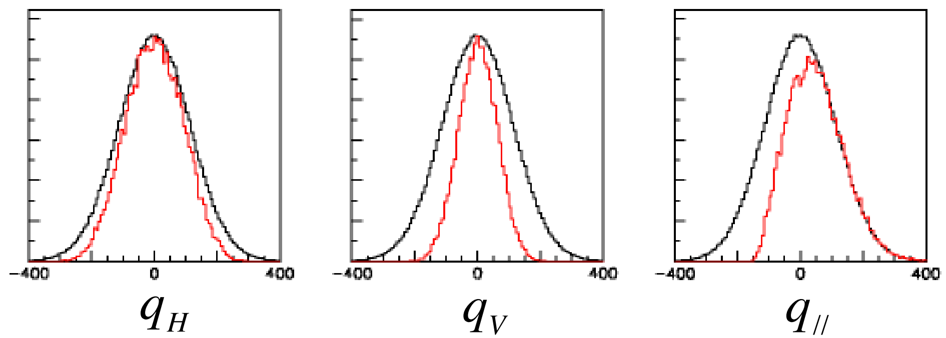




16C data

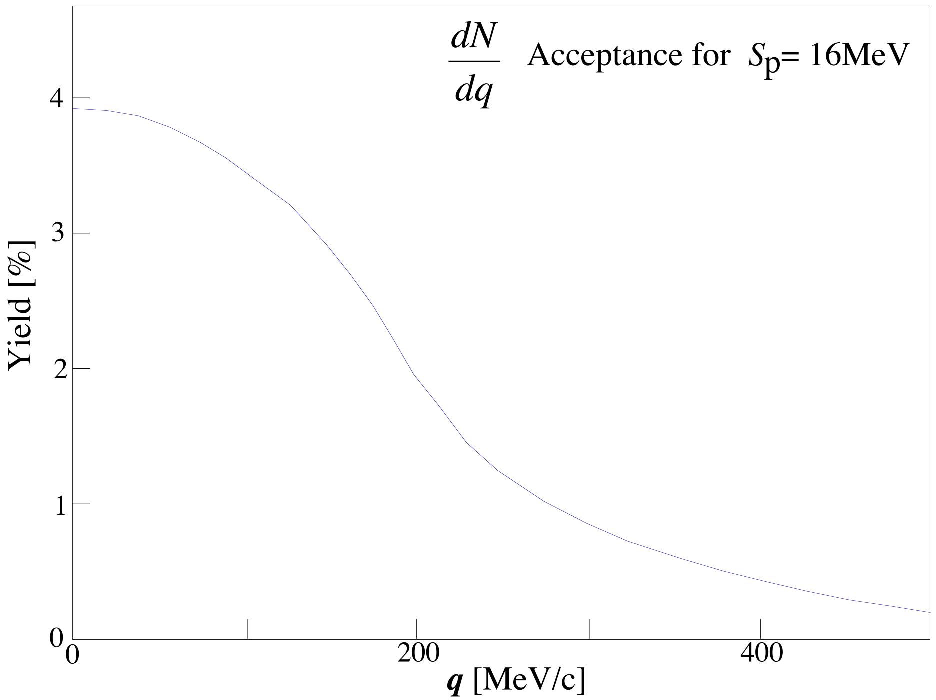


Simulation



Acceptance Correction (Simulation)

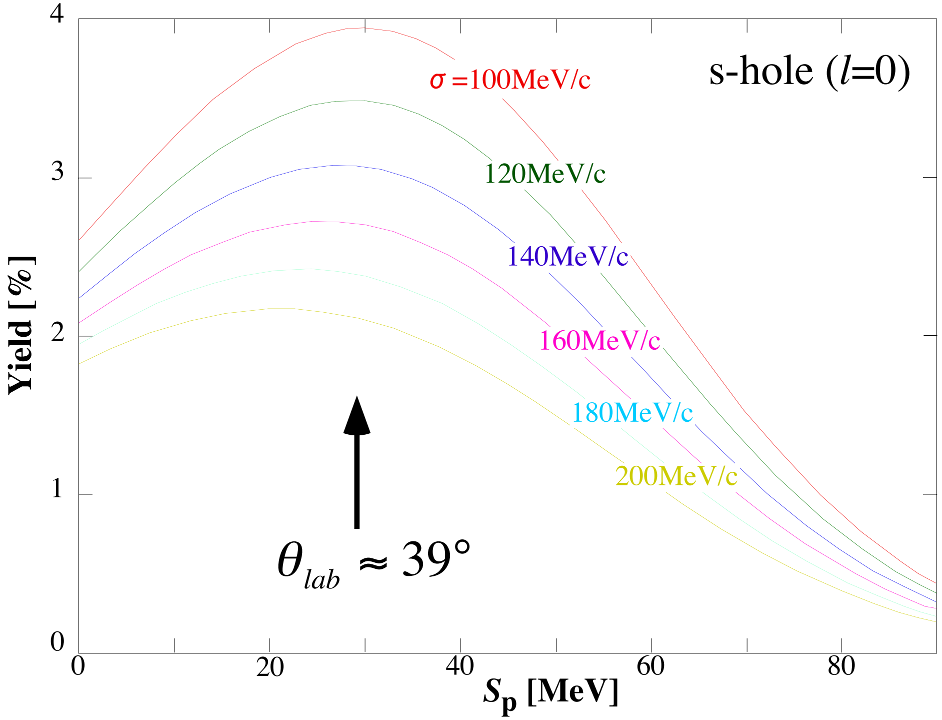
(1) Momentum distribution $\frac{dN}{dq}$



Assumption

* p-p angular distribution isotropic in p-p CM

(2) Separation Energy distribution



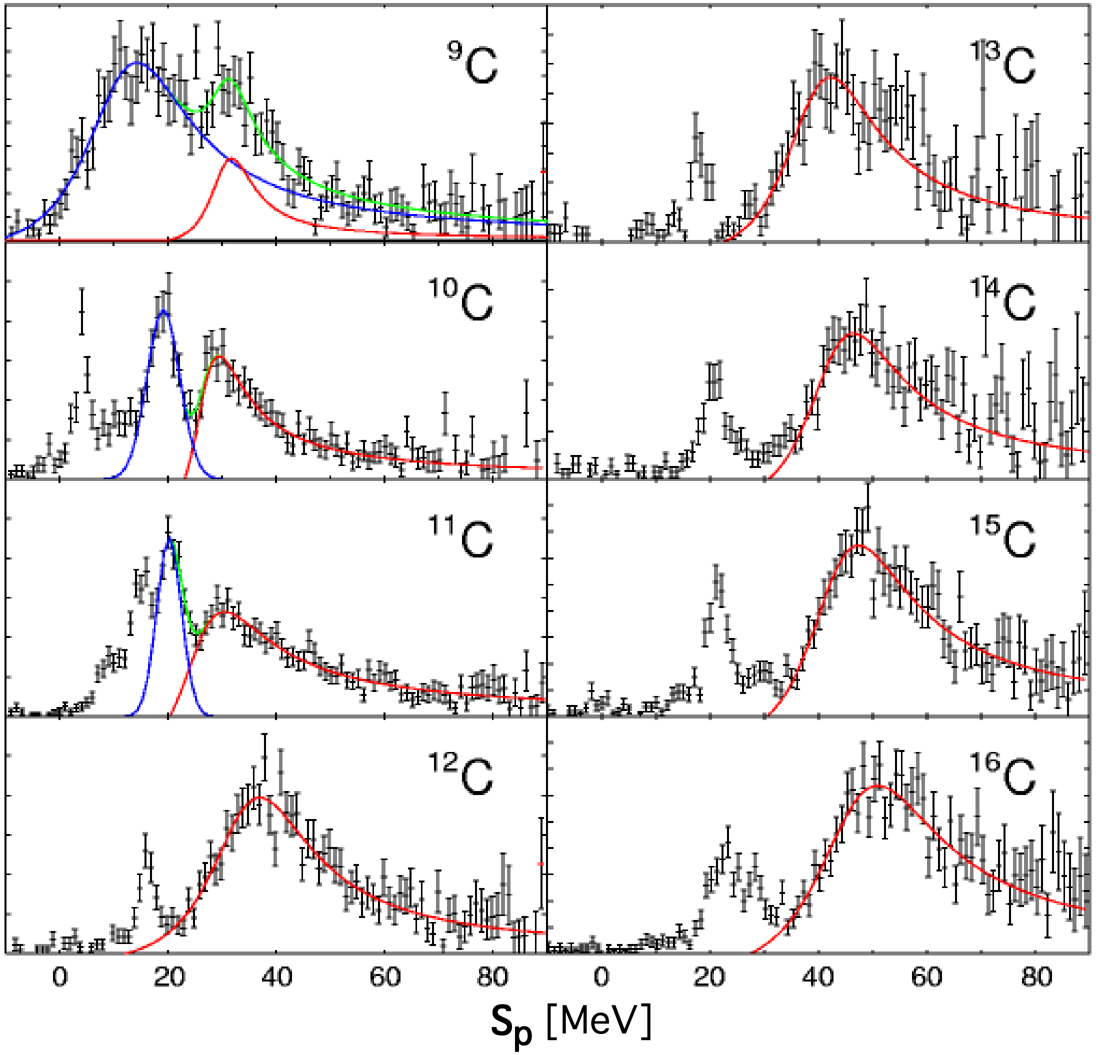
Assumption

* p-p angular distribution isotropic in p-p CM
* Momentum Distribution : Harmonic Osc.

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

S_p Distribution : s-hole states

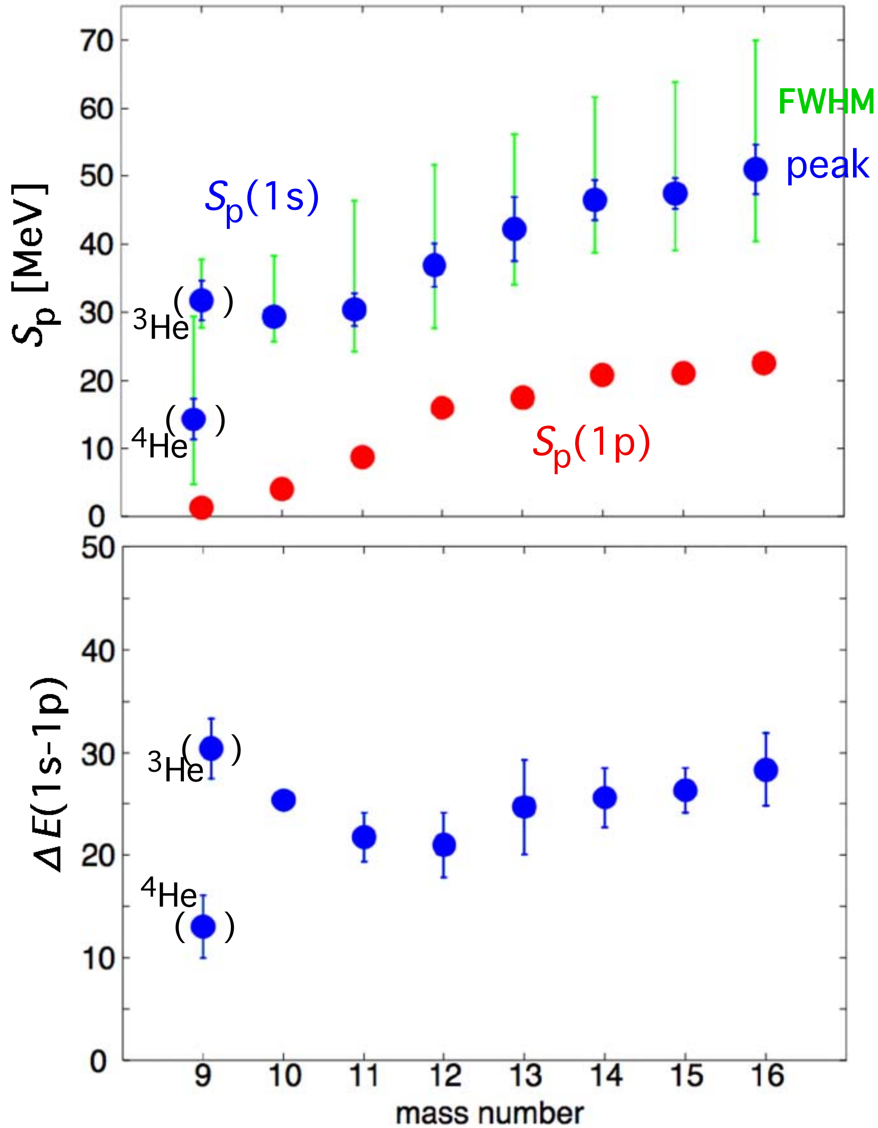
Systematic observation of s-hole states



Fitting:

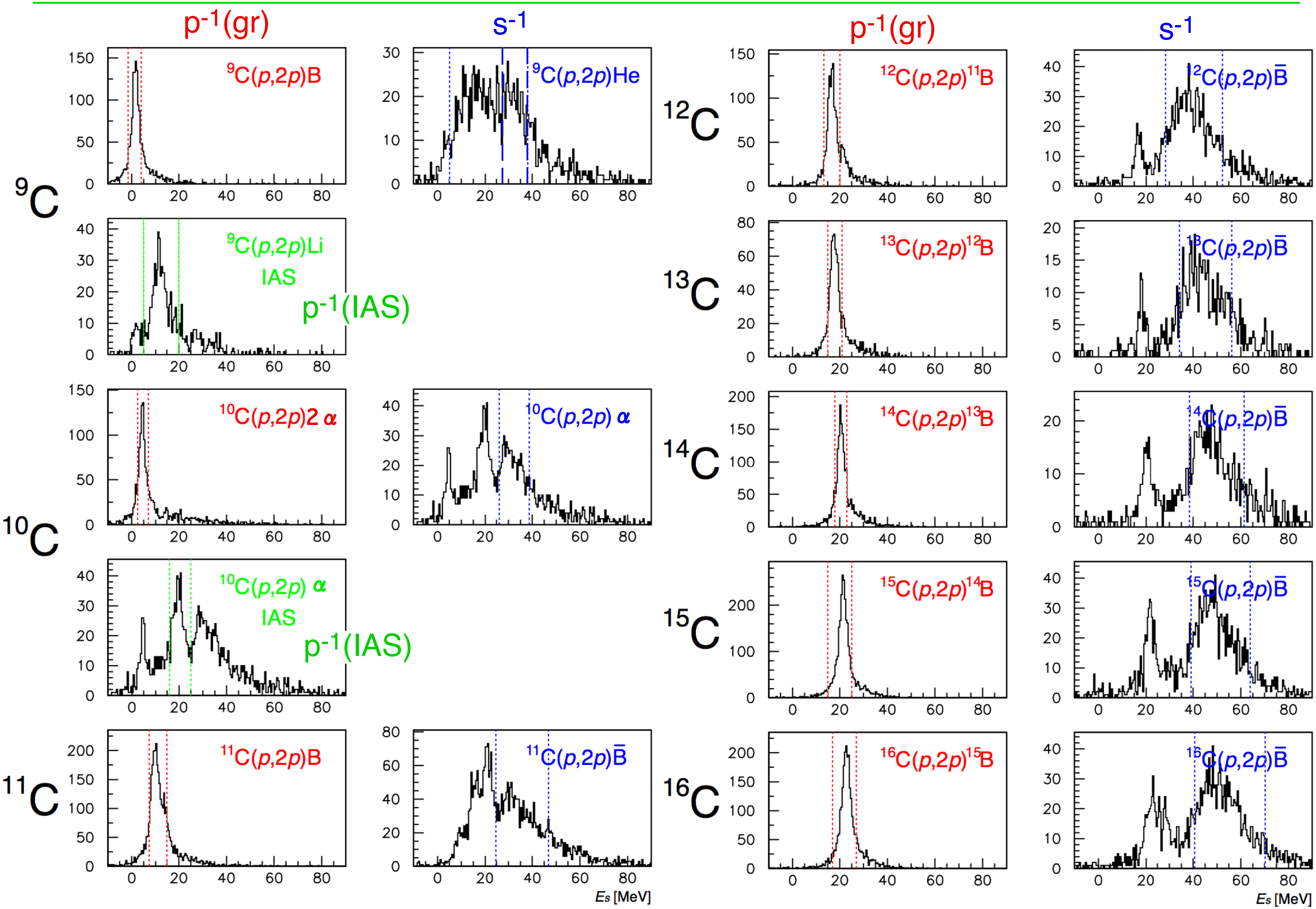
$$f(s_p) = \frac{s_p - a}{(s_p - b)^2 + c^2}$$

→ Peak
Width (FWHM)

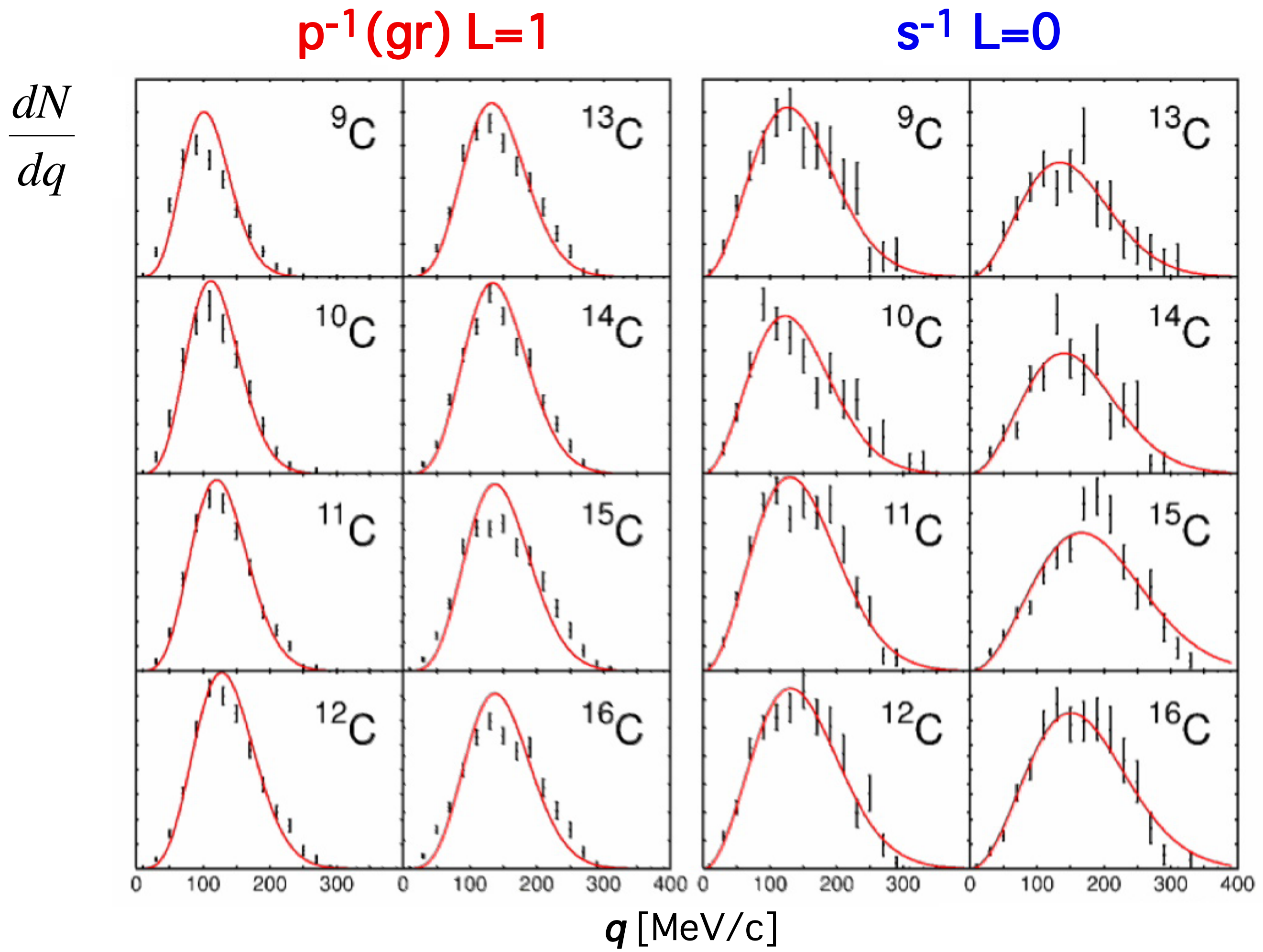


Energy gas widening on both sides

S_p selection for momentum distribution



Momentum Distribution



Fitting :

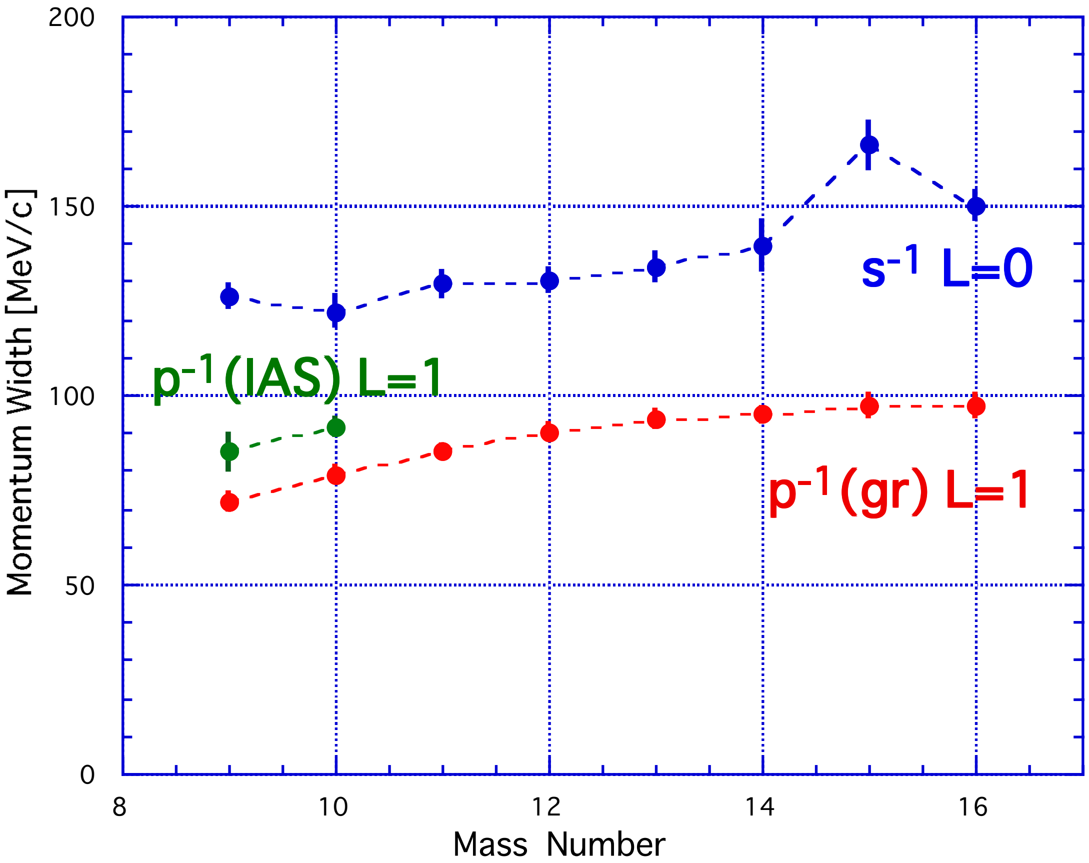
Harmonic Osc. shape

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

$\rightarrow$

σ_0	s-hole	L=0
σ_1	p-hole (gr)	L=1

Width of Momentum Distribution



Width $\sigma_0(\mathrm{s}),\ \sigma_1(p)$

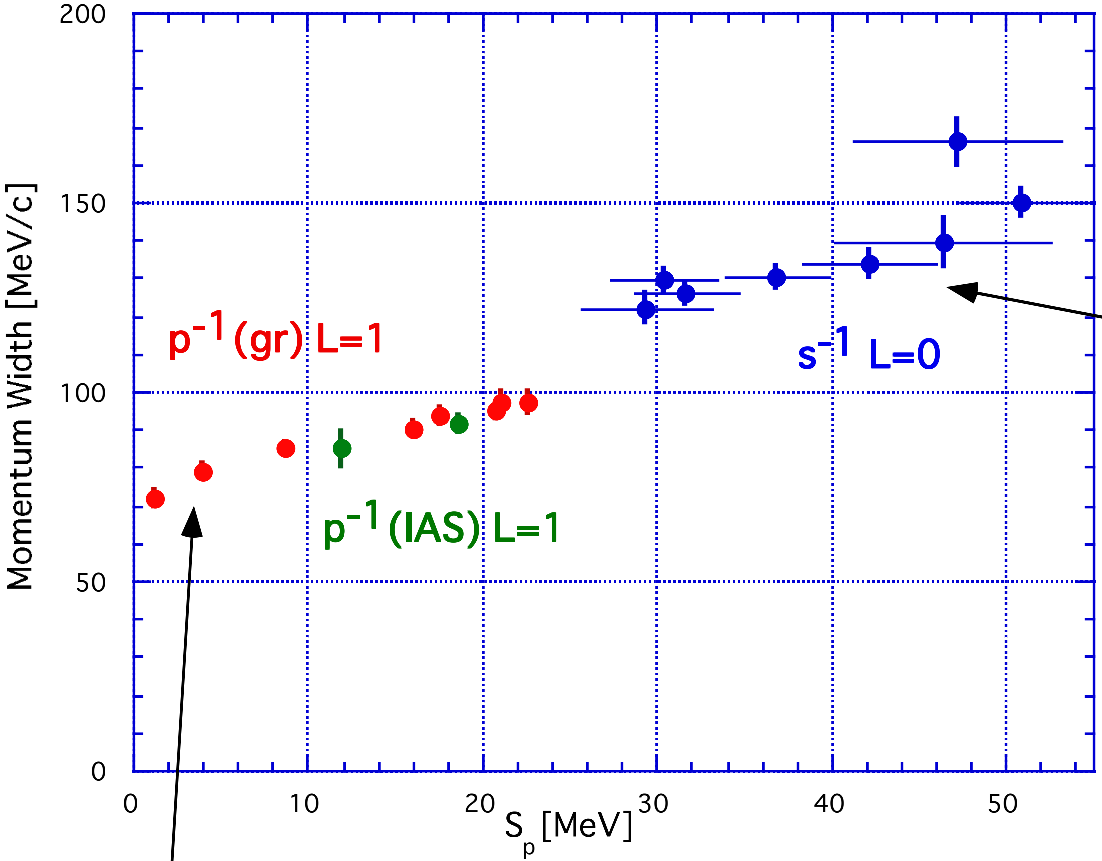
Harmonic Osc. shape

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

p^{-1} : width increases as S_p becomes larger

s-1: width increases toward neutron-rich side

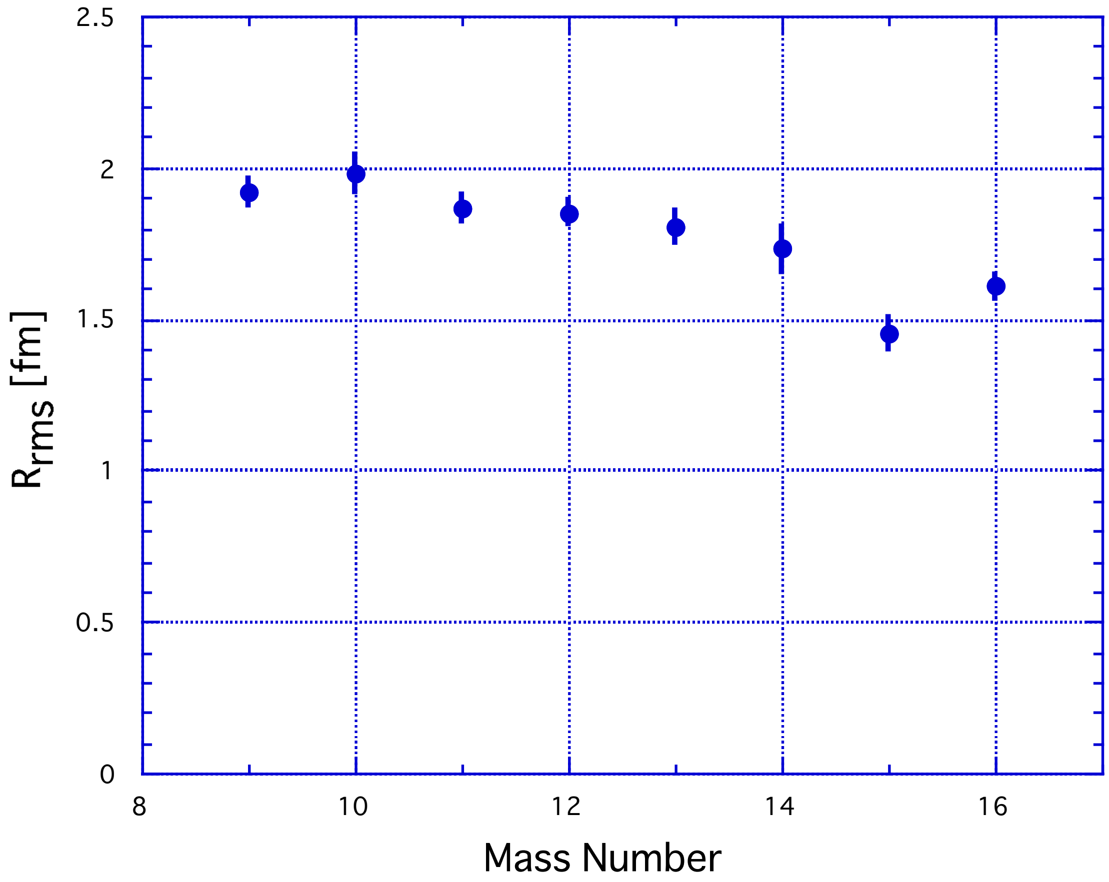
Momentum Width : Separation-Energy Dep.



Still have S_p dep. ?

Weak-binding nature
of valence proton(s)
in proton-rich nuclei

Rms Radius of $\pi 1s_{1/2}$ Orbit



Assuming Harmonic Oscillator :

$$R^{1s}_{rms} = \sqrt{\frac{3}{2}\frac{\hbar c}{\sigma_s}}$$

smaller towards neutron-rich side (shirinking)

Total (p,2p) Yield

Total (p,2p) Yield $\propto$ Effective proton number (spectroscopic factor)

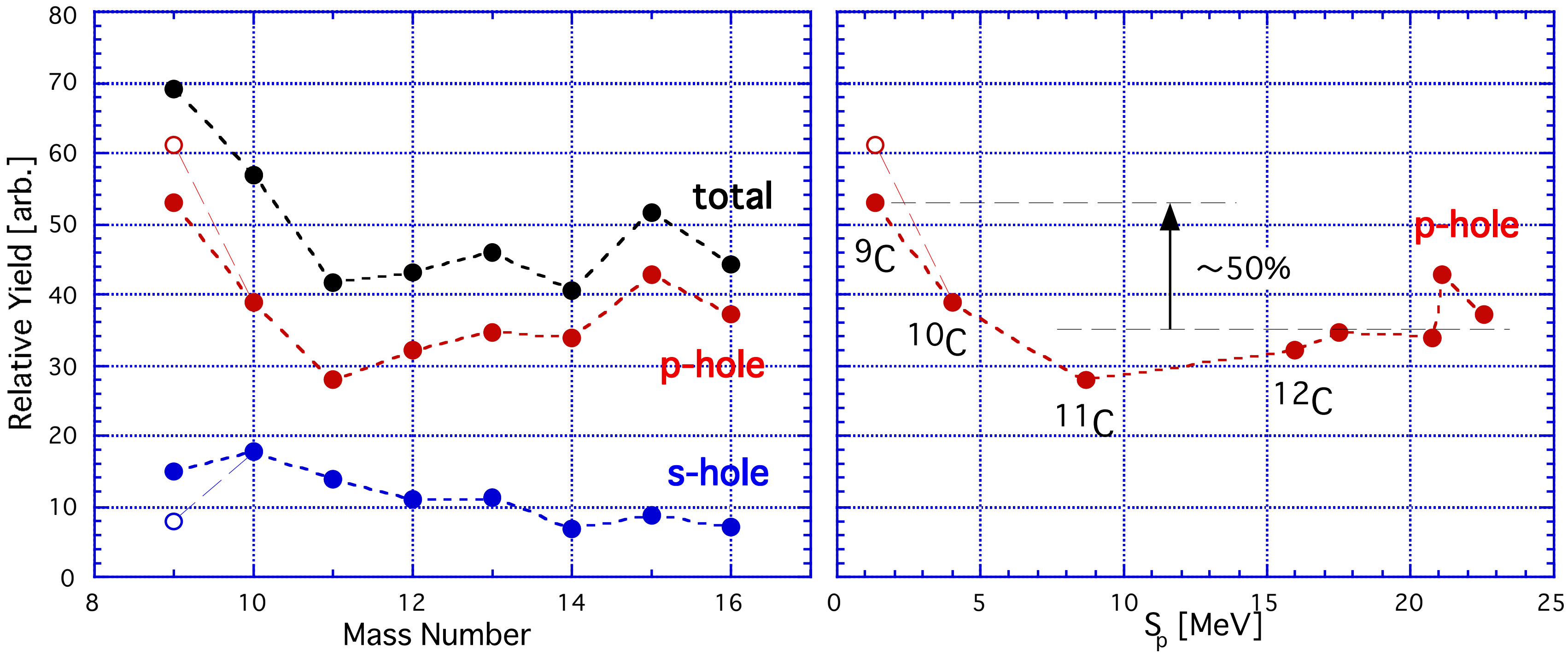
Separation of "p-hole" & "s-hole" :

p-hole : p(C,2p)Bx

s-hole : p(C,2p)$\overline{\mathrm{B}}$x & S_p>proton threshold

+ acceptance correction

Isotoropic in pp CM & Harmonic Osc.



^{9}C (S_p=1.3MeV)

Yield from p shell is about 50% larger

effective proton number/spectroscopic factor larger

Summary

$^{9\text{-}16}C(p,2p)^{8\text{-}15}B$ proton knockout reactions @250 MeV/A were measured
for systematic information of weakly to strongly-bound valence protons(1p)
deeply-bound inner-shell protons(1s)

(1) separation-energy distribution
momentum distribution : measured
total (p,2p) yield
decay mode tagged : p-hole/s-hole states separated

(2) Valence shell ($1p_{3/2}$) orbit : S_p=1.3-23MeV

○ momentum distribution :
quantitatively consistent with simple calculation, adjusting S_p

○ total (p,2p) yield :
^{9}C (S_p=1.3MeV) yield is larger by about 50%
effective proton number/spectroscopic factor is larger

(3) Inner shell ($1s_{1/2}$) orbit : S_p=30-50MeV

○ s-hole states observed systematically

○ energy gap $\Delta E(s_{1/2}\text{-}p_{3/2})$
minimum around ^{12}C, wider on both sides

○ charge rms radii of s-orbit(core)
shirinks from ∼2fm to ∼1.5fm between ^{9}C and ^{16}C