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

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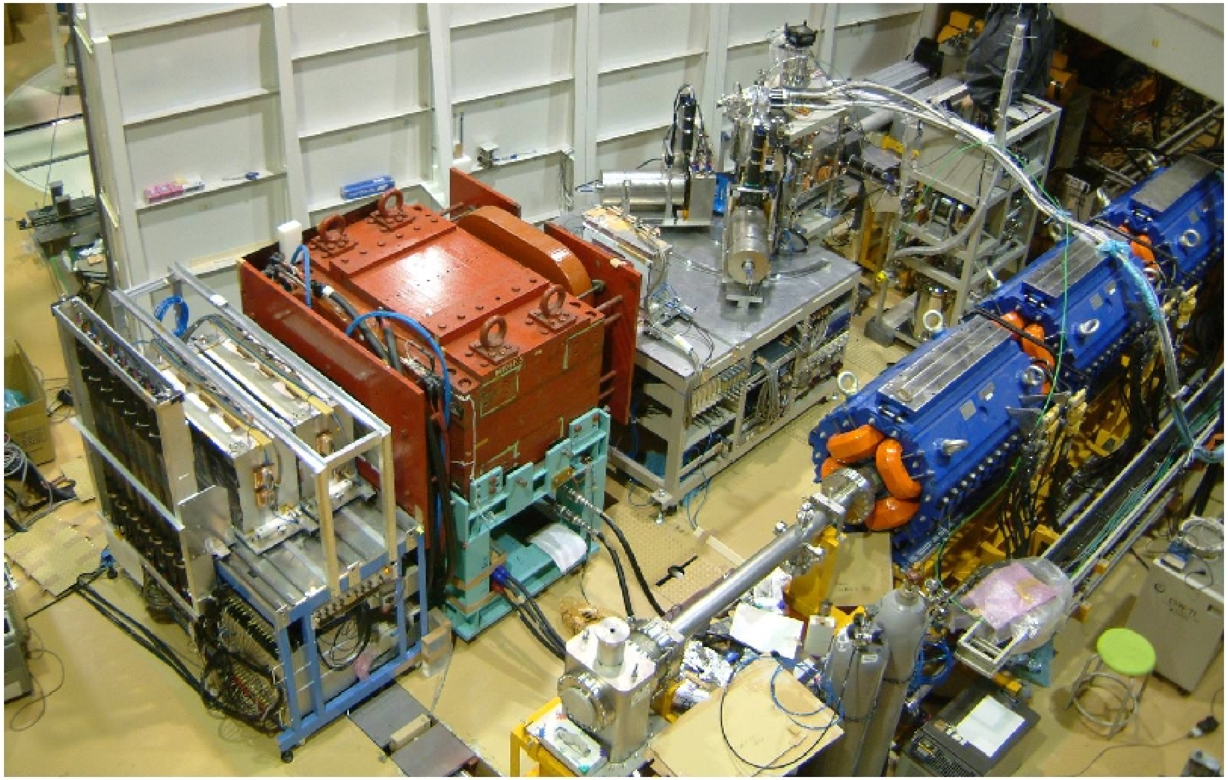


Overview of the experimental setup
at HIMAC facility, NIRS.

Motivation and experimental tool

Study of unstable nuclei

- Neutron halo,
- New magic numbers,
- Cluster structure.

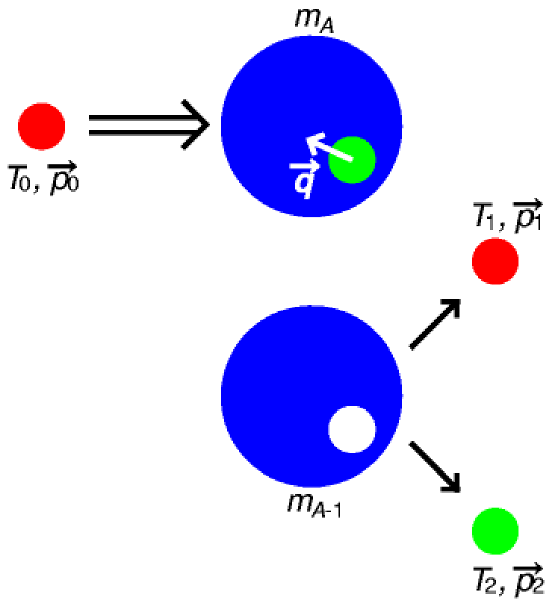
⋮

} Information of the single particle state.

Knockout reaction: (p, pN) $\cdots$experimental tools to obtain the information of the single particle state.

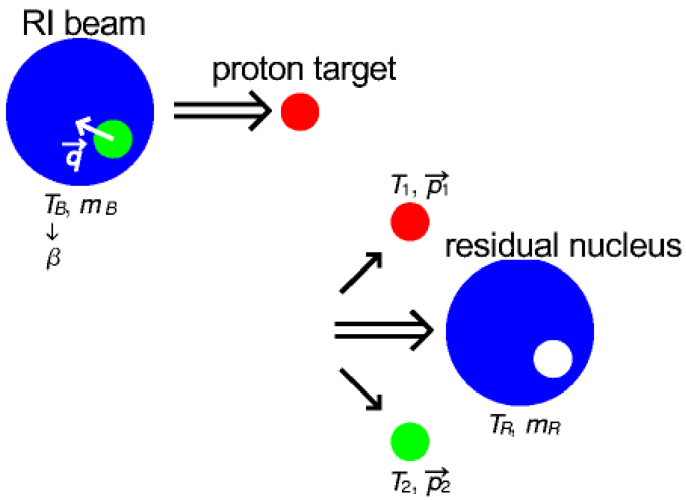
$(p, 2p)$ $\cdots$Study of the proton single particle state through the proton hole state.

- Separation energy (structure of the hole state),
- Momentum of bound proton in nuclei,
- Angular momentum,
- Relative yield....



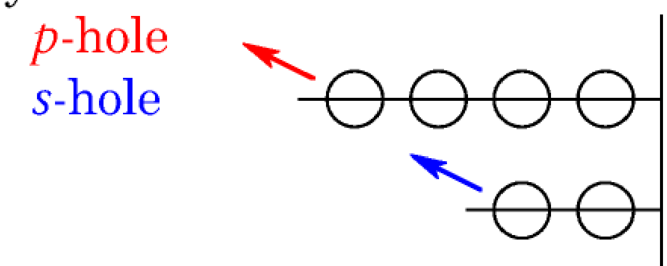
(p,2p) reaction with the inverse kinematics

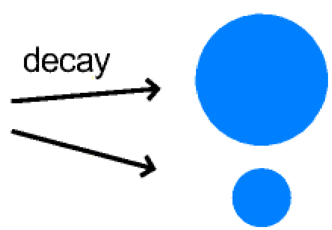
Inverse kinematics



- RI beam (secondary beam).
- Measurement of energies and momenta of a pair of scattered protons.
- Ejection of residual nucleus into forward angle.

  ⋯ decay mode of hole state.





- Small solid angle.
- Detection of residual nucleus itself.

Proton separation energy:

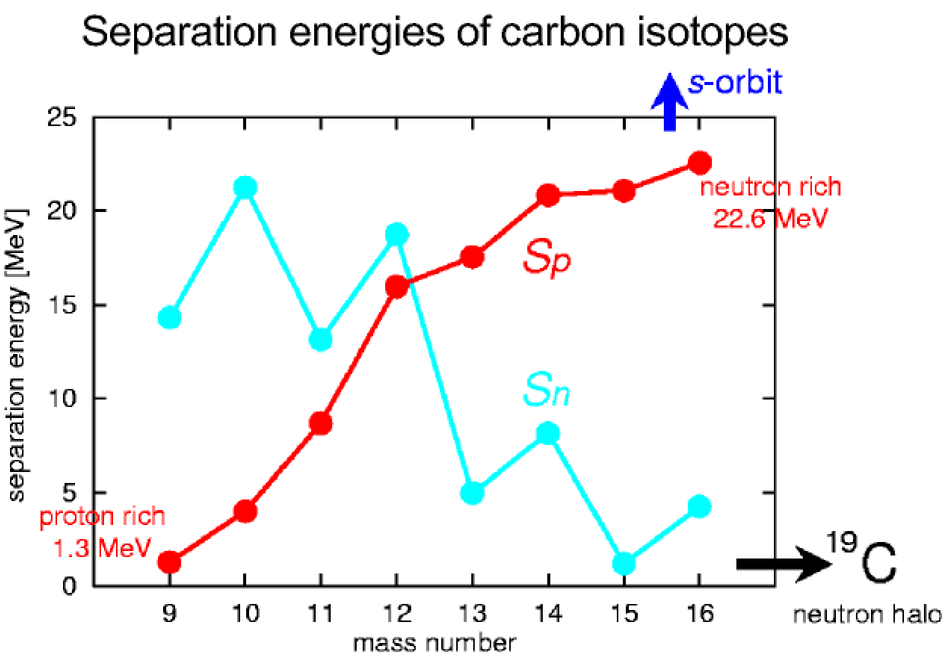
$$E_s = -m_p(\gamma - 1) - \gamma(T_1 + T_2) + \beta\gamma(\vec{p_1} + \vec{p_2})_{\parallel} - \frac{q^2}{2m_R}$$

Momentum of bound proton:

$$\vec{q}_{\perp} = (\vec{p_1} + \vec{p_2})_{\perp}$$

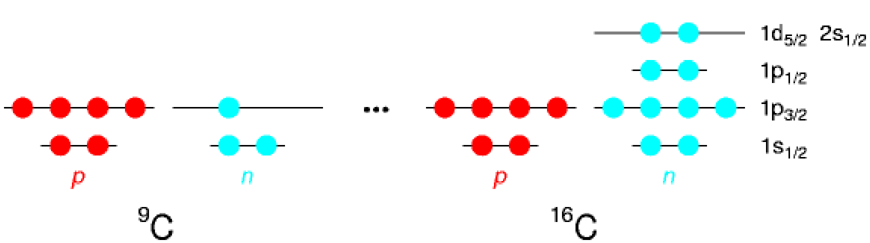
$$\vec{q}_{\parallel} = \frac{(\vec{p_1} + \vec{p_2})_{\parallel}}{\gamma} - \beta\left(m_B - m_R - \frac{q^2}{2m_R}\right)$$

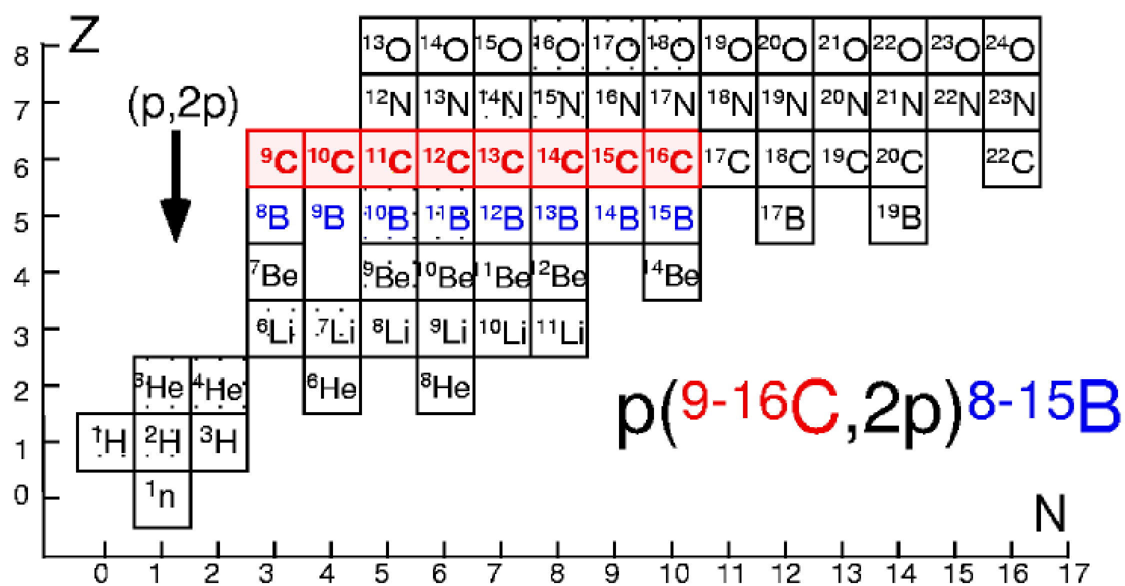
Subjects of research ~ carbon isotopes



Systematics of the transition in proton single particle states of carbon isotopes.

- *p*-orbit
  weakly-bound ⟷ strongly-bound
  (~1 MeV) (~23 MeV)
- *s*-orbit
  very strongly-bound *s*-hole state
  (30-50 MeV)

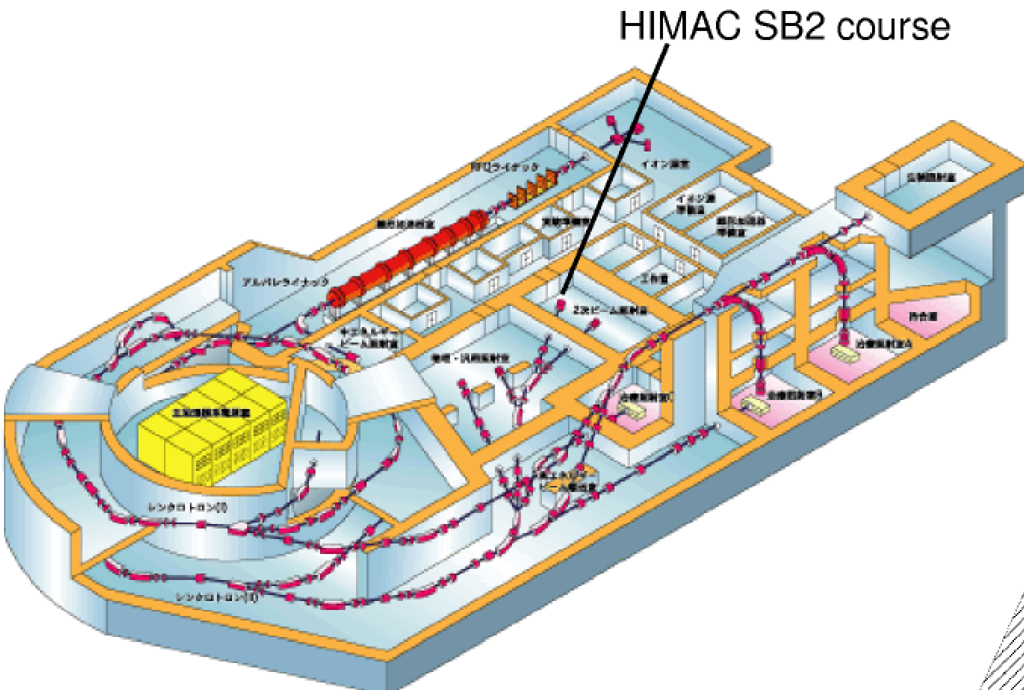




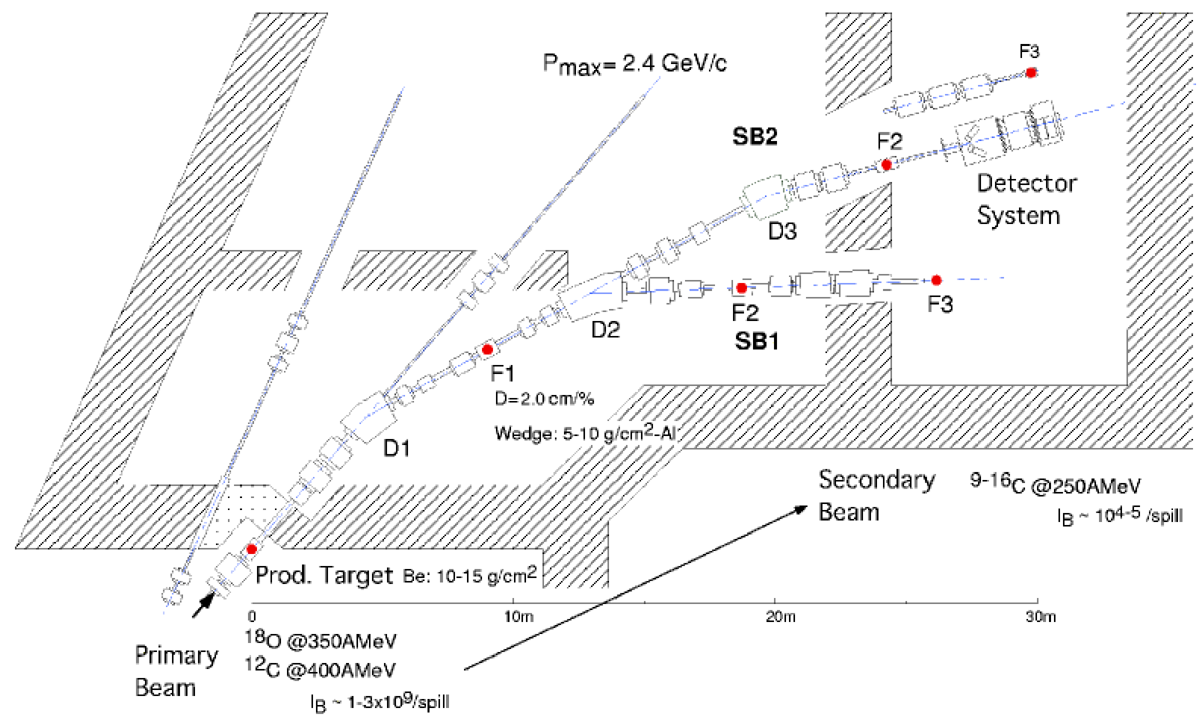
Experimental facility

HIMAC (Heavy Ion Medical Accelerator in Chiba),
NIRS (National Institute of Radiological Sciences).

http://www.nirs.go.jp

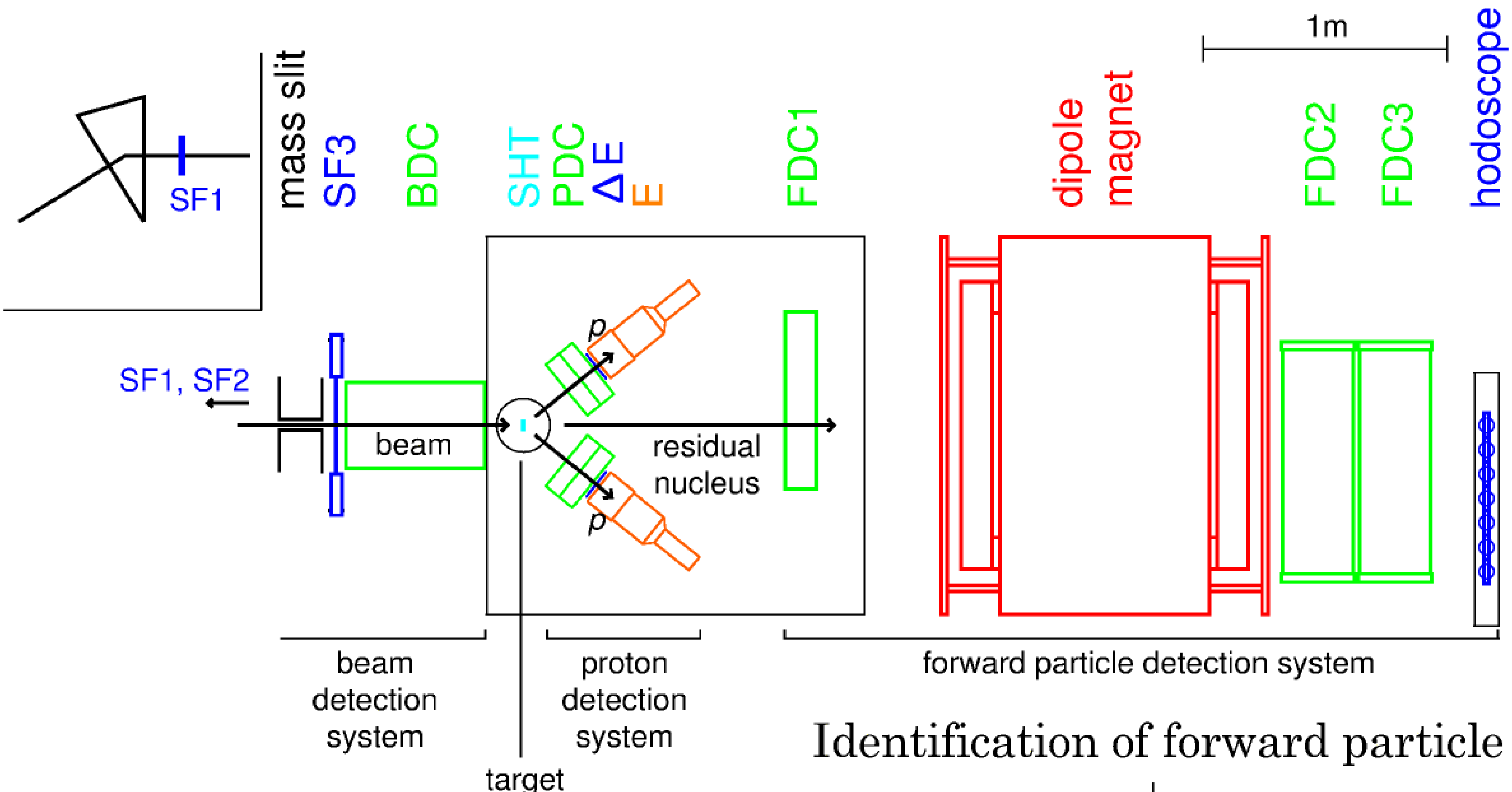


SB2 course



Experimental setup

$^{9\text{-}12}$C : ^{12}C 400A MeV primary beam
$^{13\text{-}16}$C : ^{18}O 350A MeV primary beam $\longrightarrow$ ~250A MeV secondary beam



Identification of forward particle

↓

Decay mode of hole state

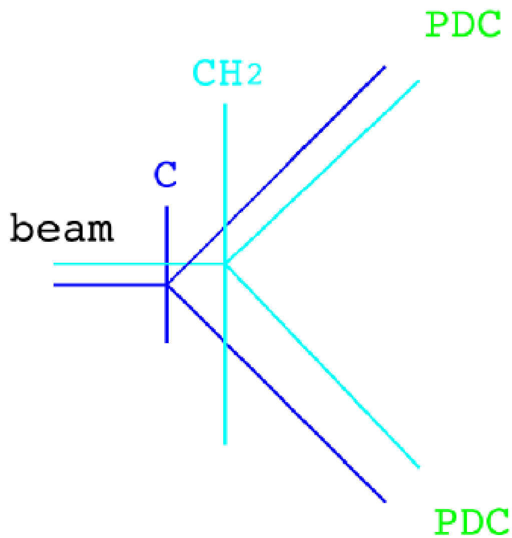
Derivation of E_s, $\vec{q}$

↓

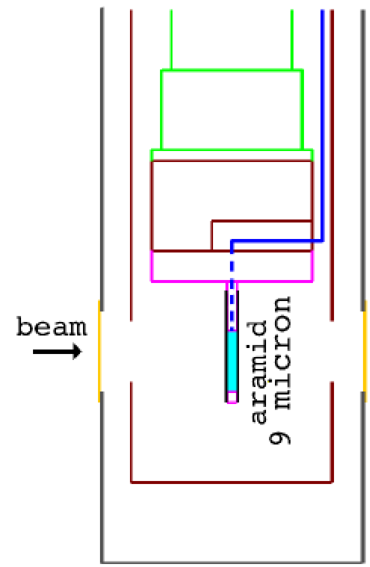
Energy structure of hole state

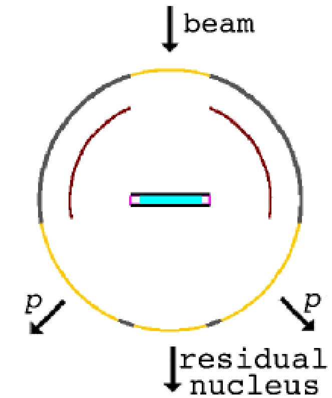
Solid hydrogen target (SHT)

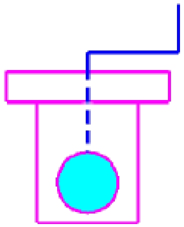
CH_2 target



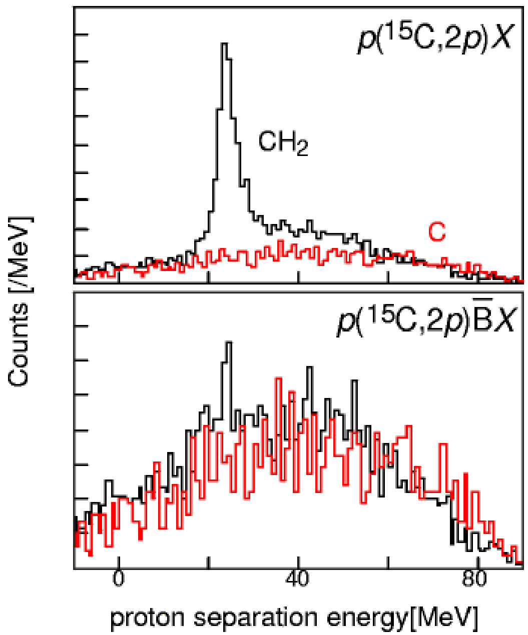
SHT

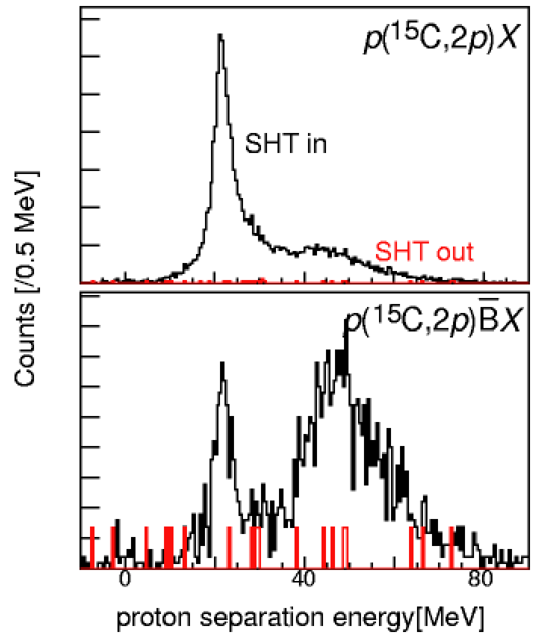




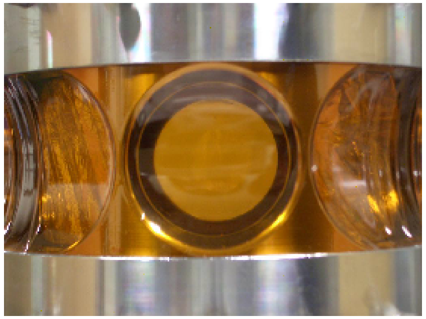


Target cell
5 mm thick
35 mm ϕ
$0.04\ \mathrm{g/cm^2}$

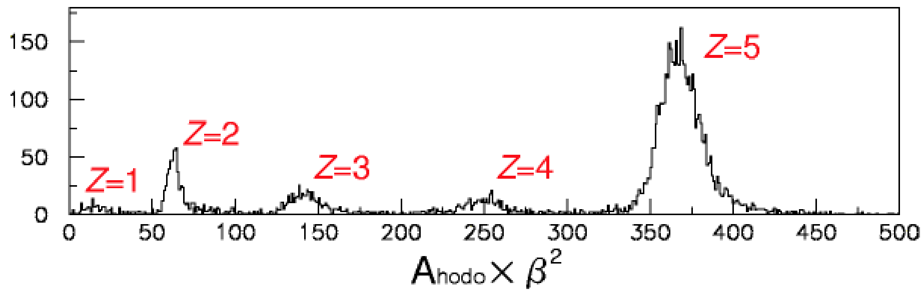


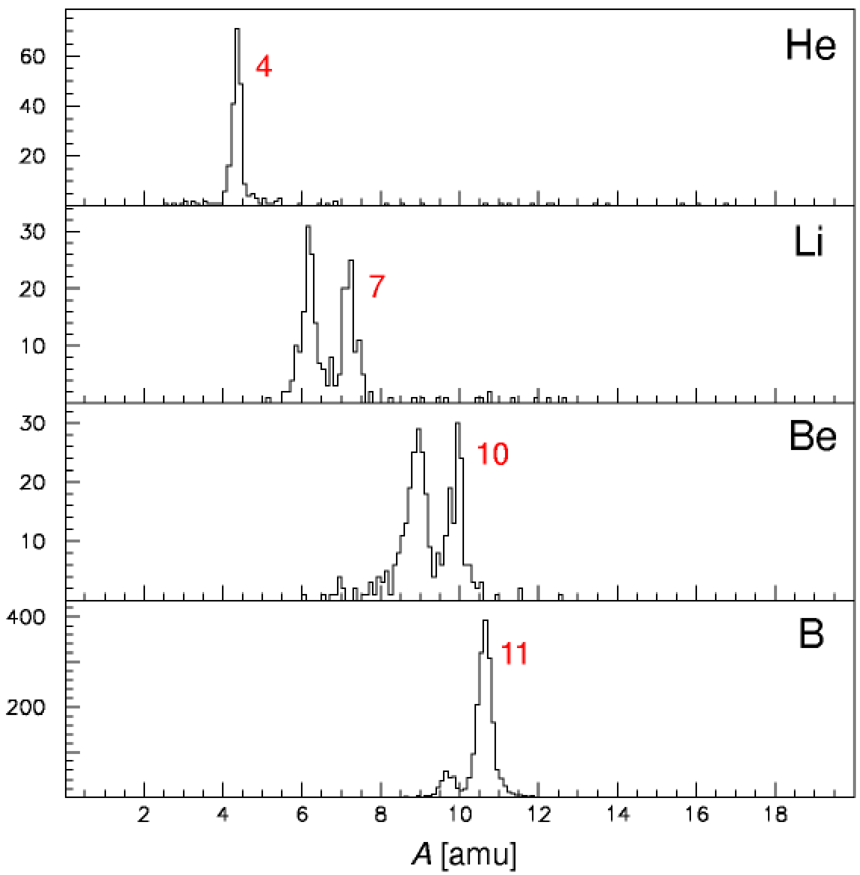


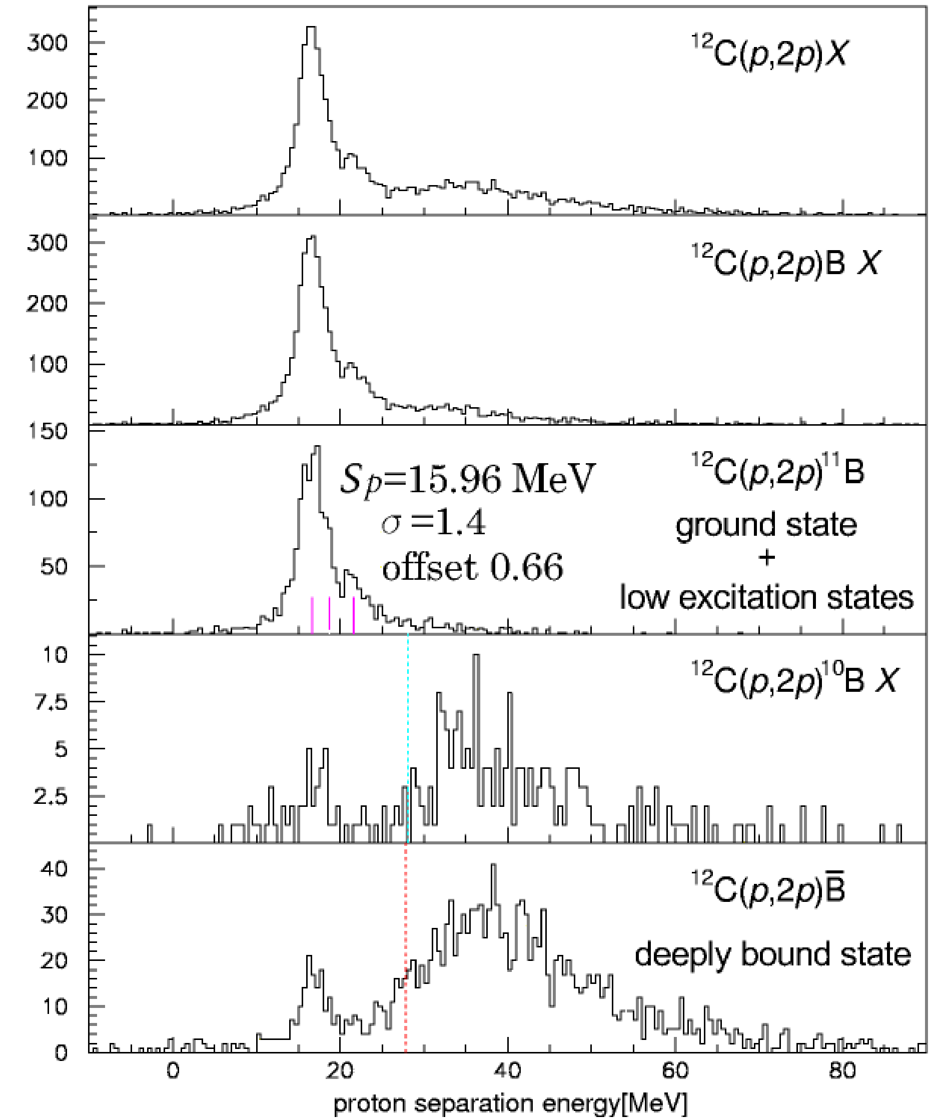
S/N~100

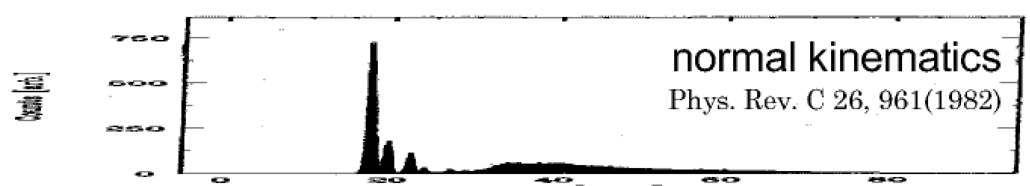


$p(^{12}C,2p)^{11}B^*$

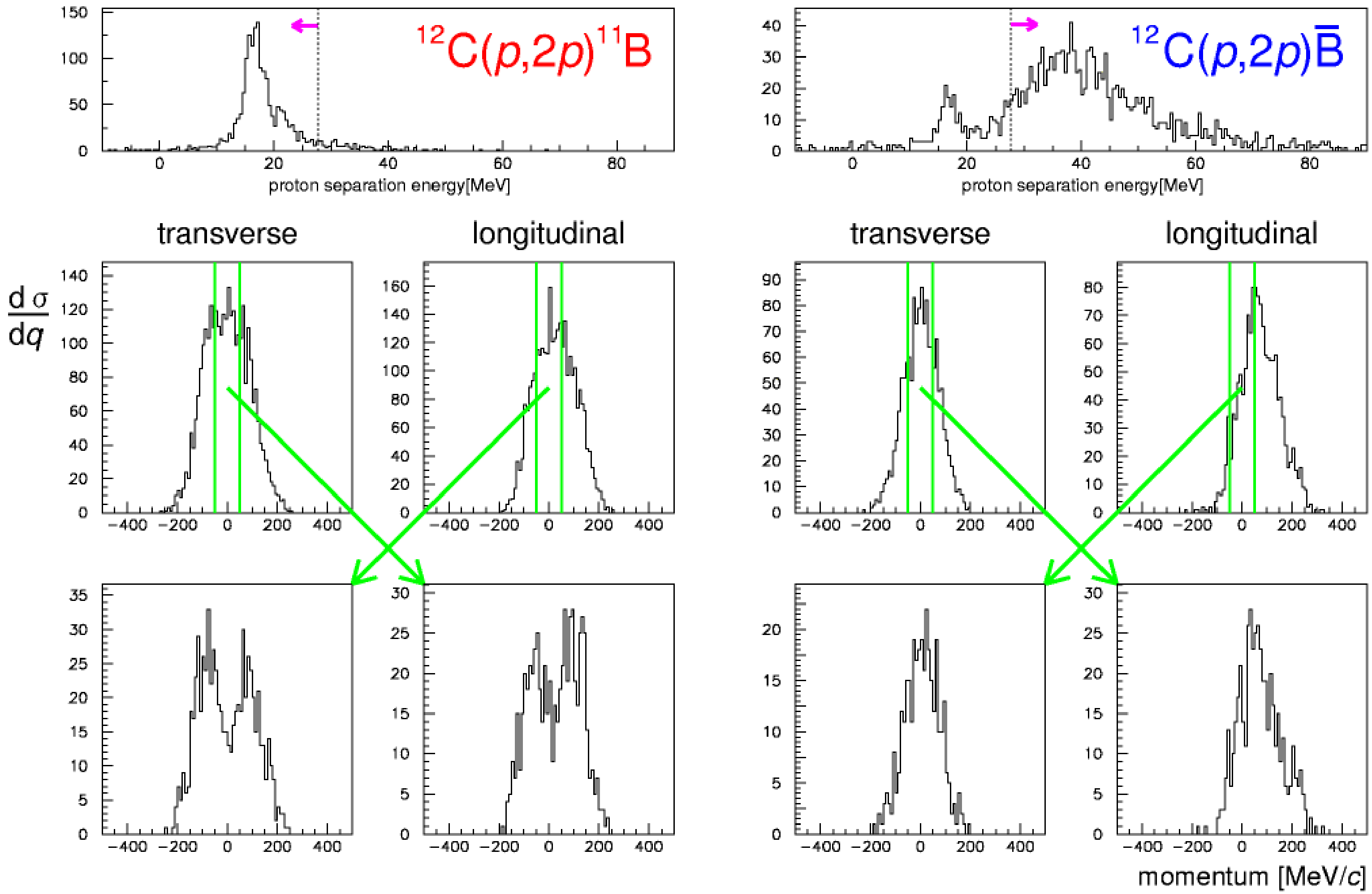

Z=1
Z=2
Z=3
Z=4
Z=5
A_hodo × β^2


He
4
Li
7
Be
10
B
11
A [amu]


12C(p,2p)X
12C(p,2p)B X
Sp=15.96 MeV
σ =1.4
offset 0.66
12C(p,2p)11B
ground state
+
low excitation states
12C(p,2p)10B X
12C(p,2p)B̄
deeply bound state
proton separation energy[MeV]


normal kinematics
Phys. Rev. C 26, 961(1982)

Discrimination of orbits

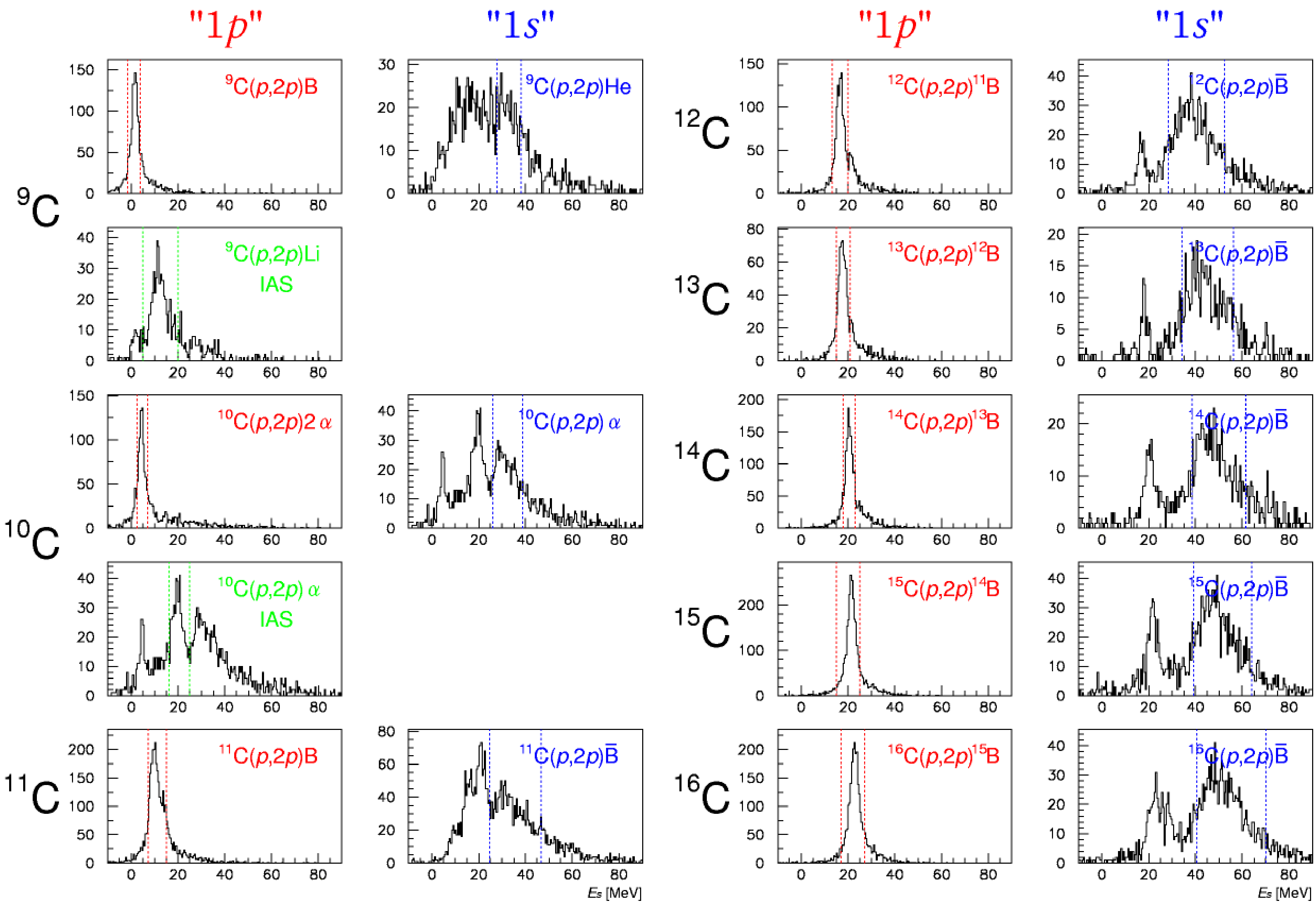


l=1
"1p"
^{11}B ground state

l=0
"1s"
$\bar{B}$ > proton emission threshold

Discrimination of orbits based on the decay mode of the residual nucleus.

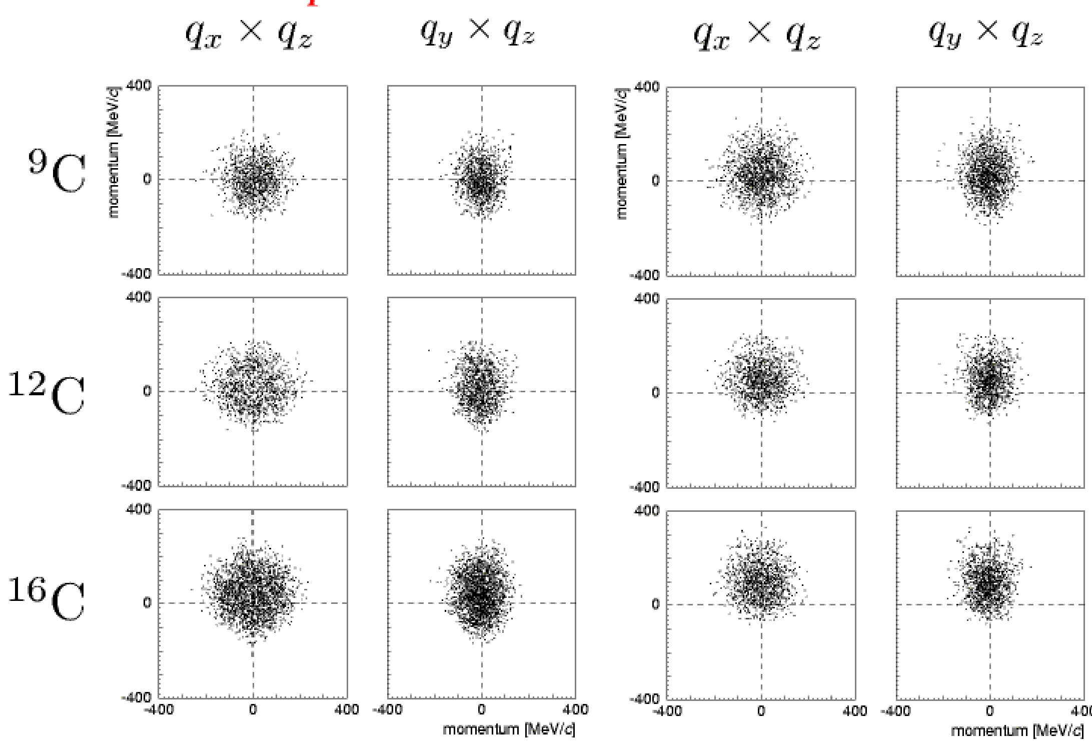
Energy spectra

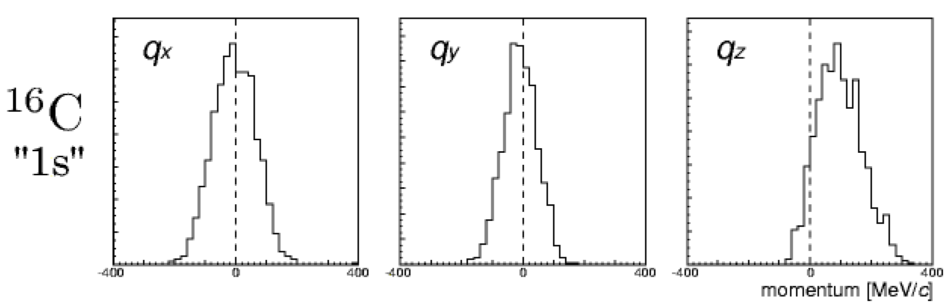


Correction for the acceptance

Momentum distributions

"$1p$" (GND) "$1s$"



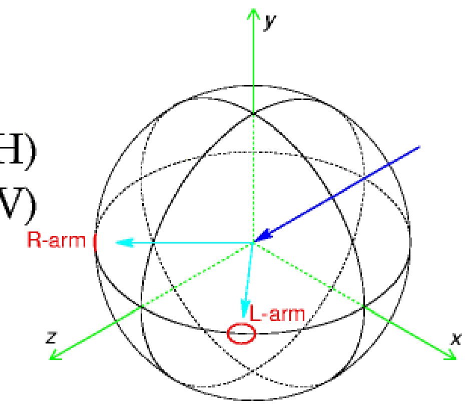


narrow off-center

Finite acceptance of detectors

$39^\circ \pm 9^\circ$ (H)

$0^\circ \pm 9^\circ$ (V)



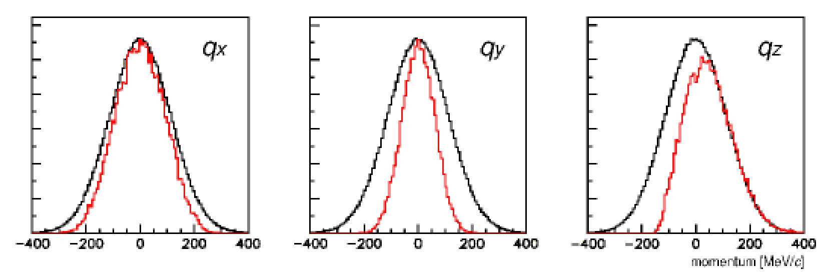
Simulation

- Momentum distribution
  $\cdots$harmonic oscillator.

$$\left.\frac{d^3\sigma}{d\vec{q}^3}\right|_{1s} \propto \exp\left(-\frac{|\vec{q}|^2}{\sigma_q^2}\right)$$

$$\left.\frac{d^3\sigma}{d\vec{q}^3}\right|_{1p} \propto |\vec{q}|^2 \exp\left(-\frac{|\vec{q}|^2}{\sigma_q^2}\right)$$

- Isotropic scattering in CM system.
- Select the events both protons enter L/R-arm.

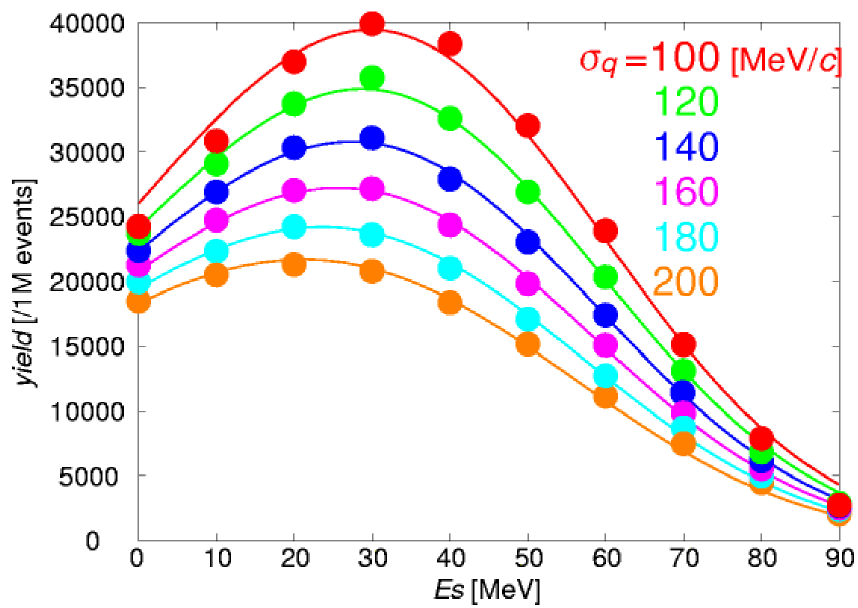


Correction for the acceptance (cont.)

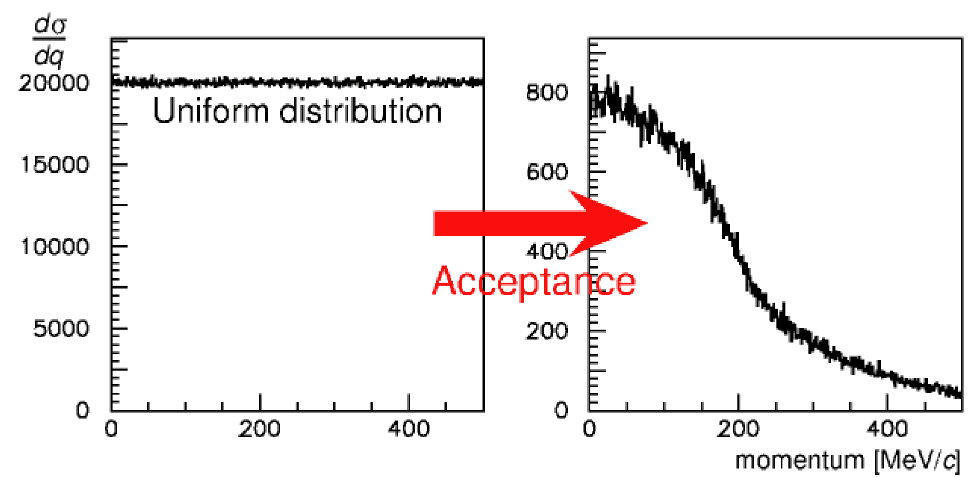
Correction of the proton separation energy spectrum.

Correction of the radial momentum distribution.

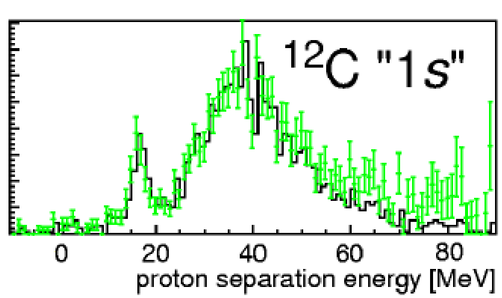
$Y^{1s}(E_s, \sigma_q)$ (simulation)

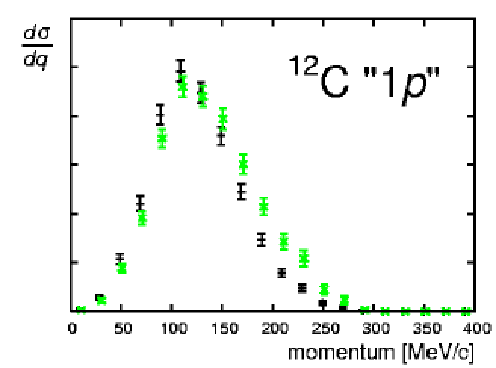


l=1, E_s=15.967 MeV (assuming ^{12}C)



Acceptance varies depending on the separation energy and the momentum.

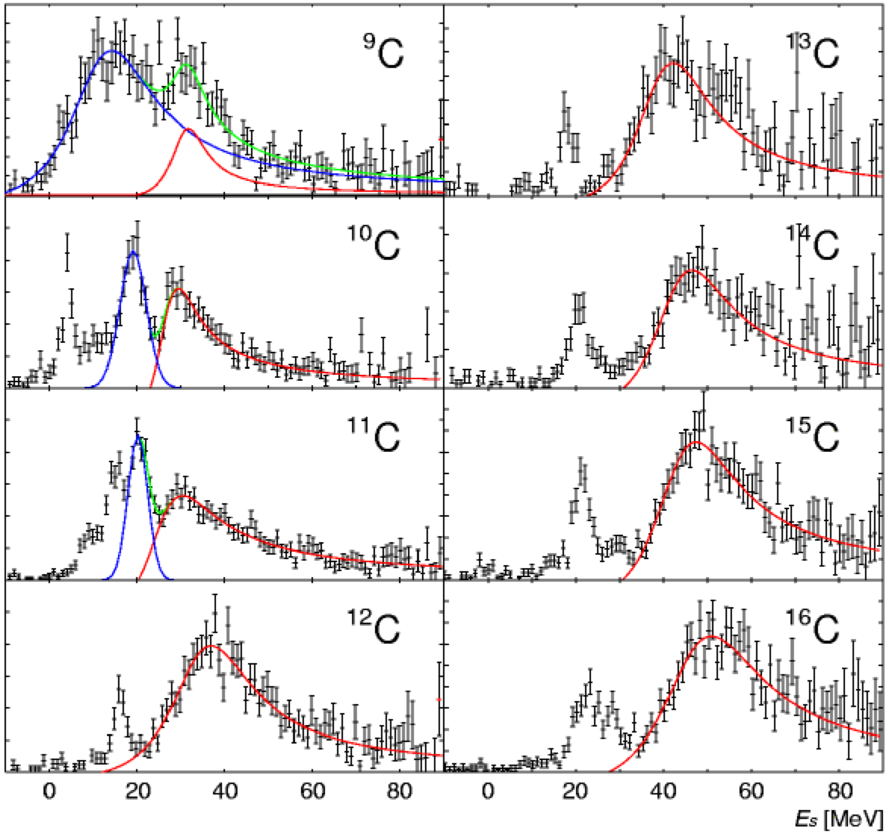




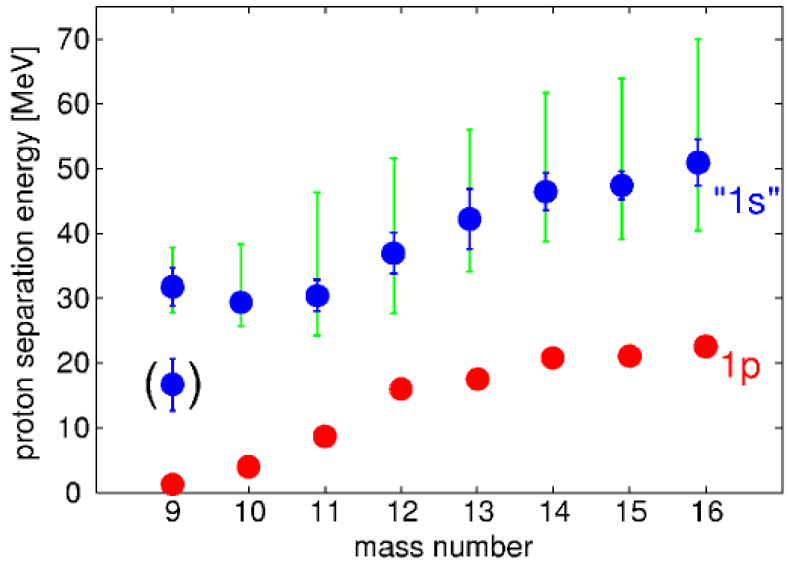
Proton separation energy of *s*-orbit

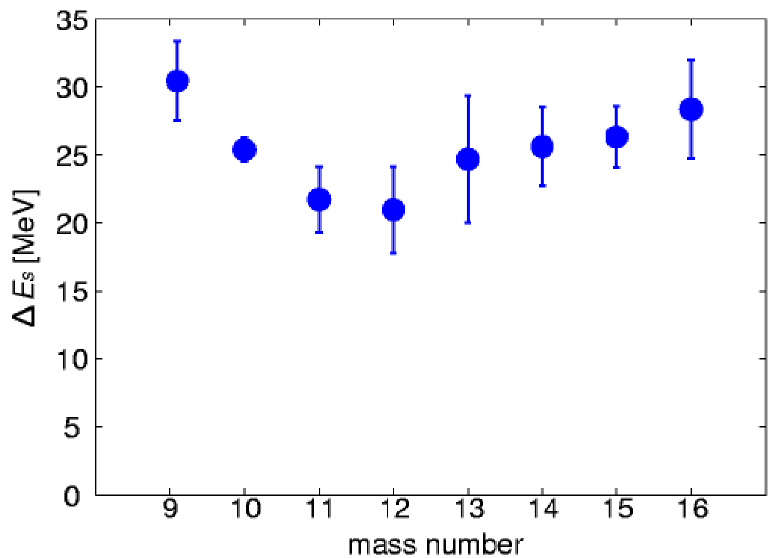
"1s" ··· assuming a function.

Phys. Rev. C 21, 2613 (1980)



Systematic observation of *s*-hole states.





- Minimum at ^{12}C .
- Increases toward both proton- and neutron-rich sides.

Momentum distribution

Radial momentum distribution $\dfrac{d\sigma}{dq}$

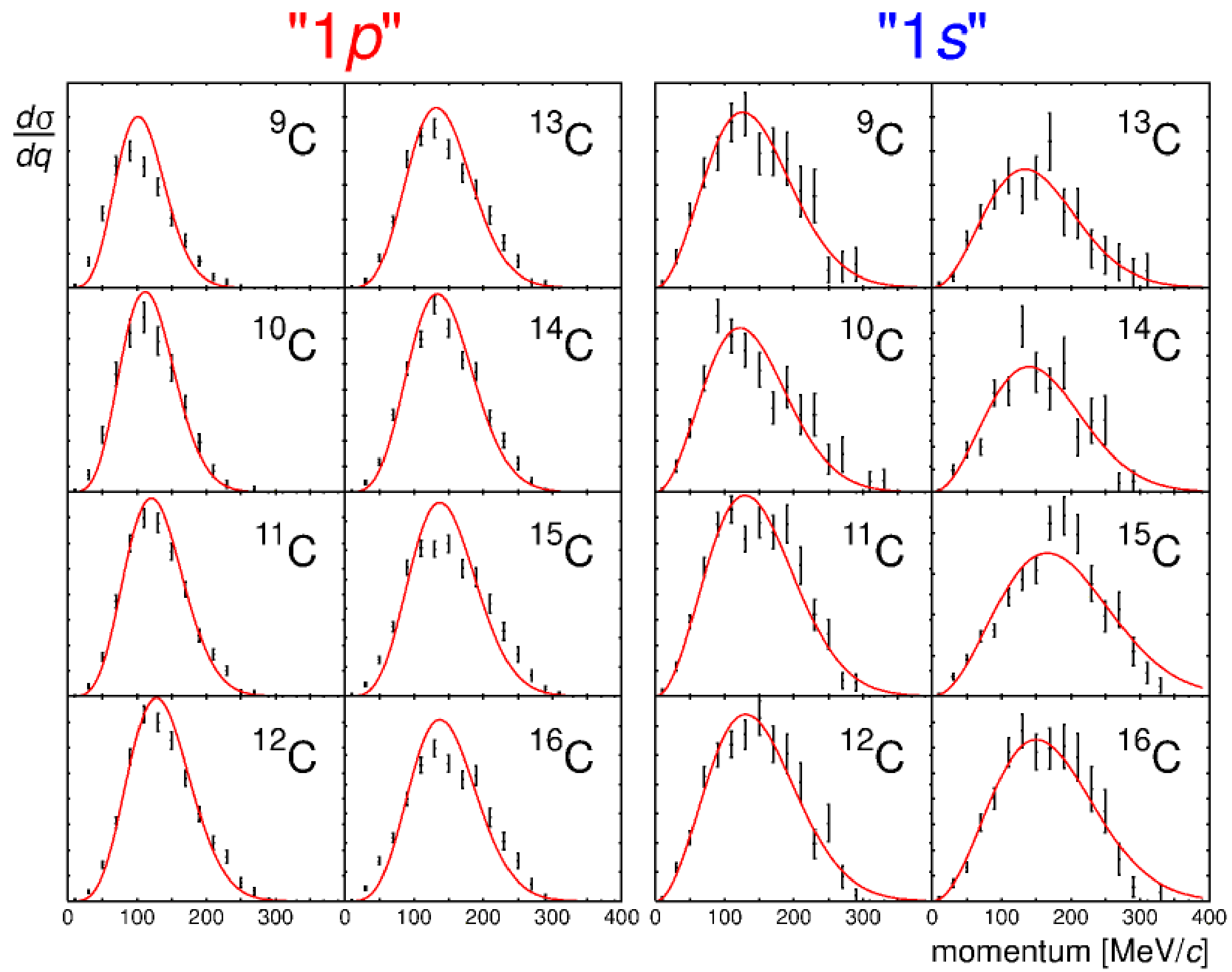
Harmonic oscillator:

- *s*-orbit

$$\left.\frac{d\sigma}{dq}\right|_{1s} \propto |\vec{q}|^2 \exp\left(-\frac{|\vec{q}|^2}{\sigma_q^2}\right)$$

- *p*-orbit

$$\left.\frac{d\sigma}{dq}\right|_{1p} \propto |\vec{q}|^4 \exp\left(-\frac{|\vec{q}|^2}{\sigma_q^2}\right)$$



Width of momentum distribution

σ_q of harmonic oscillator.

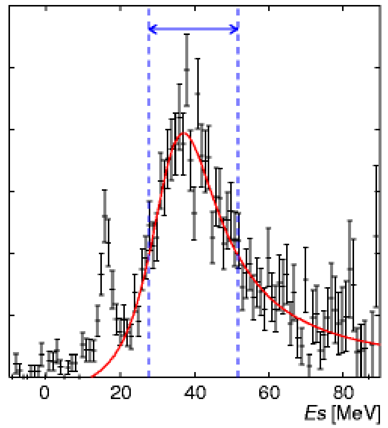
- *s*-orbit

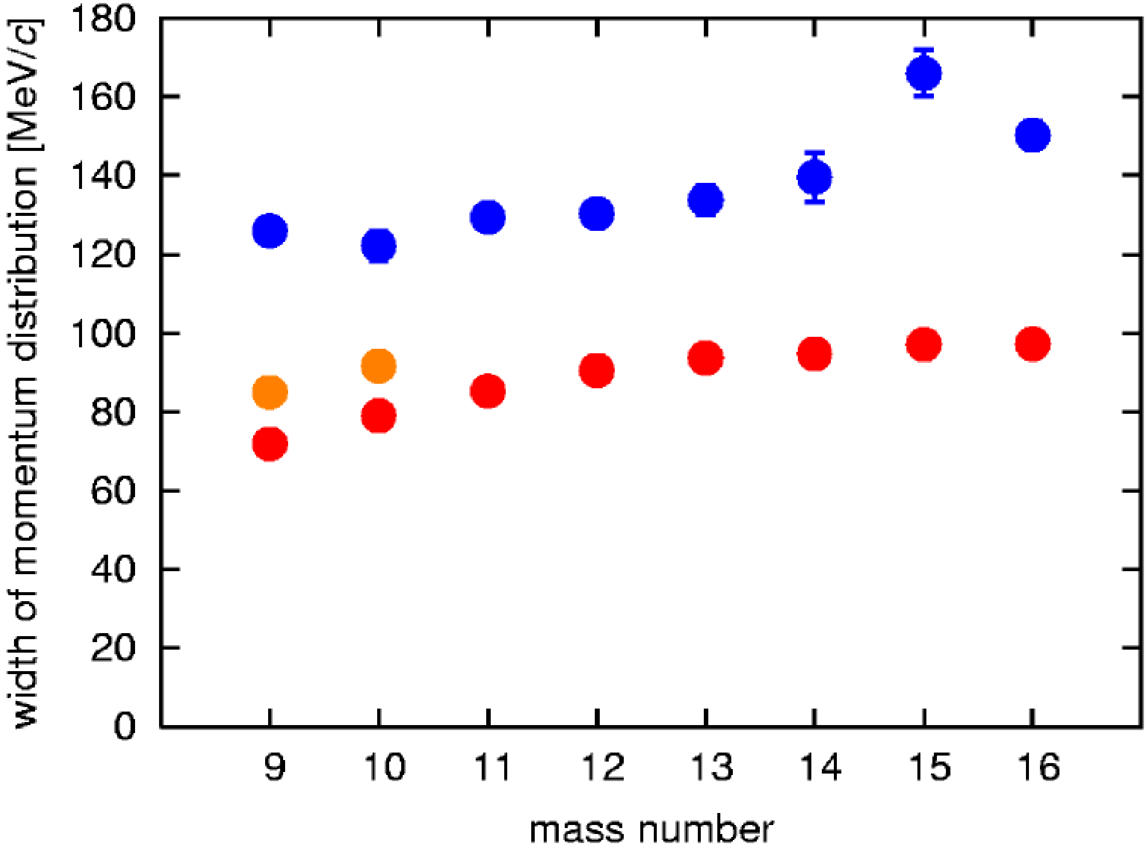
$$\left.\frac{d\sigma}{dq}\right|_{1s} \propto |\vec{q}|^2 \exp\left(-\frac{|\vec{q}|^2}{\sigma_q^2}\right)$$

- *p*-orbit

$$\left.\frac{d\sigma}{dq}\right|_{1p} \propto |\vec{q}|^4 \exp\left(-\frac{|\vec{q}|^2}{\sigma_q^2}\right)$$

Energy range



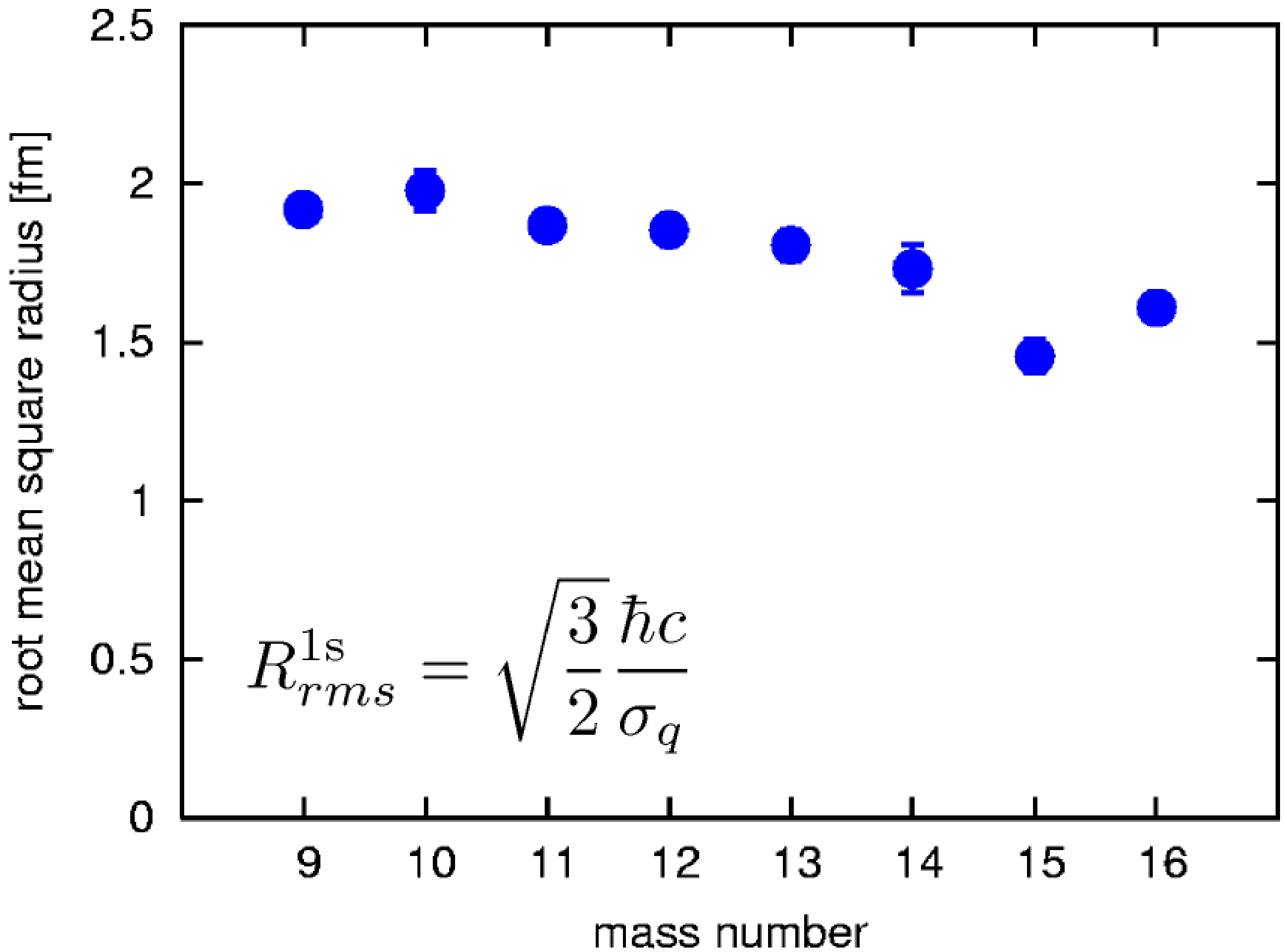


"1*s*"$\cdots$ σ_q increases with mass number in neutron rich side.

"1*p*"$\cdots$ σ_q decreases with mass number in proton rich side.

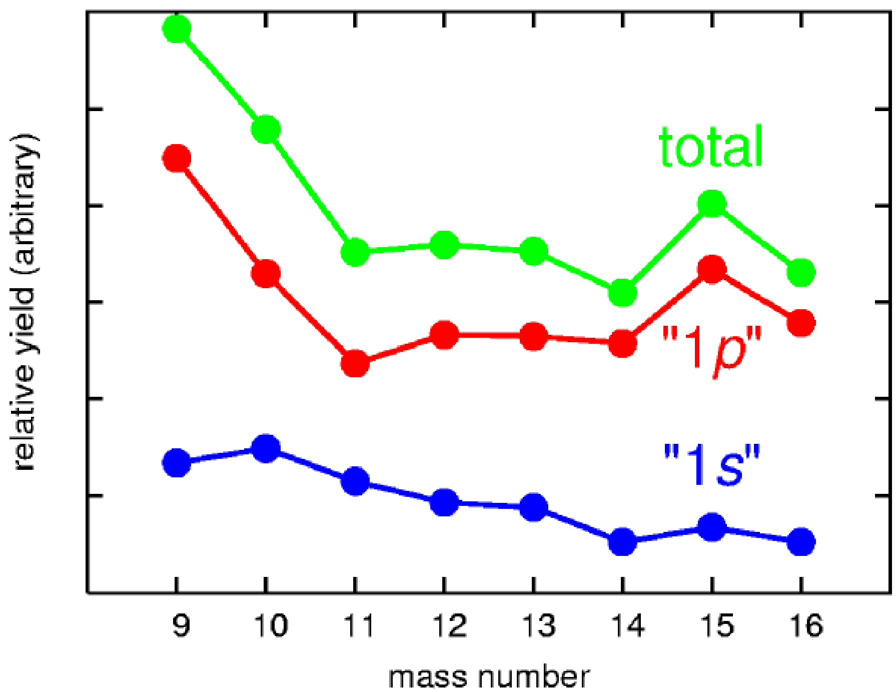
IAS$\cdots$ σ_q is broader than that of ground state.

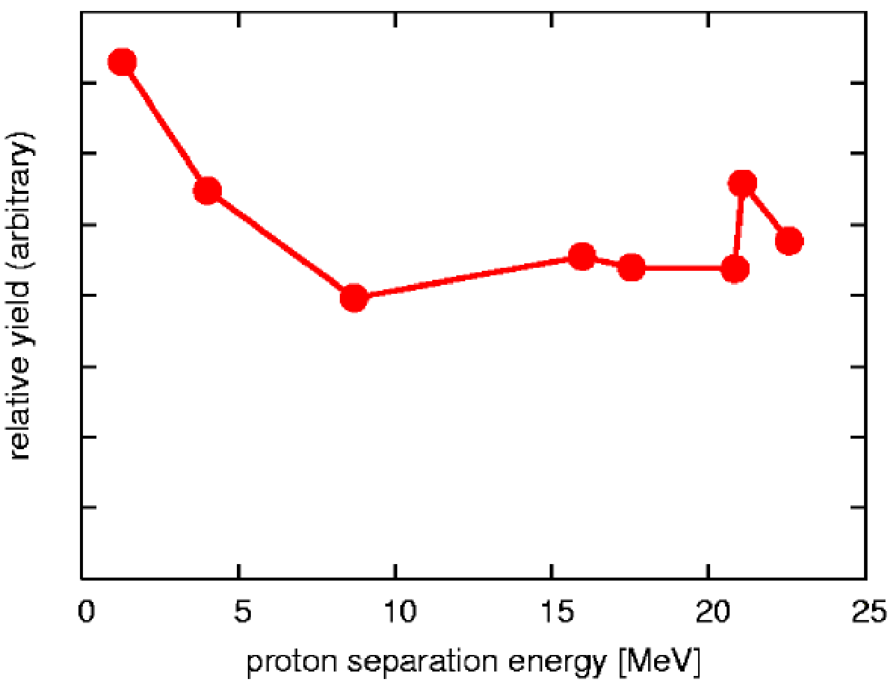
Root mean square radius of $\pi\ s_{1/2}$-orbit



Shrinkage of $\pi\ s_{1/2}$-orbit.

Relative yield





Total$\cdots$Almost constant between ^{11}C and ^{16}C .

Increase in ^{9,10}C $\leftarrow$ "1p".

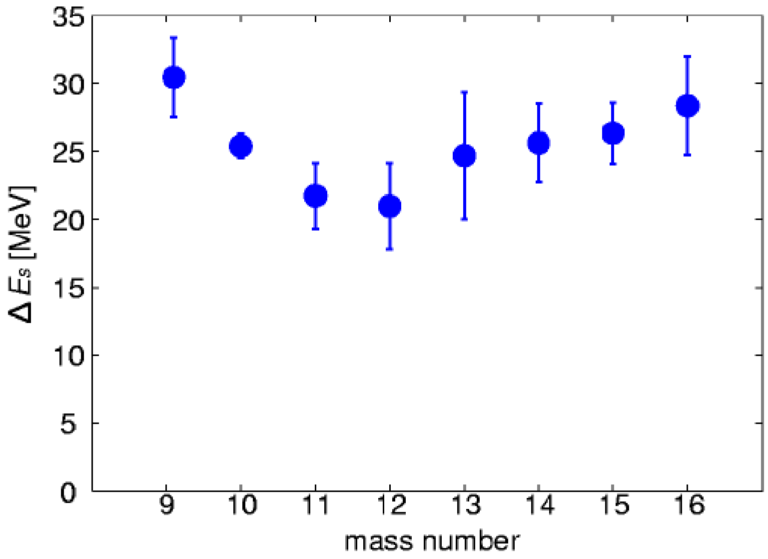
Weakly bound nucleon $\rightarrow$ easy-to-be knocked-out.

Summary

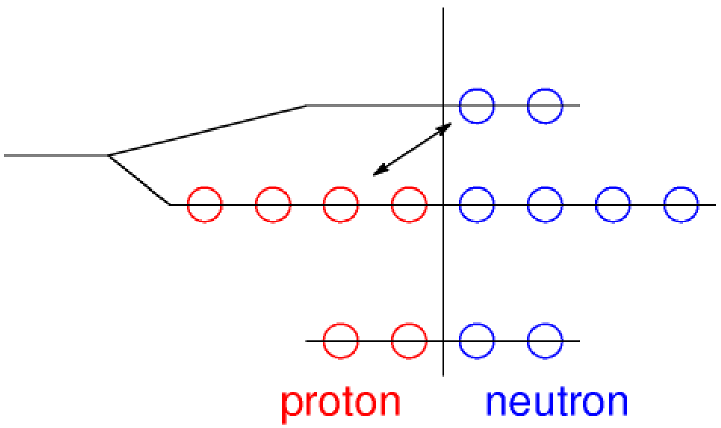
- Proton knockout reaction is one of the powerful tools to study the single particle states of bound protons in nucleus.
- We studied (*p*,2*p*) reactions on $^{9\text{-}16}\mathrm{C}$ with the inverse kinematics to observe:
  - Proton separation energy,
  - Momentum of bound proton in nuclei,
  - Decay mode of the residual nucleus.
- We established the methodology of proton knockout experiment with the inverse kinematics.

- The energy resolution is typically 1.4 MeV (rms).
- Discrimination of knockouts from *p*- and *s*-orbit could be achieved based on the decay mode of residual nucleus.
- We observed the proton sigle particle states, especially deeply-bound $\pi\ s_{1/2}$-orbit, systematically.
  - Energy gap shows minimum at $^{12}\mathrm{C}$, and increases toward both proton- and neutron-rich sides.
  - σ_q of *p*-orbit decreases in proton-rich side.
  - σ_q of *s*-orbit increases in neutron-rich side.
  - Relative yields increase in $^{9,10}\mathrm{C}$, because of the effect of *p*-orbit.

l-*s* splitting



Phys. Rev. Lett 87, 082502 (2001)

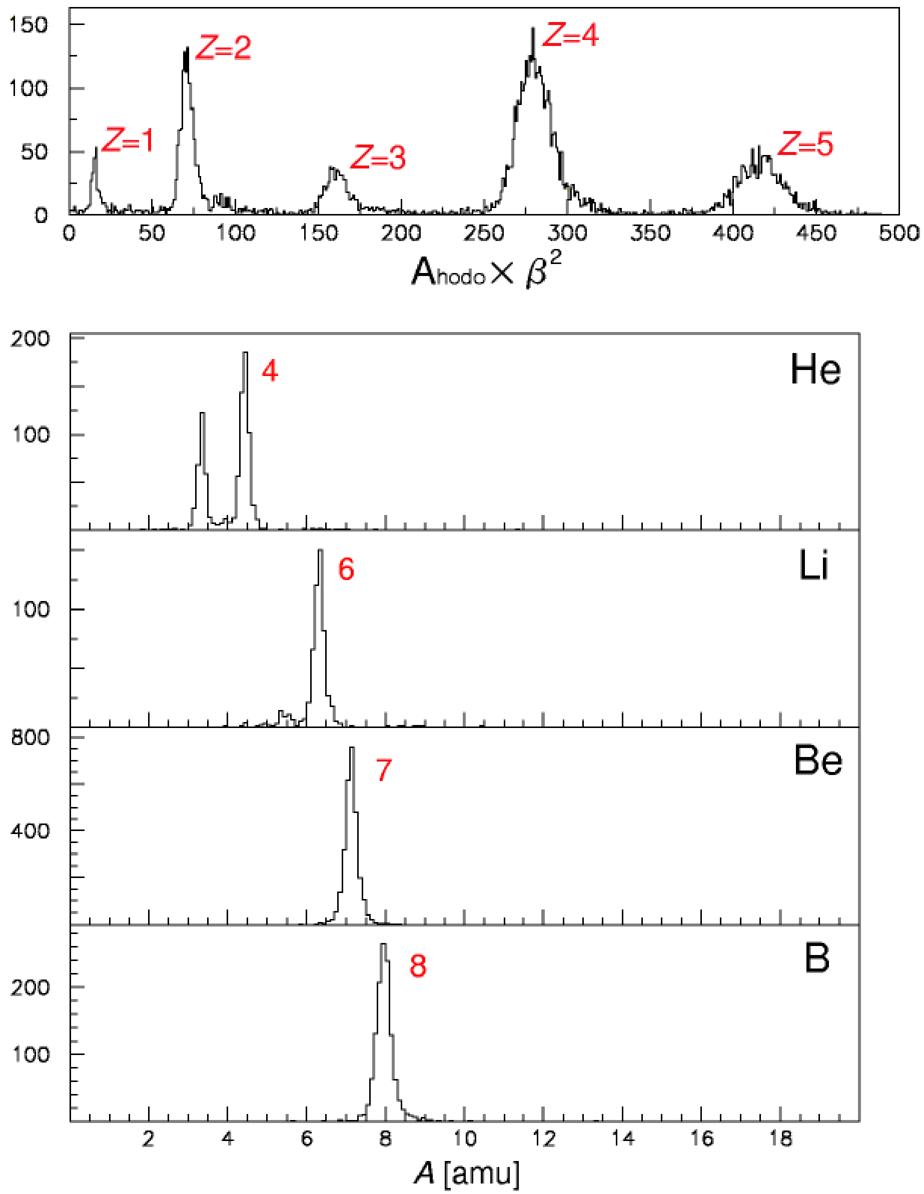


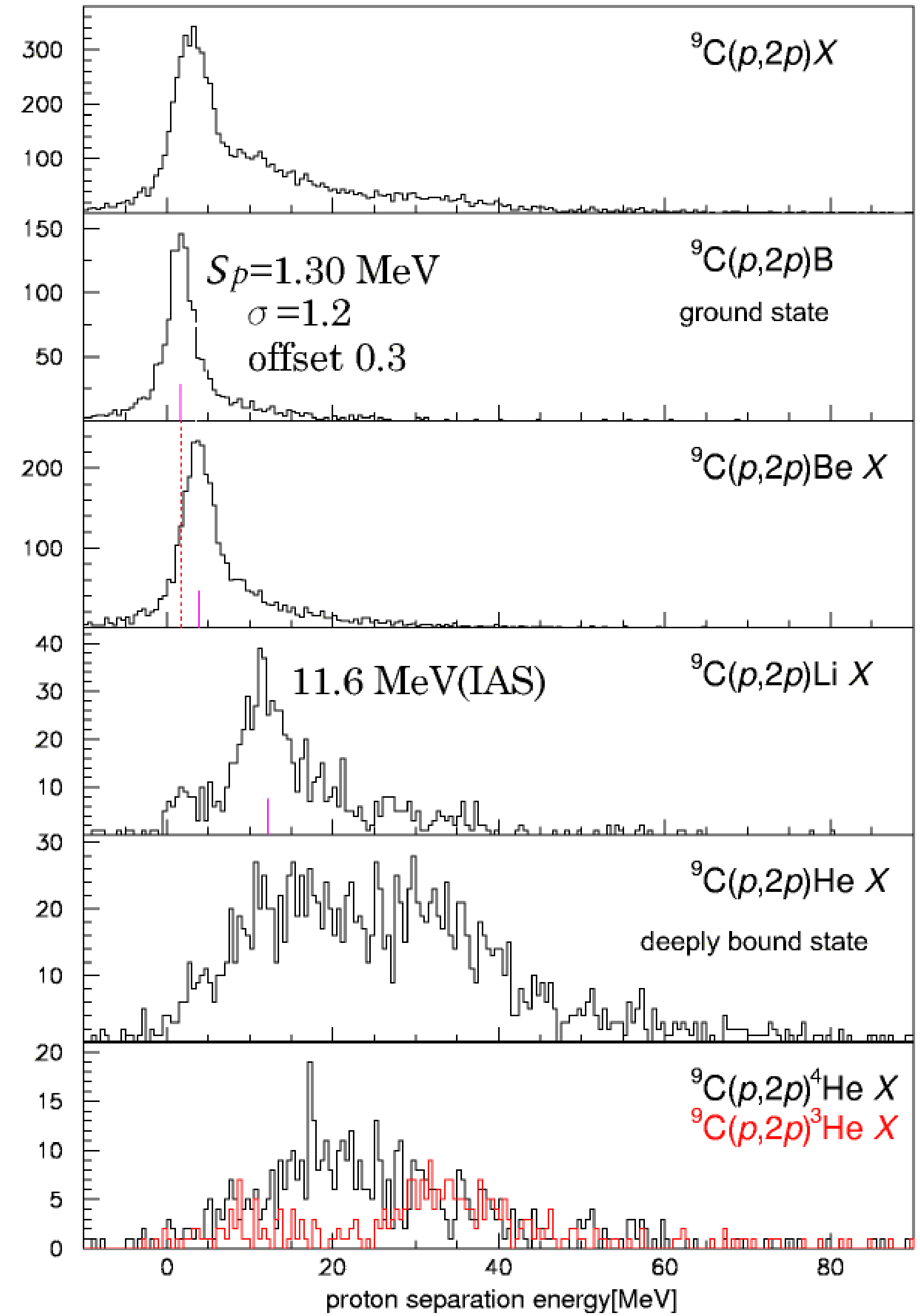
$j_> = l + \frac{1}{2}$ protons

$\updownarrow$ attractive force

$j_< = l - \frac{1}{2}$ neutrons

$p(^{9}\mathrm{C},2p)^{8}\mathrm{B}^{*}$

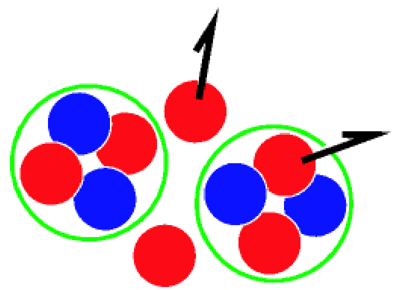




$p(^{10}\mathrm{C},2p)\,^{9}\mathrm{B}^{*}$

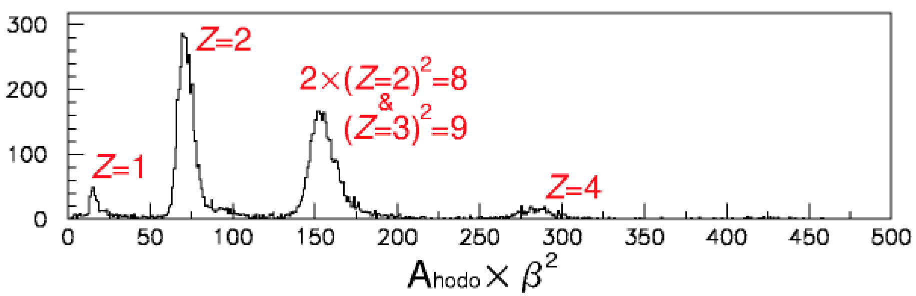
^{9}B:unbound

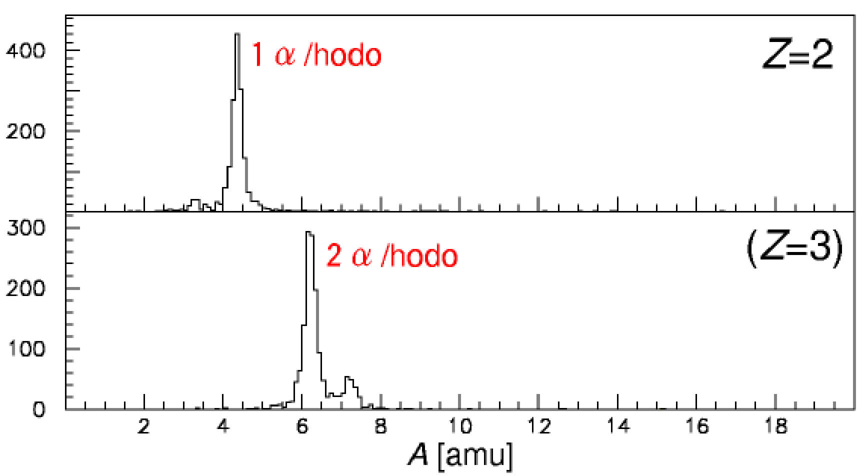
$$^{9}\mathrm{B} \rightarrow {}^{8}\mathrm{Be}+p$$
$$\searrow \quad 2\alpha$$

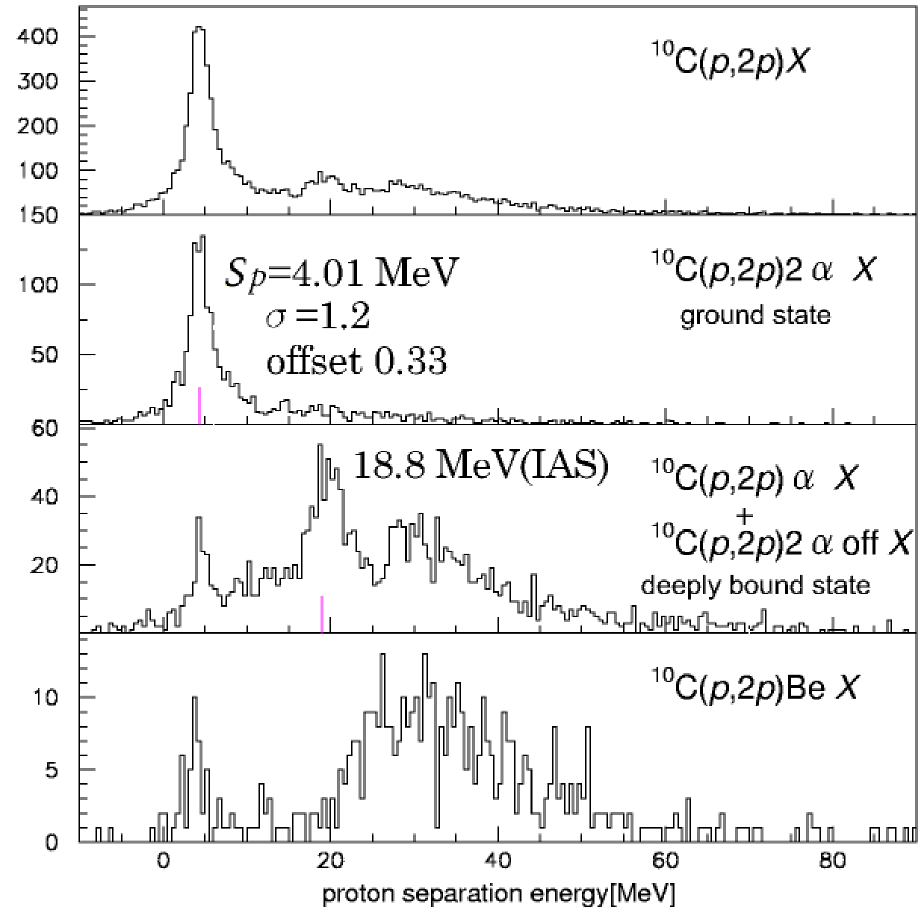


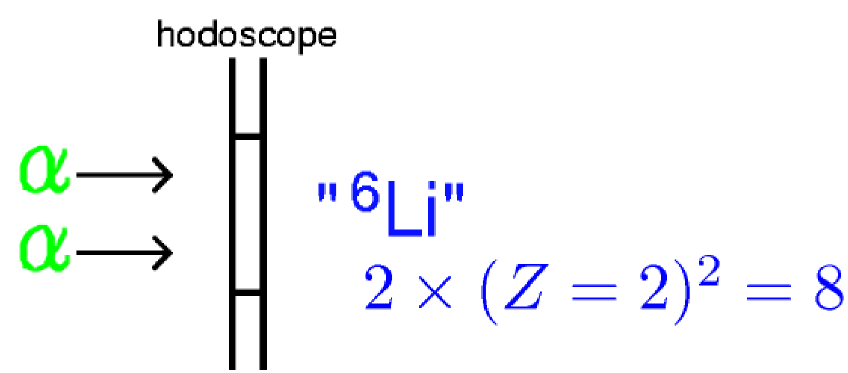
$Q_p(^{9}\mathrm{B})=185.1$ [keV]

$Q_\alpha(^{8}\mathrm{Be})=91.8$ [keV]

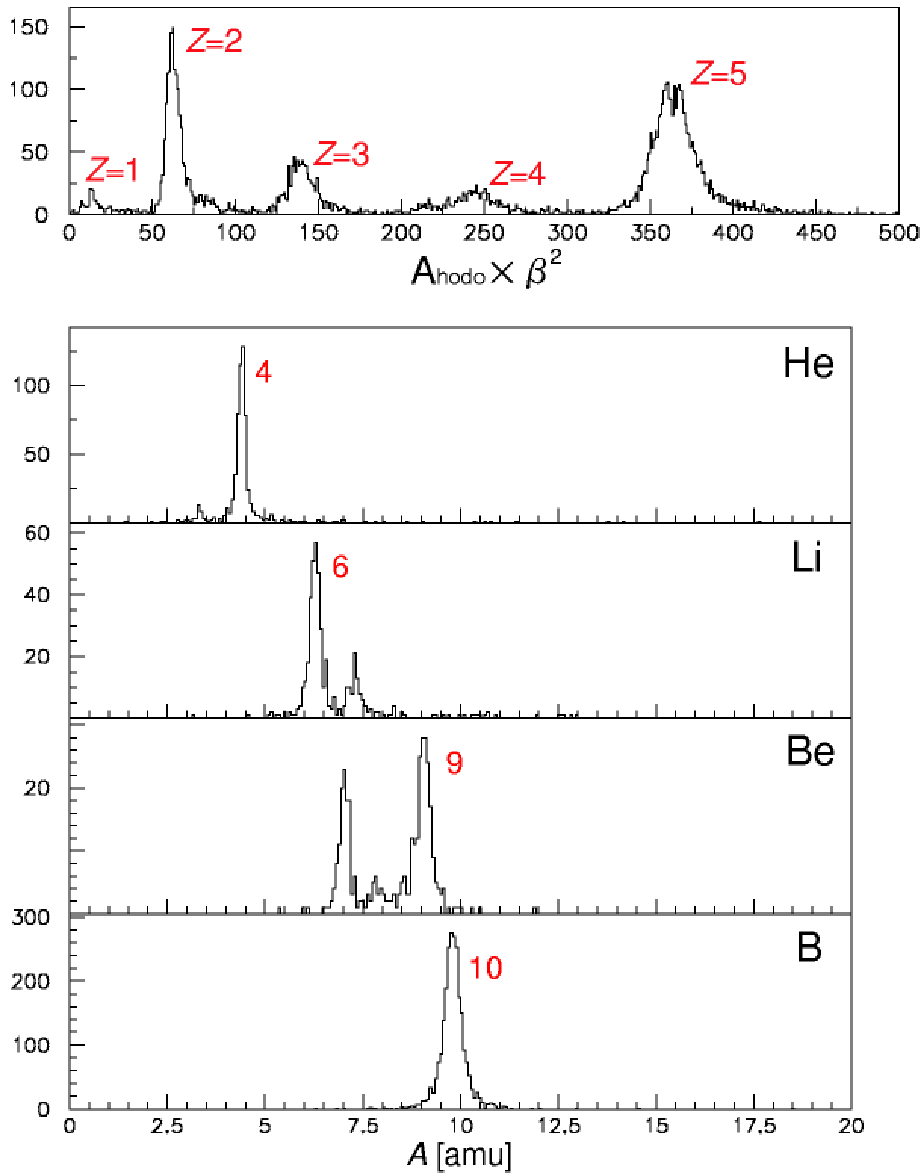




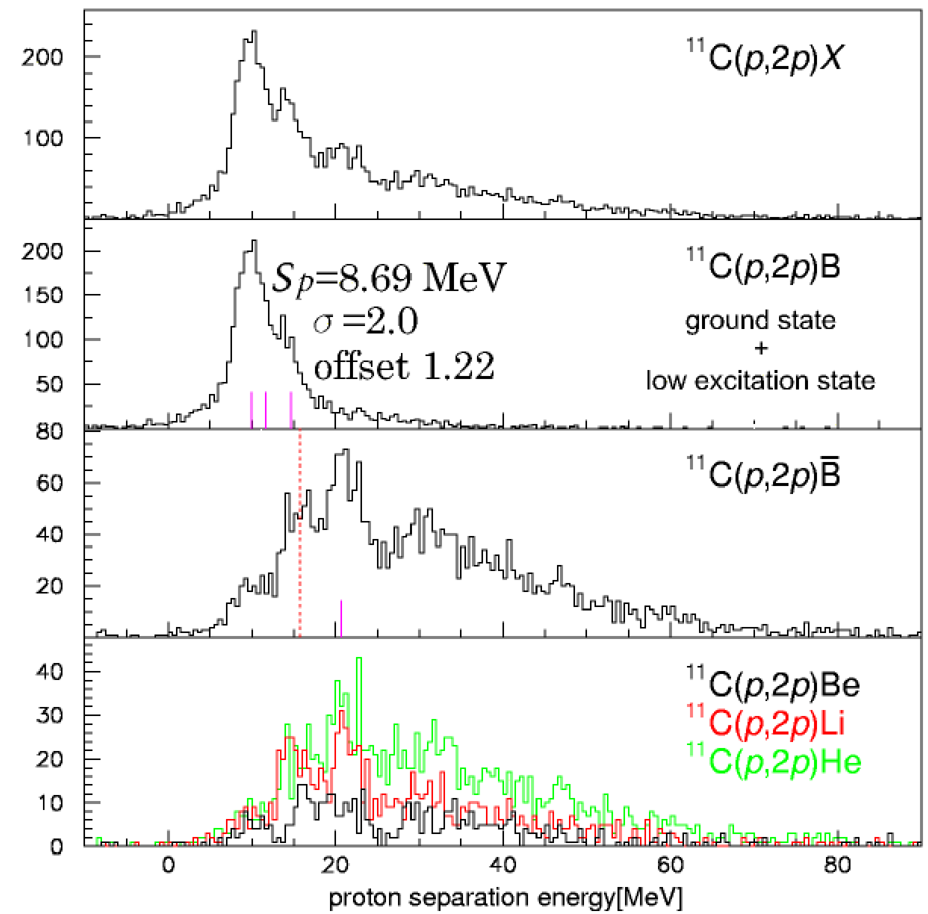




$p(^{11}C,2p)^{10}B^*$

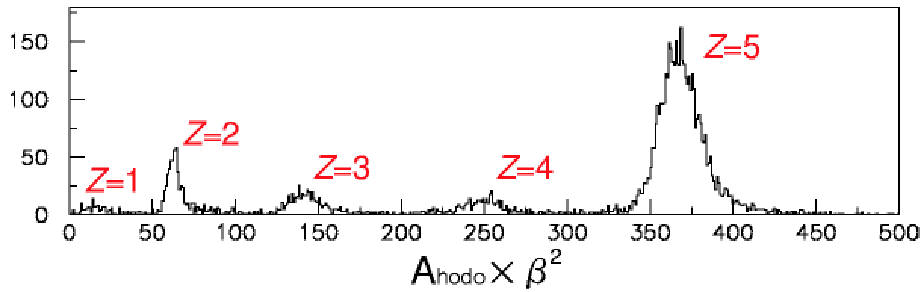


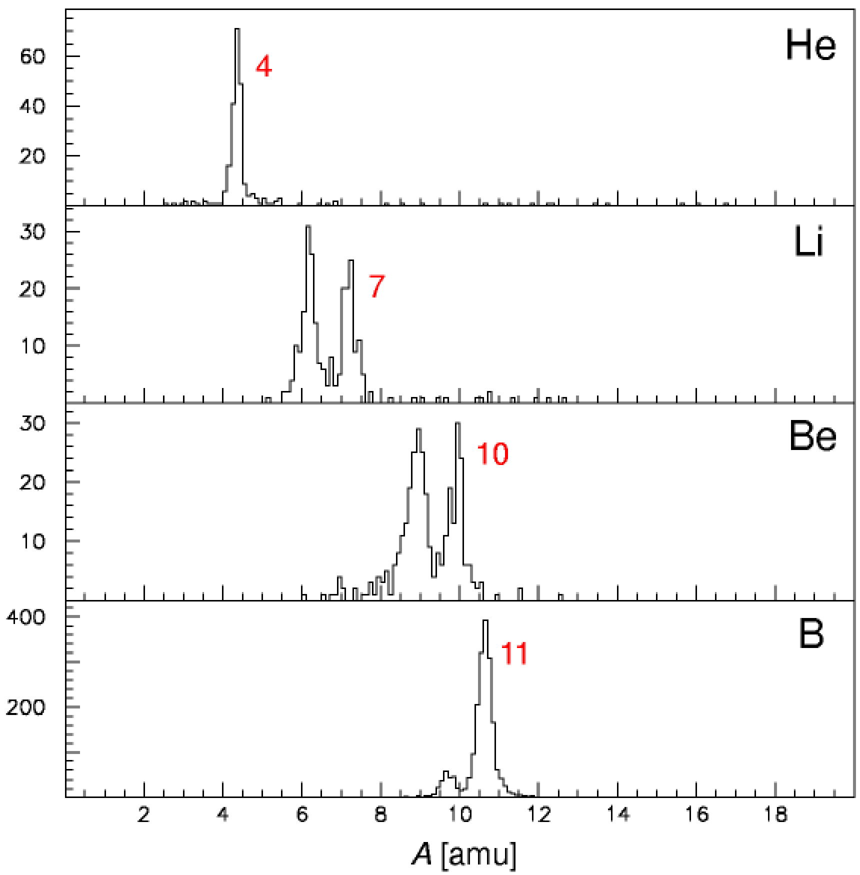
Z=1
Z=2
Z=3
Z=4
Z=5
A_{hodo} × β²
He
4
Li
6
Be
9
B
10
A [amu]

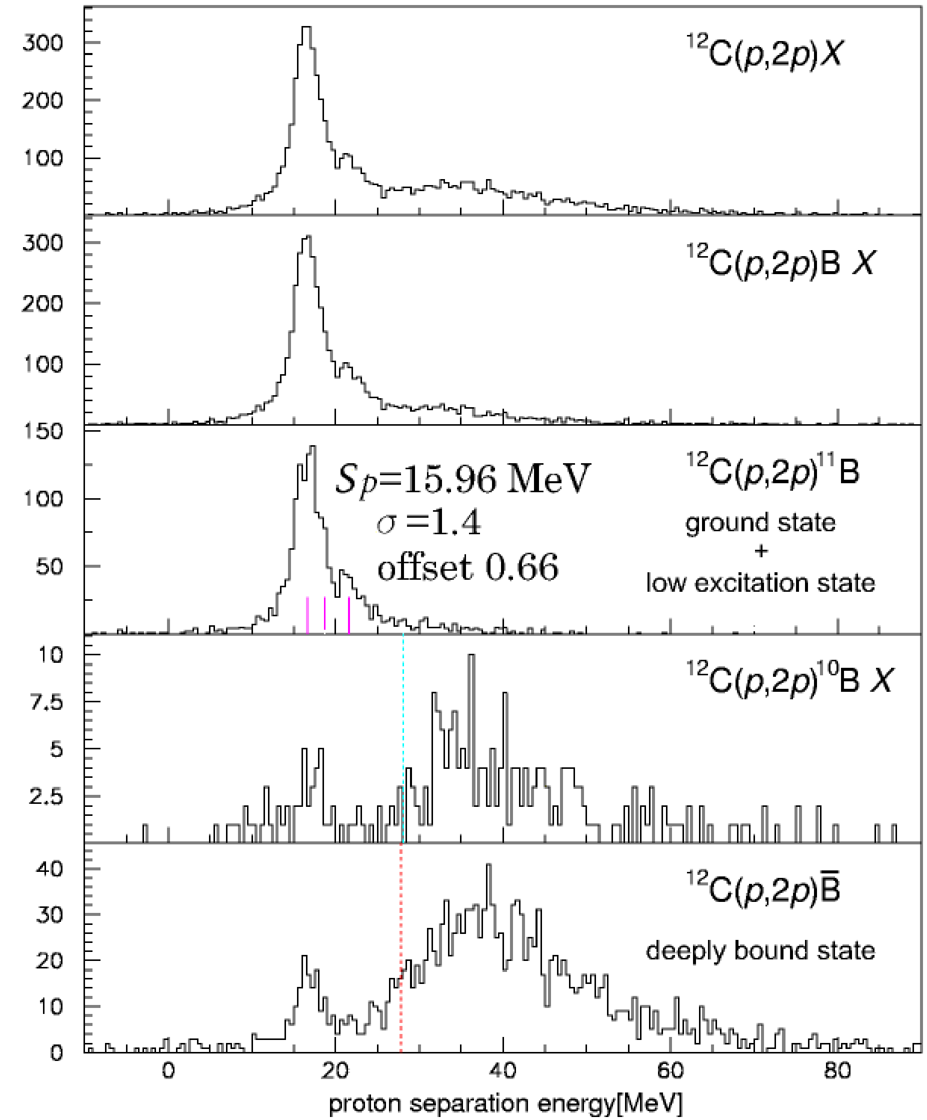


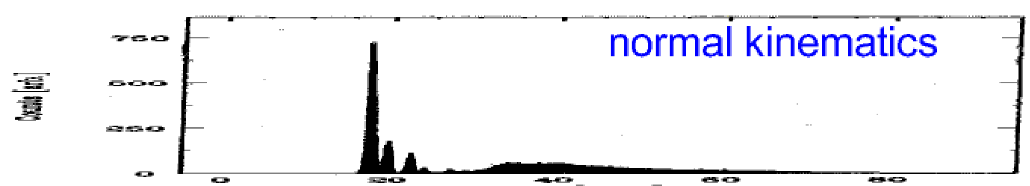
¹¹C(p,2p)X
¹¹C(p,2p)B
Sp=8.69 MeV
σ =2.0
offset 1.22
ground state
+
low excitation state
¹¹C(p,2p)B̄
¹¹C(p,2p)Be
¹¹C(p,2p)Li
¹¹C(p,2p)He
proton separation energy[MeV]

$p(^{12}C,2p)^{11}B^*$

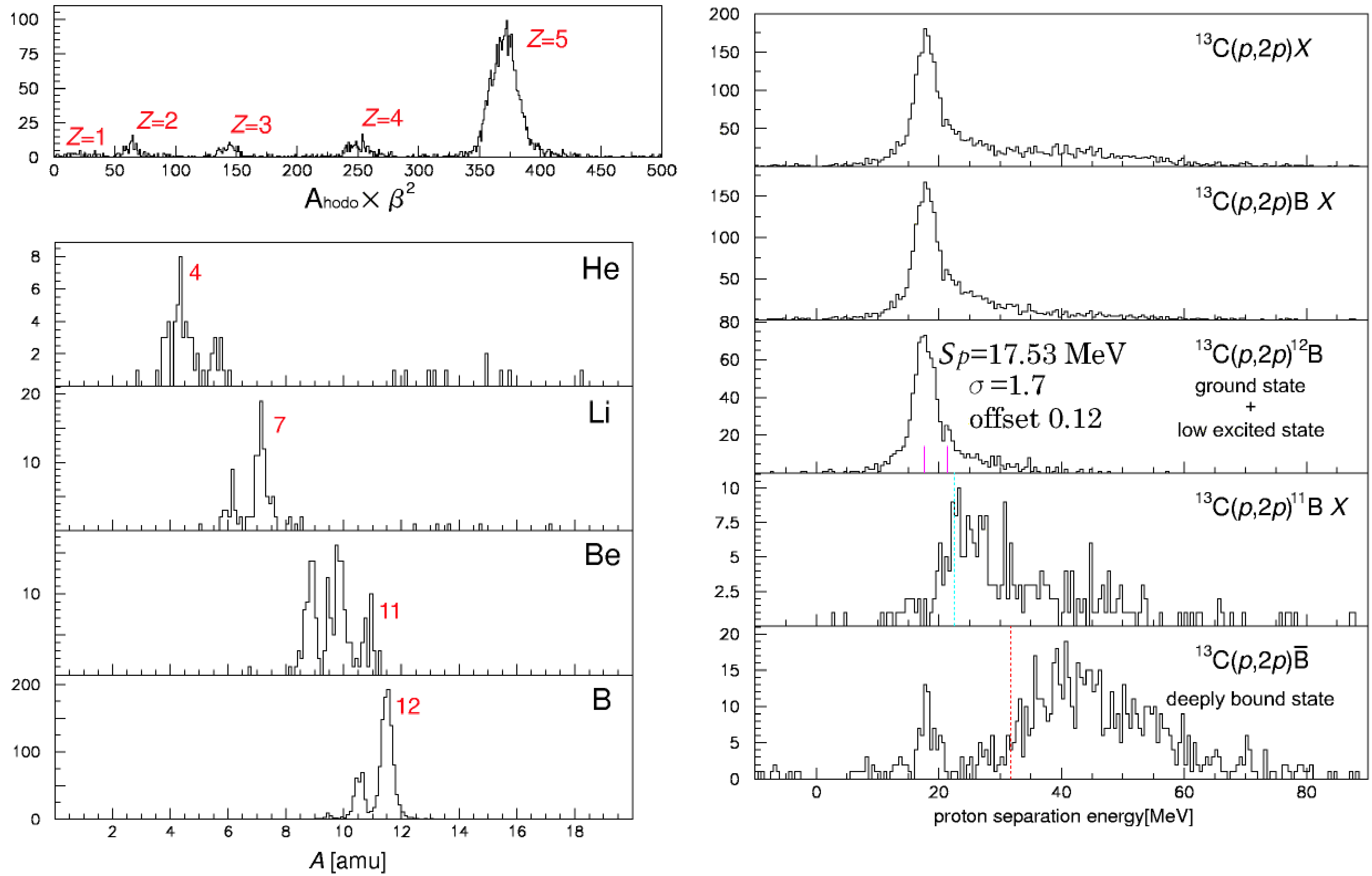

Z=1
Z=2
Z=3
Z=4
Z=5
A_hodo × β²


He
4
Li
7
Be
10
B
11
A [amu]

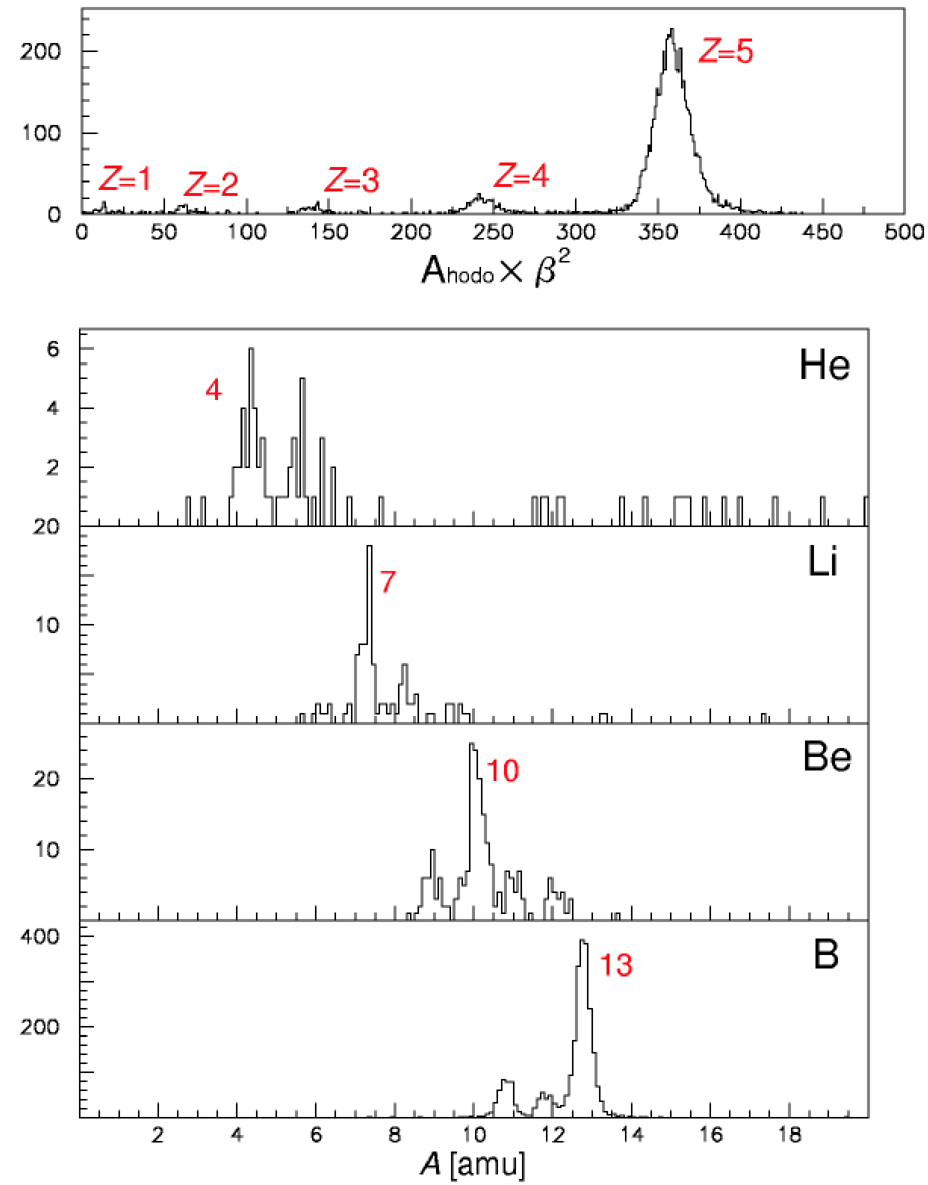

¹²C(p,2p)X
¹²C(p,2p)B X
¹²C(p,2p)¹¹B
ground state
+
low excitation state
Sp=15.96 MeV
σ =1.4
offset 0.66
¹²C(p,2p)¹⁰B X
¹²C(p,2p)B̄
deeply bound state
proton separation energy[MeV]

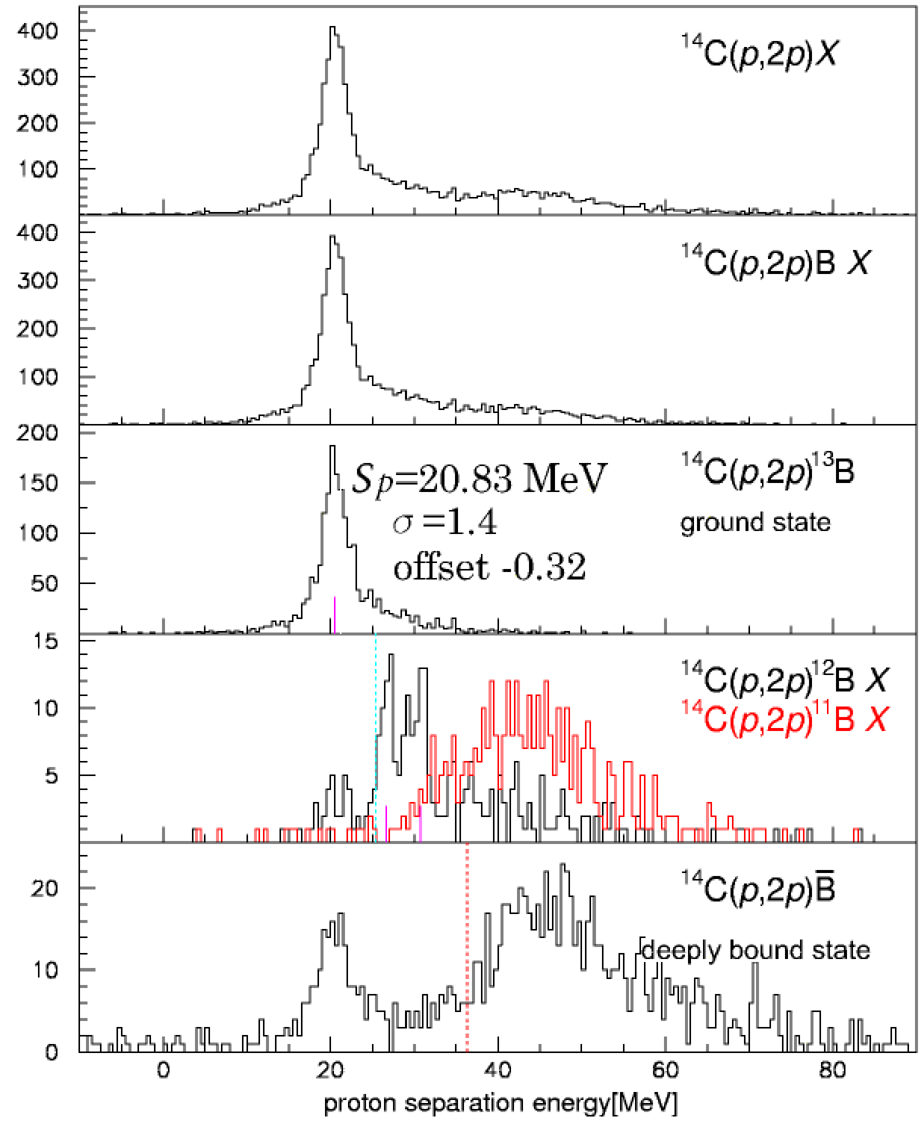

normal kinematics

$p(^{13}\mathrm{C},2p)^{12}\mathrm{B}^*$

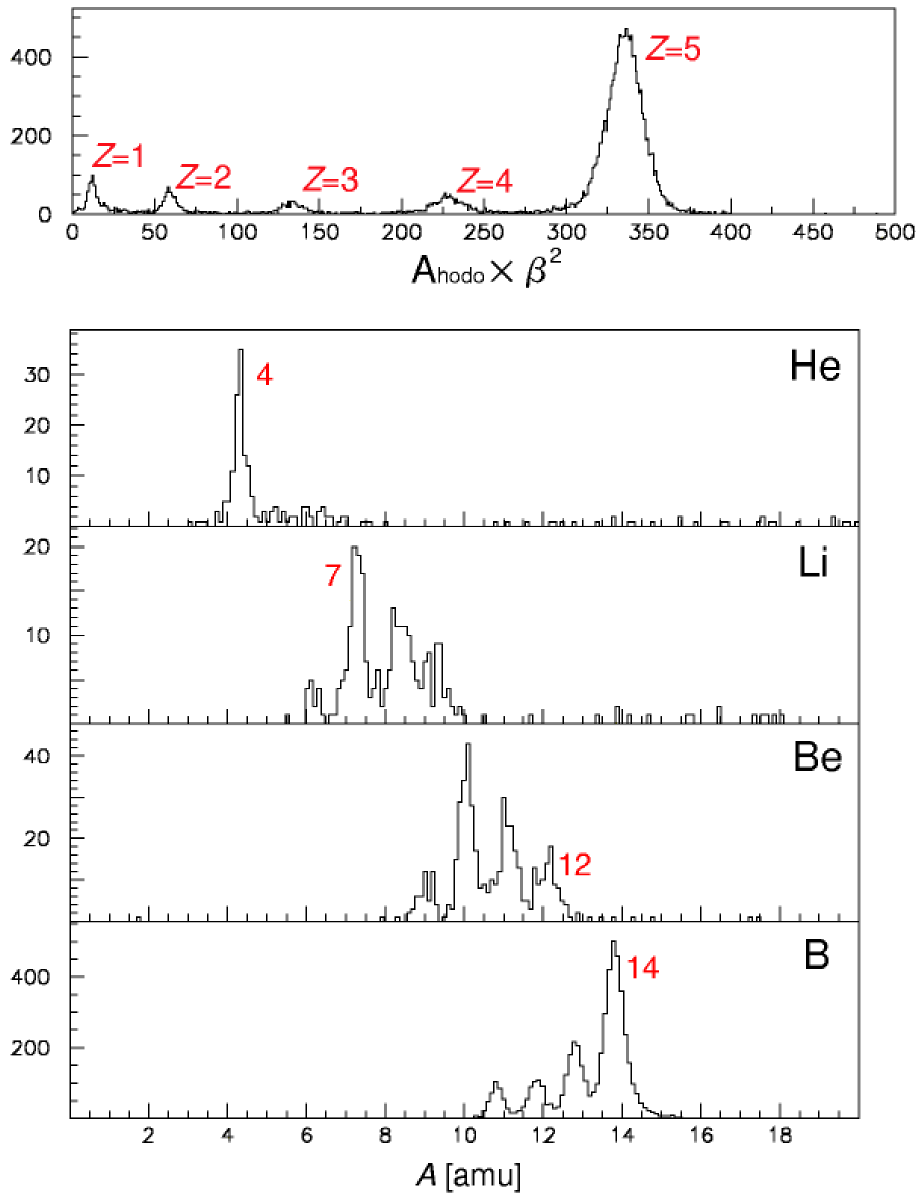


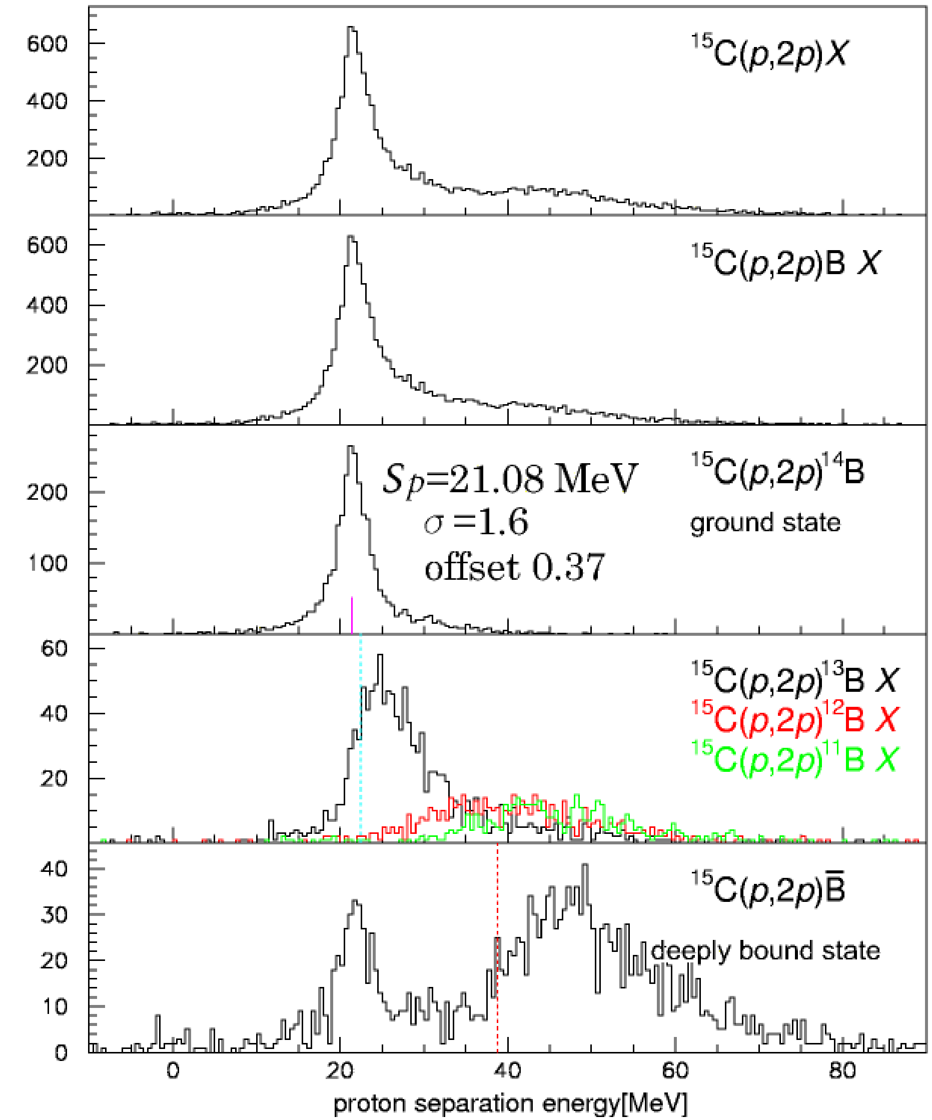
$p(^{14}C,2p)^{13}B^*$


Z=1
Z=2
Z=3
Z=4
Z=5
$A_{hodo} \times \beta^2$
He
4
Li
7
Be
10
B
13
A [amu]

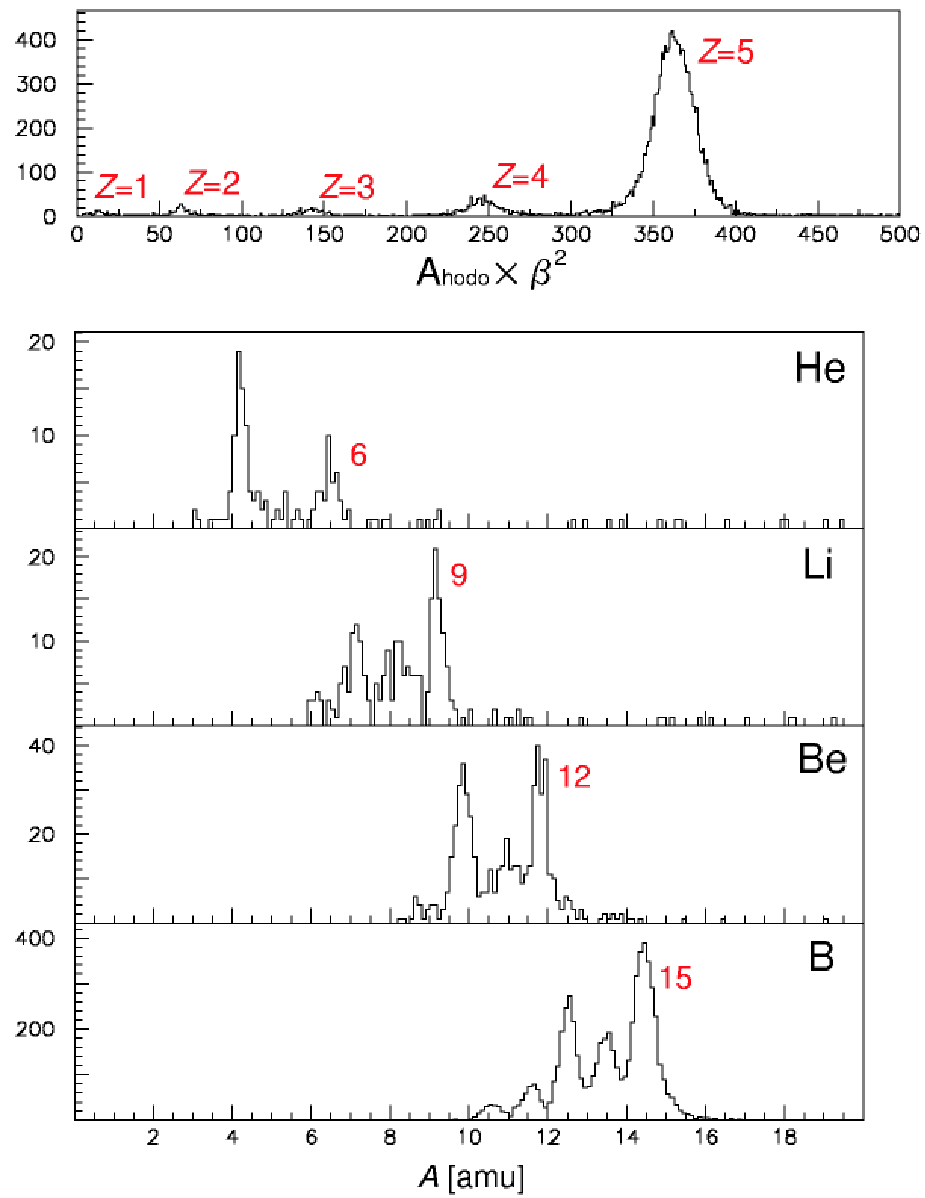

$^{14}C(p,2p)X$
$^{14}C(p,2p)B\ X$
$^{14}C(p,2p)^{13}B$
ground state
S_p=20.83 MeV
σ=1.4
offset -0.32
$^{14}C(p,2p)^{12}B\ X$
$^{14}C(p,2p)^{11}B\ X$
$^{14}C(p,2p)\bar{B}$
deeply bound state
proton separation energy[MeV]

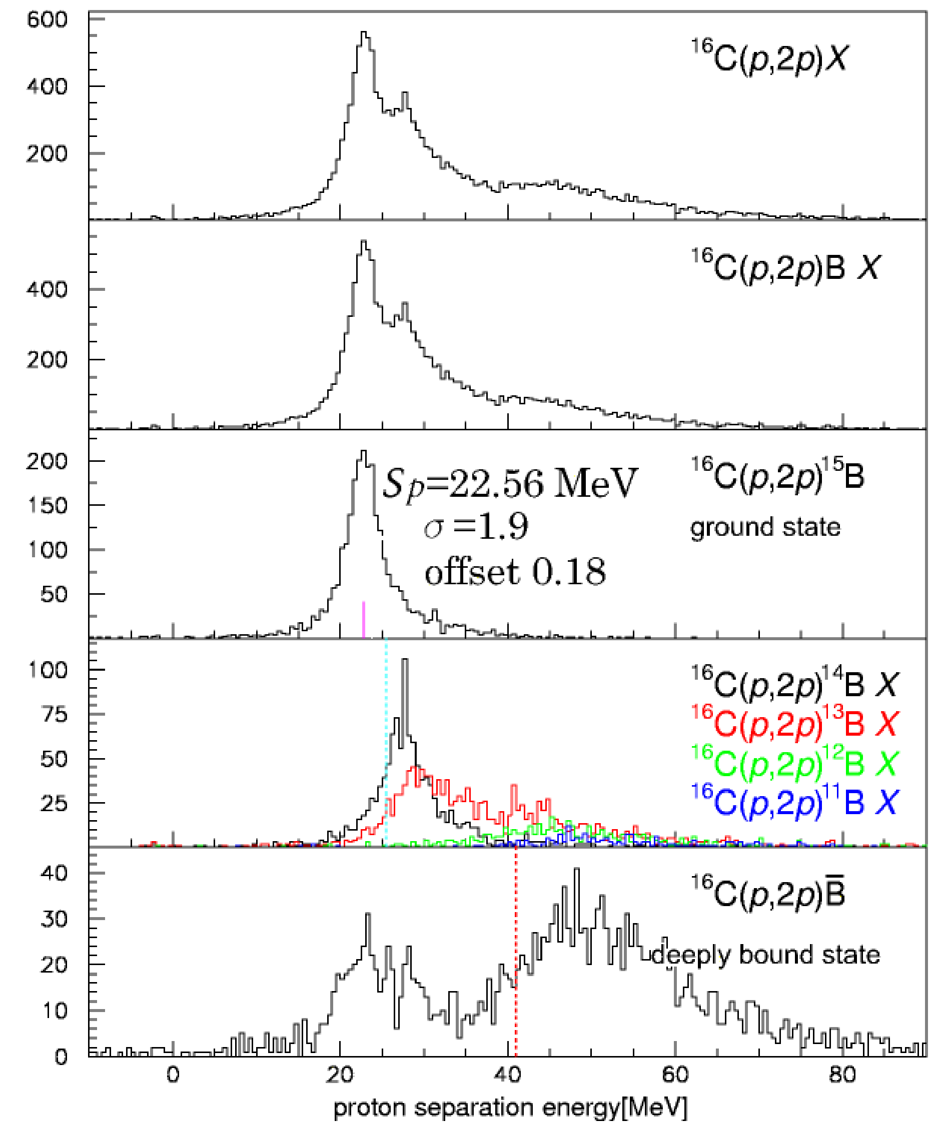
$p(^{15}\mathrm{C},2p)^{14}\mathrm{B}^*$





$p(^{16}\mathrm{C},2p)^{15}\mathrm{B}^{*}$





Momentum density distribution

Momentum density distribution $\frac{d^3\sigma}{d\vec{q}^3}$