Recent measurements of reaction cross section and related topics

Intermediate energies (<100 A MeV)

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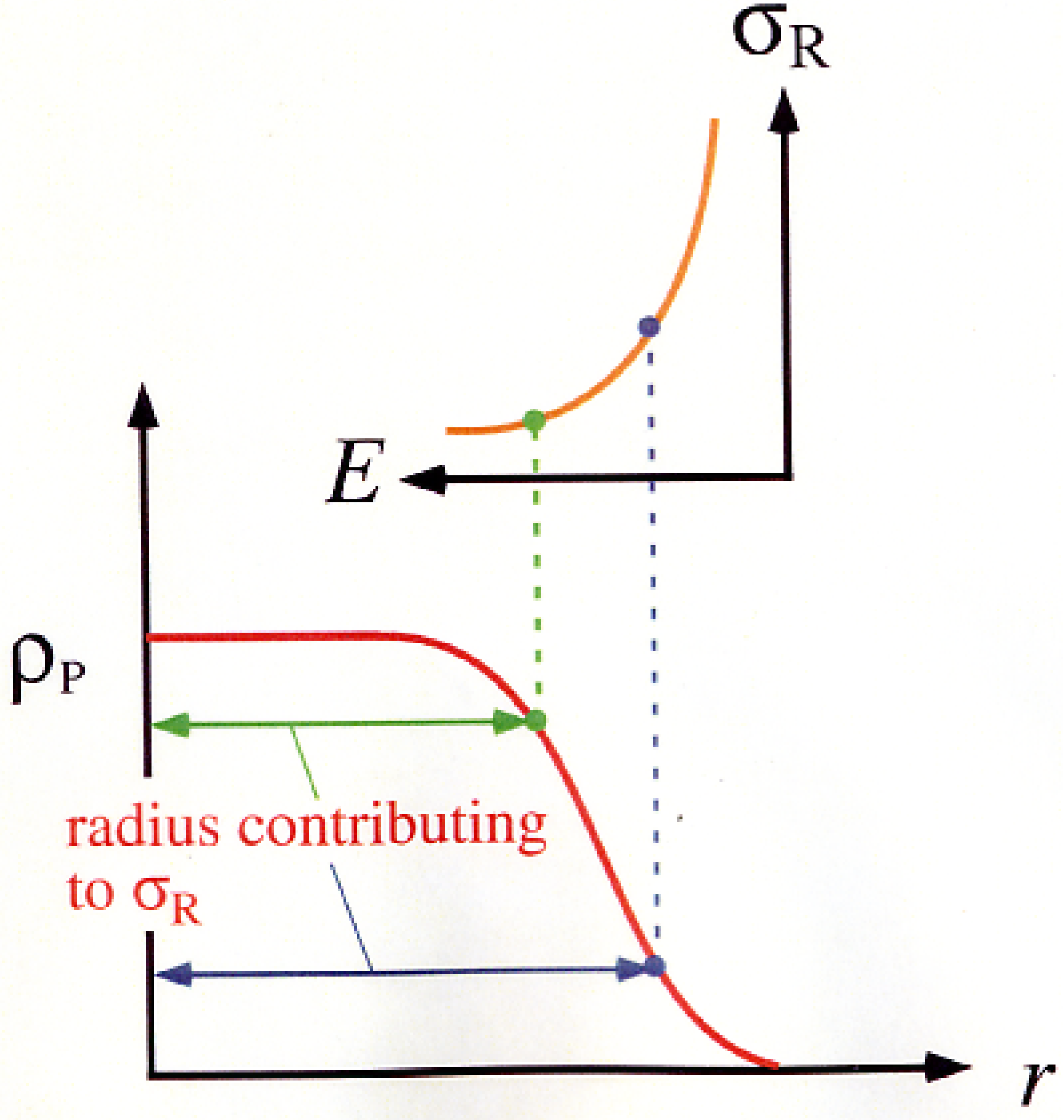
Unstable nuclei

$\sigma_R \Rightarrow \rho$

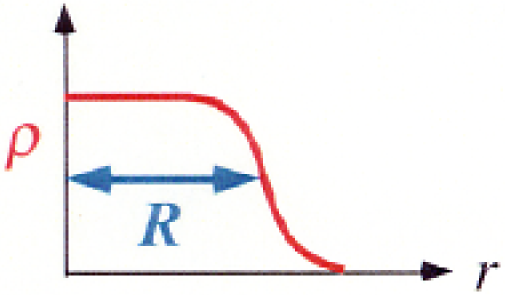
- Motivation for σ_R measurement
- What is σ_R?
- How to measure σ_R — Production/Separation/Identification of RI-beams
- Experimental setup — RIPS in RIKEN / RIBLL in IMP
- Experimental result — $^{16}C/^{14}Be$
- Analysis procedure — Glauber model Finite range
- Deduced matter densities — $^{16}C/^{11}Li/^{14}Be$
- New measurement for $p_{//}$ of fragments — $^{23}O \rightarrow ^{21,22}O$, $^{17}B \rightarrow ^{15}B$, $^{16}C \rightarrow ^{14,15}C$
- Summary


σR
E
ρP
radius contributing
to σR
r

Density distribution (ρ)

- $A>16$, Yukawa type

$$\rho(r) = \rho_0 \left[1 + \exp((r-\boldsymbol{R})/\boldsymbol{a}) \right]^{-1}$$



$\boldsymbol{R}$: radius parameter,

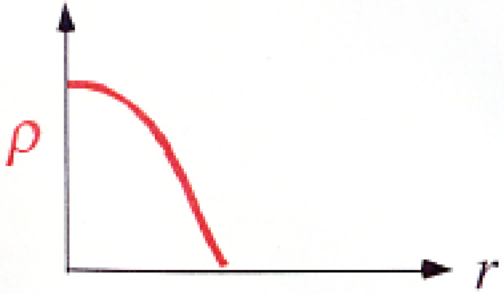
$\boldsymbol{a}$: diffuseness parameter

- $A<20$, Harmonic-oscillator type

$$\rho(r) = 2\pi^{-3/2} \lambda^{-3} (1-1/\boldsymbol{A})^{-2/3} \exp(-x^2) (1 + (\boldsymbol{N}-2)/3x^2)$$

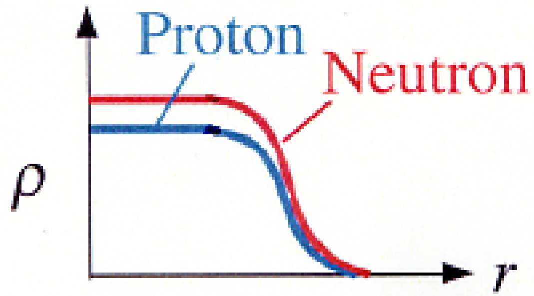
$$x^2 = (r/\lambda)^2$$

λ : size parameter



Nuclear size for stable nuclei

- $R \propto A^{1/3}$
- Neutron radii ≈ proton radii even for ^{208}Pb



⇨ No neutron skin!

- Diffuseness is constant. $a \sim 0.6$ fm

⇩

How are unstable nuclei?

What is σ_R?

- Definition of interaction cross section (σ_I);

Cross section for the change of Z and/or N in incident nucleus

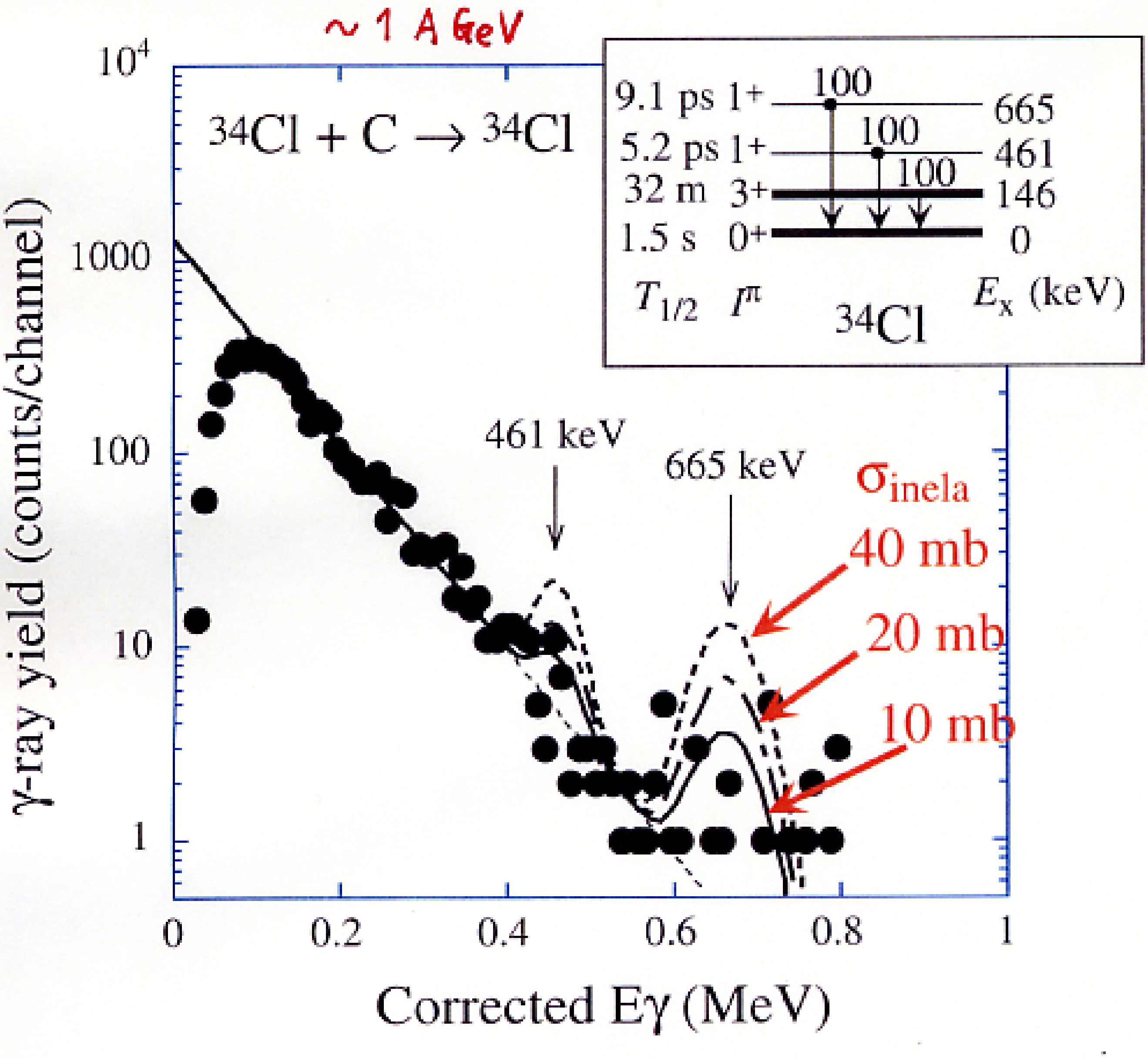
Important for Glauber-model analysis

- Relationship to reaction cross-section (σ_R)

$\sigma_R = \sigma_I + \sigma_{inela}$, σ_{inela}: inelastic cross-section

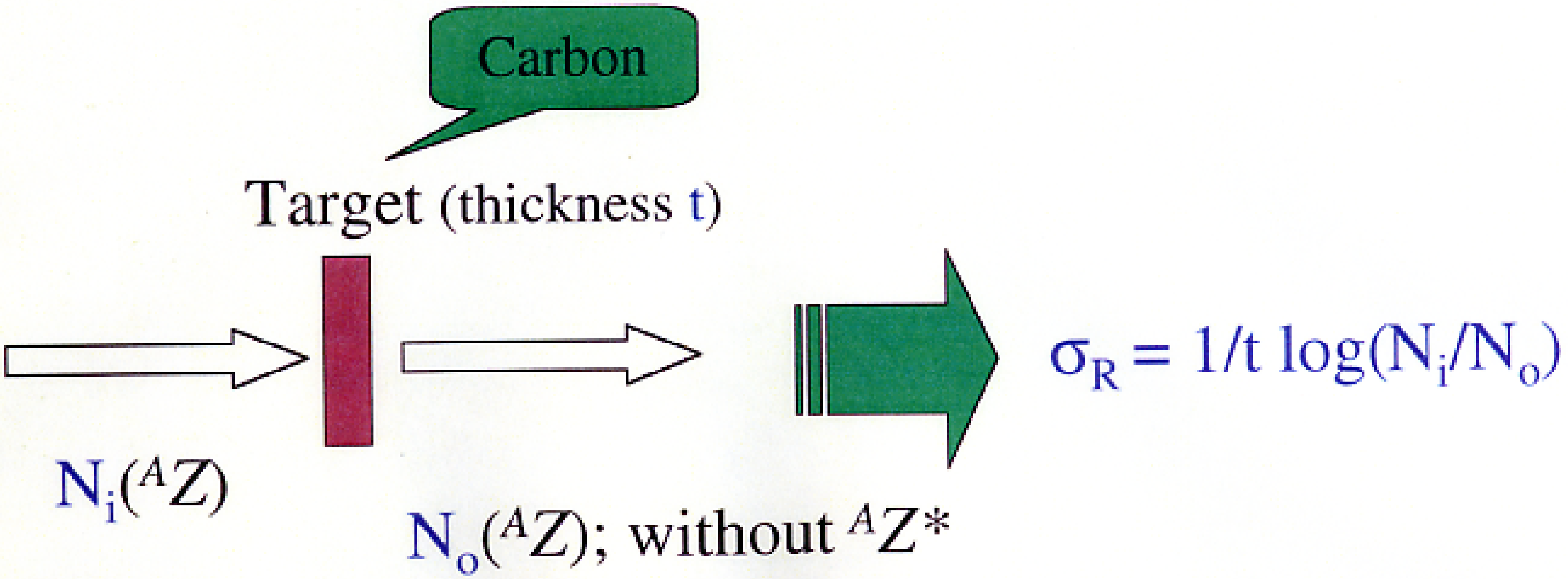
If σ_{inela} is small enough, $\sigma_R \approx \sigma_I$.

At relativistic energy (~1 A GeV)


~ 1 A GeV
$^{34}Cl + C \rightarrow ^{34}Cl$
9.1 ps 1+ 100 665
5.2 ps 1+ 100 461
32 m 3+ 100 146
1.5 s 0+ 0
$T_{1/2}$ I^{π} ^{34}Cl E_x (keV)
461 keV
665 keV
σ_{inela}
40 mb
20 mb
10 mb
γ-ray yield (counts/channel)
Corrected Eγ (MeV)
10^4
1000
100
10
1
0
0.2
0.4
0.6
0.8
1

Principle of measurement

Transmission method



Measurement of σ_R

- Production of energetic RI beam

  Projectile fragmentation

  ↓

  Projectile fragment separator

- Particle identification

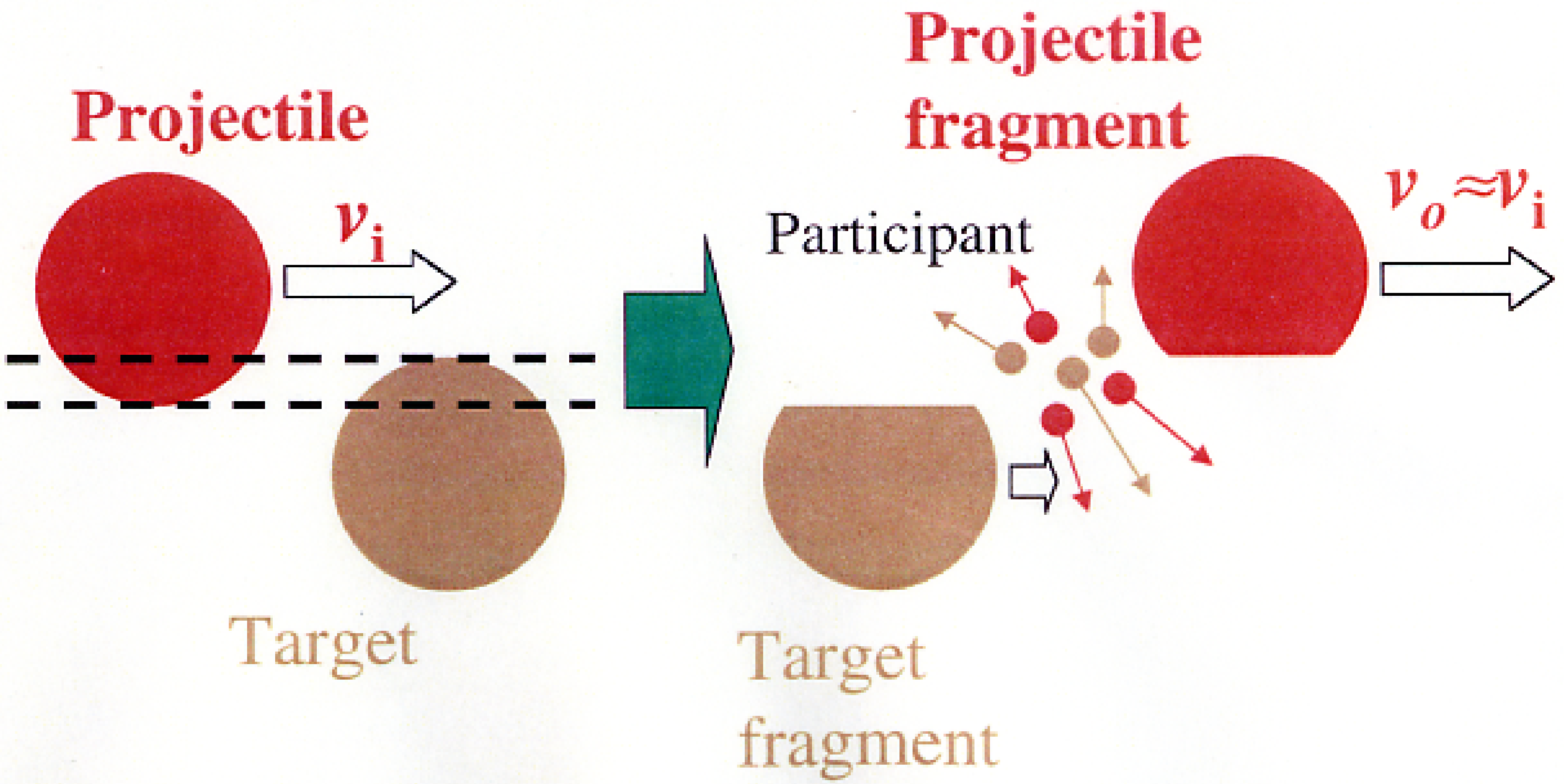
  Upstream/downstream of target

  $B\rho$-ΔE-TOF method

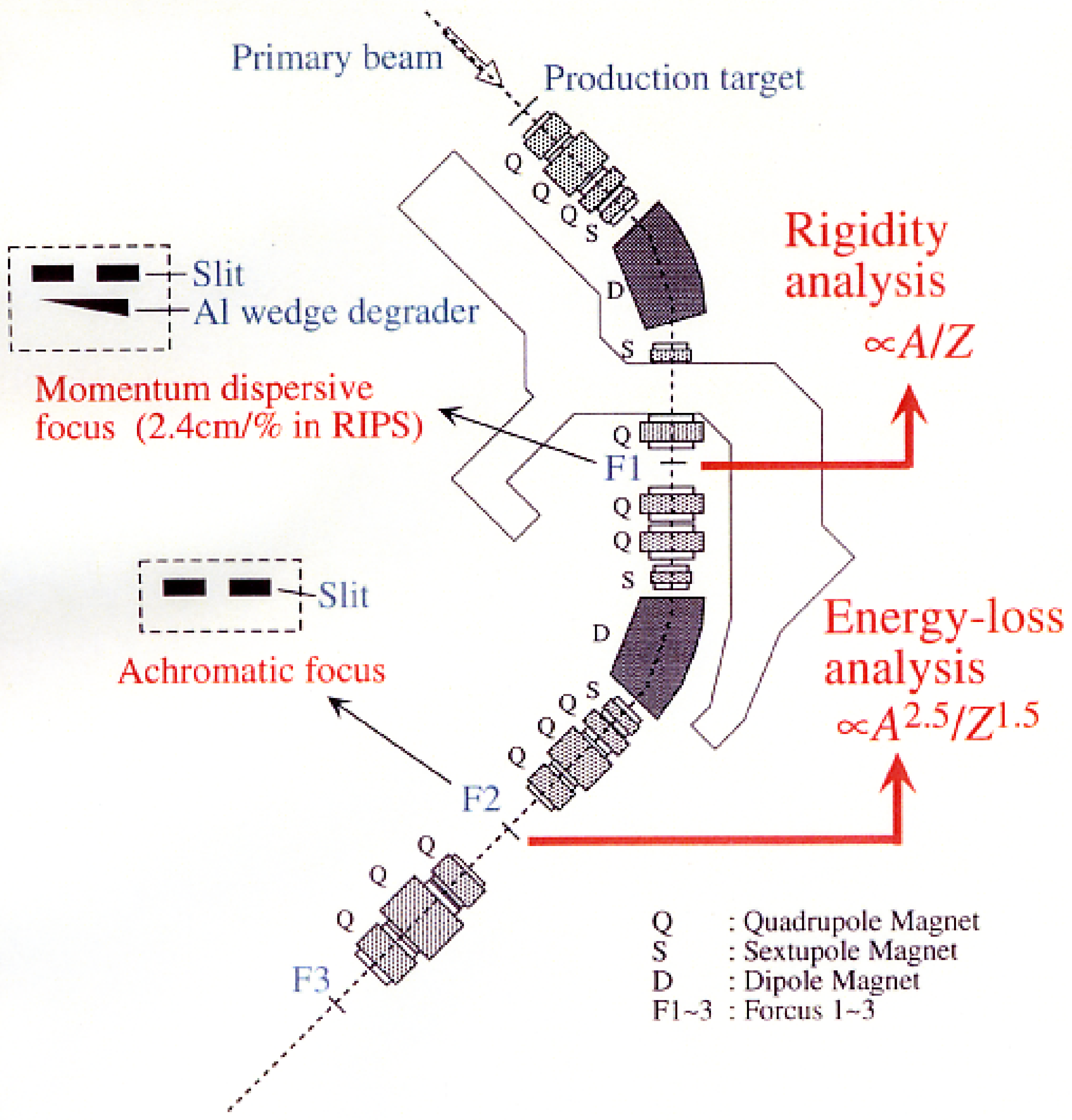
  ΔE-E-TOF method

Projectile fragmentation

Dominant more than ~30 *A* MeV



Principle of separation (RIPS)



How to identify particle

- A, $\mathbf{Z}$, (v) should be identified.

  $\mathrm{TOF} \propto 1/v$

  $\Delta E \propto \mathbf{Z}^2/v^2$

  $B\rho \propto \mathbf{A}v/\mathbf{Z}$ (if $\mathbf{Z} = \boldsymbol{Q}$. $\boldsymbol{Q}$;charge)

  $E \propto \mathbf{A}v^2$

1) $B\rho$-ΔE-TOF method
2) ΔE-E-TOF method
3) ΔE-E method

Detectors

- TOF; time-of-flight

  Rf signal from cyclotron

  Plastic scintillator with phototube ….etc.
- $\Delta E/E$; Energy-loss/Total energy

  Si solid-state detector

  Ion-chamber

  NaI(Tl) …..etc.
- Position ($B\rho$)

  Multi wire proportional chamber (MWPC)

  Parallel plate avalanche counter (PPAC) ….etc.

ACCELERATOR FACILITY LAYOUT in RIKEN

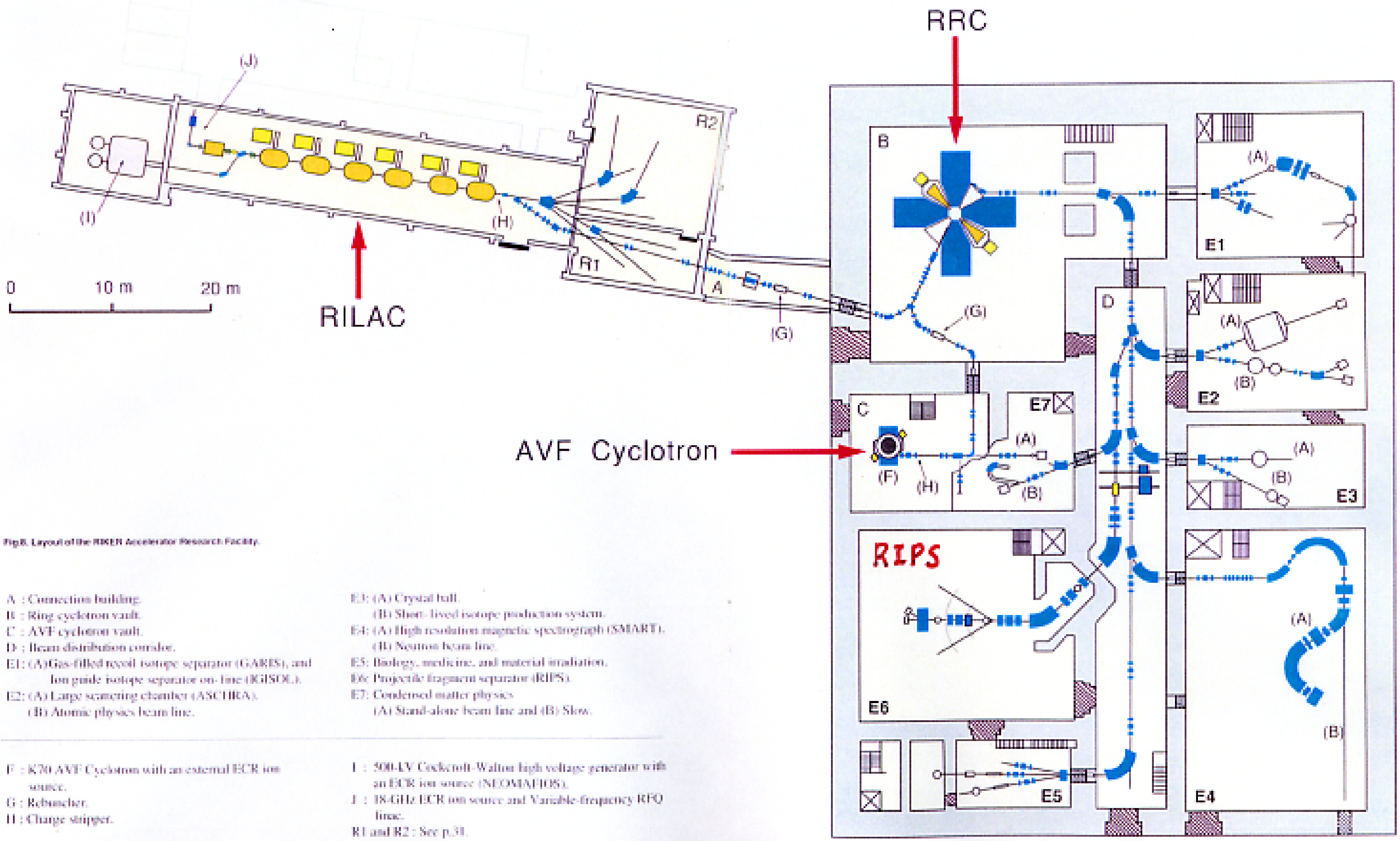


Fig.8. Layout of the RIKEN Accelerator Research Facility.

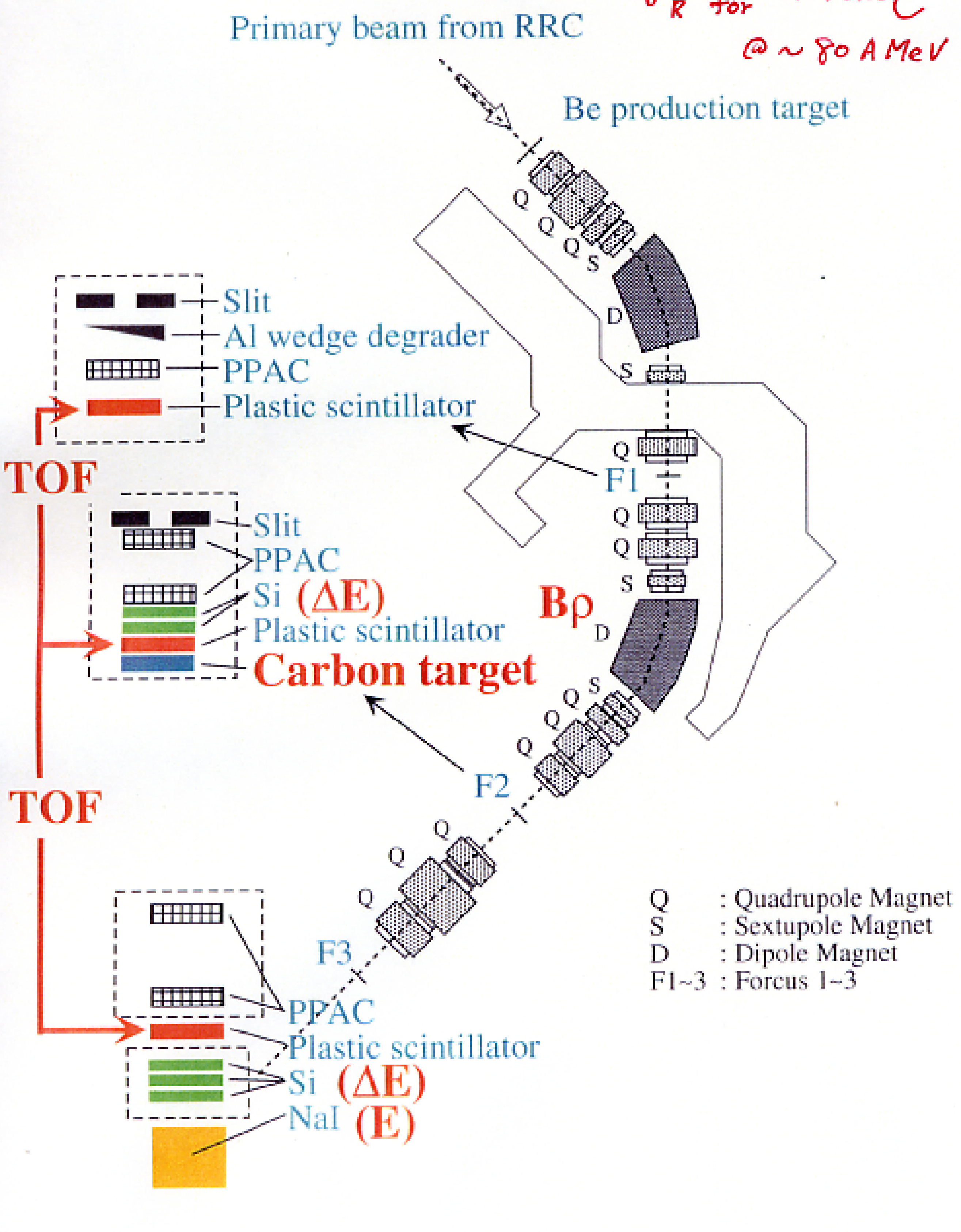
A : Connection building.
B : Ring cyclotron vault.
C : AVF cyclotron vault.
D : Beam distribution corridor.
E1: (A)Gas-filled recoil isotope separator (GARIS), and
Ion guide isotope separator on-line (IGISOL).
E2: (A) Large scattering chamber (ASCHRA).
(B) Atomic physics beam line.
E3: (A) Crystal ball.
(B) Short-lived isotope production system.
E4: (A) High resolution magnetic spectrograph (SMART).
(B) Neutron beam line.
E5: Biology, medicine, and material irradiation.
E6: Projectile fragment separator (RIPS).
E7: Condensed matter physics
(A) Stand-alone beam line and (B) Slow.

F : K70 AVF Cyclotron with an external ECR ion source.
G : Rebuncher.
H : Charge stripper.
I : 500-kV Cockcroft-Walton high voltage generator with an ECR ion source (NEOMAFIOS).
J : 18-GHz ECR ion source and Variable-frequency RFQ linac.
R1 and R2 : See p.31.

Experimental setup in RIPS

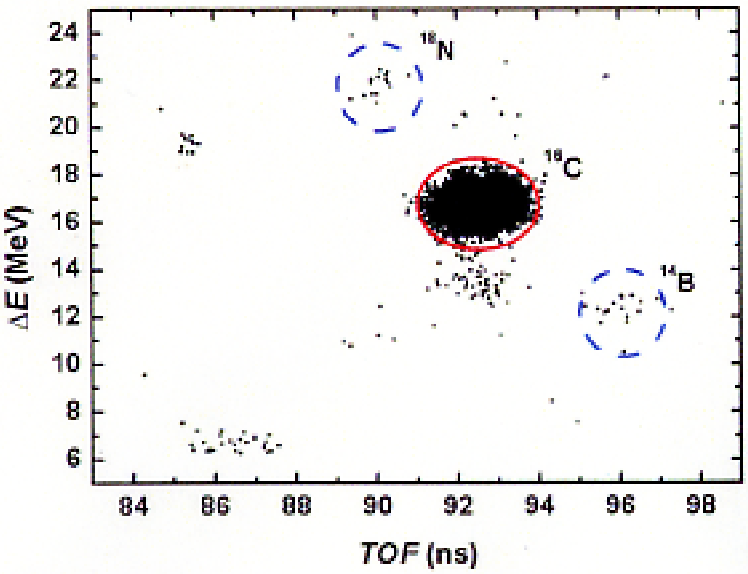
(July 2001)

σ_R for $^{12,14,15,16}C$ @ ~80 A MeV



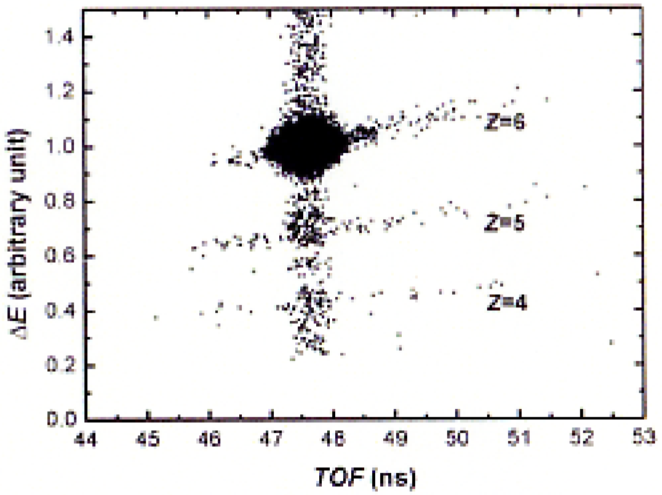
Particle identification

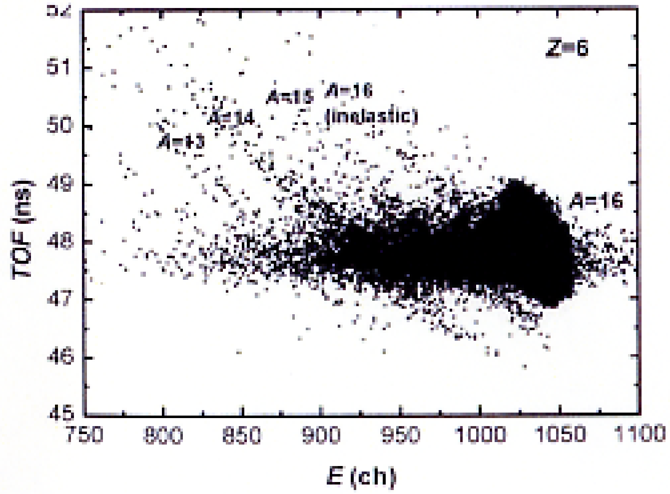
Before target



N_{in}

After target



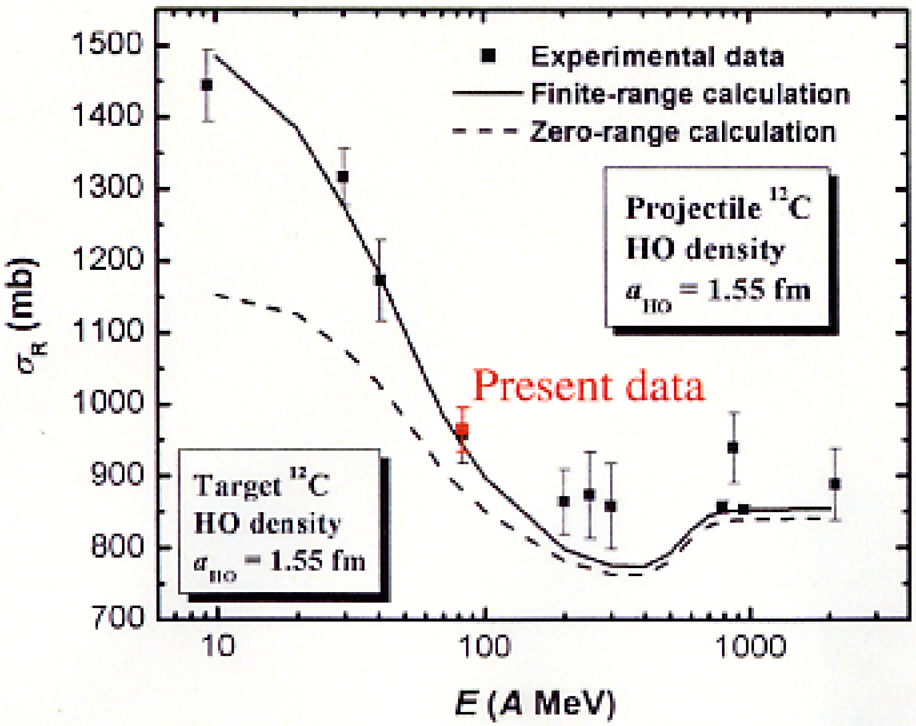


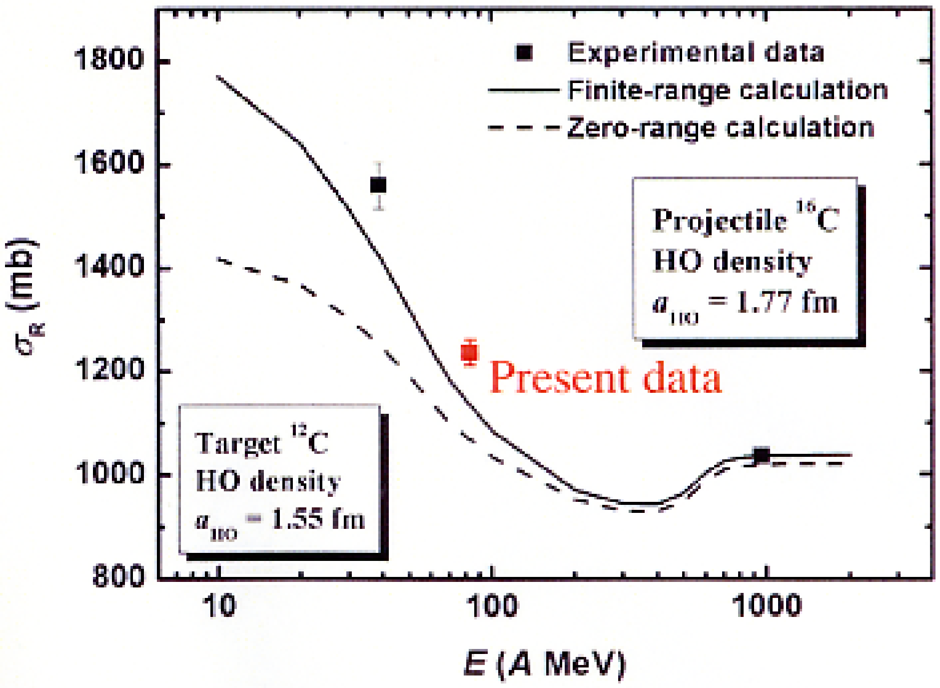
N_{out}

$$E \times T^2 \propto A$$

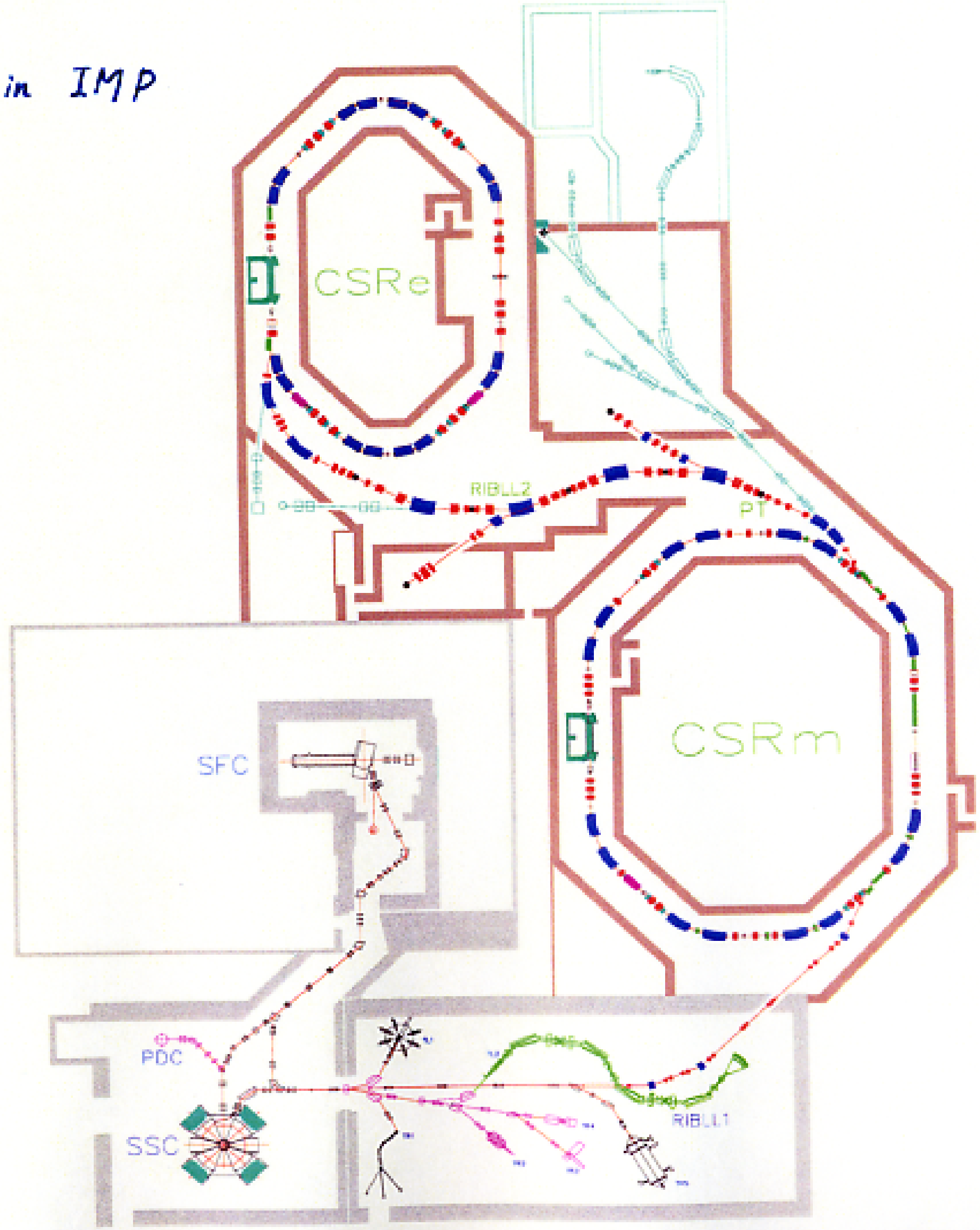
Energy dependence of σ_R

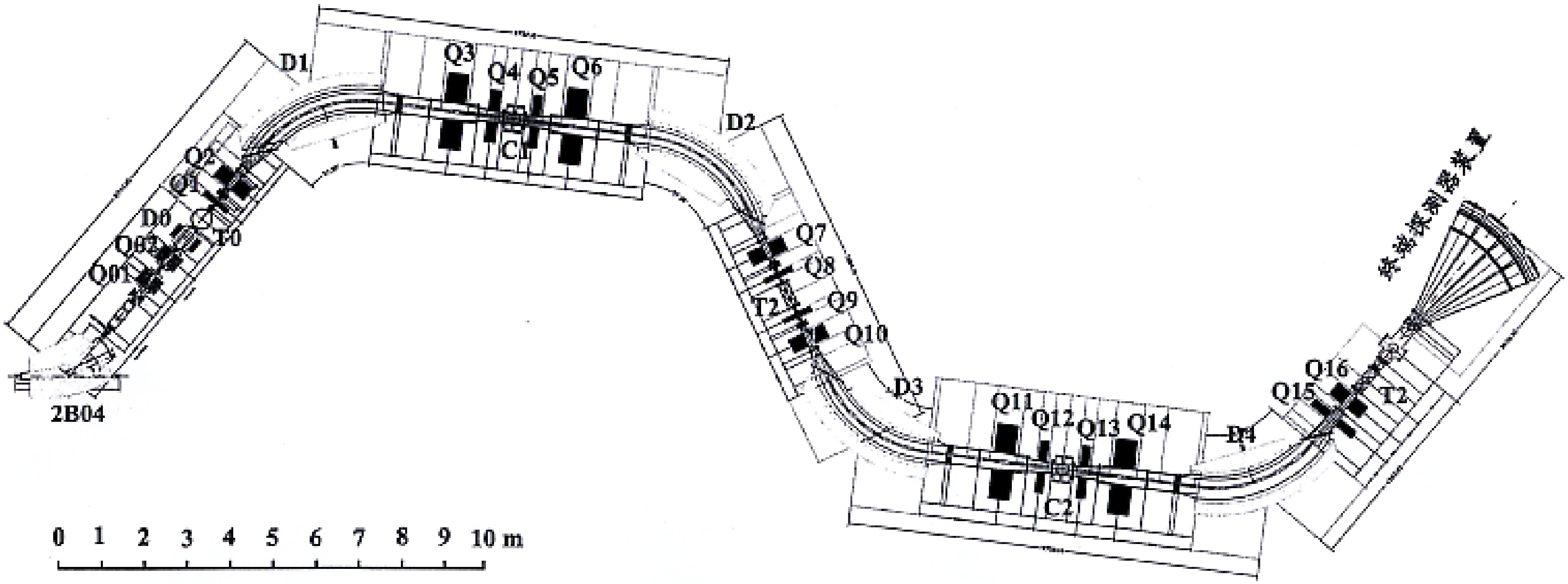
NPA in press.





Layout in IMP

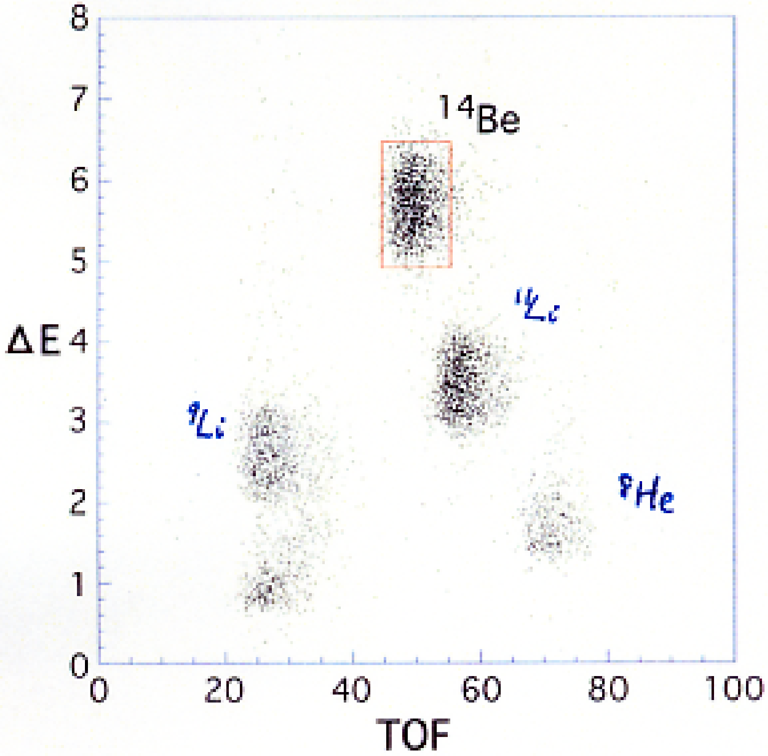




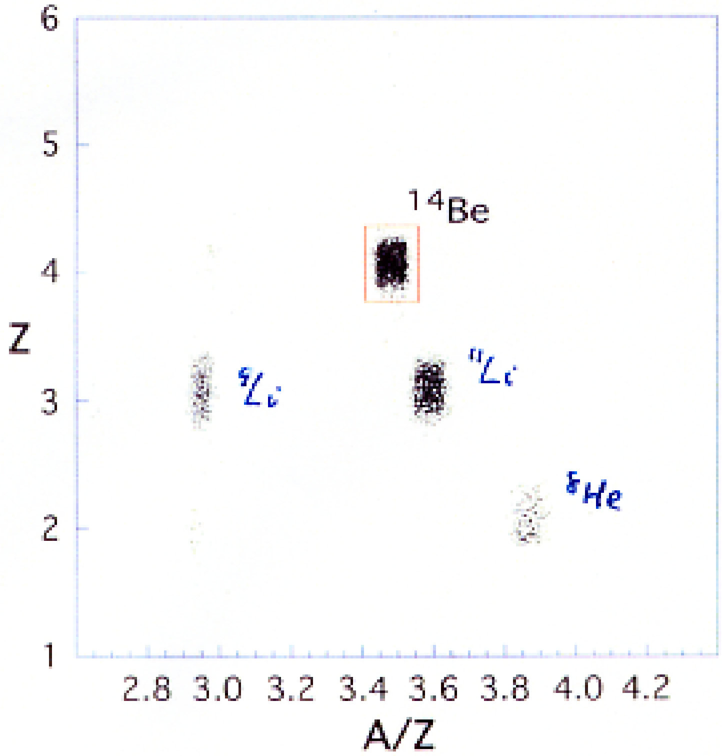
兰州放射性束流线

Radioactive Ion Beam Line in Lanzhou

PI before target



PI after target



Finite-range and zero-range

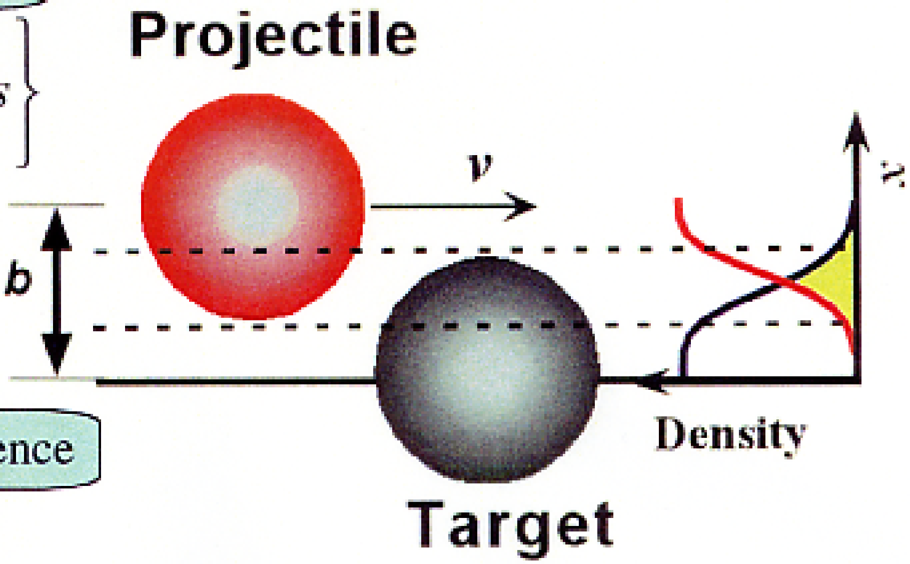
$$\sigma_R = 2\pi \int_0^\infty [1 - T(b)] b\,db$$

Zero - range

Energy dependence

$$T(b) = \exp\left\{ -\sum_{ij} \sigma_{ij} \int \rho^z_{Ti}(s) \rho^z_{Pj}(|b - s|) ds \right\}$$

$$\rho^z_{Ki}(s) = \int_{-\infty}^{\infty} \rho^z_{Ki}(\sqrt{s^2 + z^2}) dz$$



Finite - range

Energy dependence

$$T(b) = \exp\left\{ -\sum_{ij} \sigma_{ij} f_{ij}(b) \int \rho^z_{Ti}(s) \rho^z_{Pj}(|b - s|) ds \right\}$$

Range function $f_{ij}(\boldsymbol{b}) = \frac{1}{4\pi\beta_{ij}^2} \exp(-\frac{\boldsymbol{b}^2}{2\beta_{ij}^2})$

Energy dependence

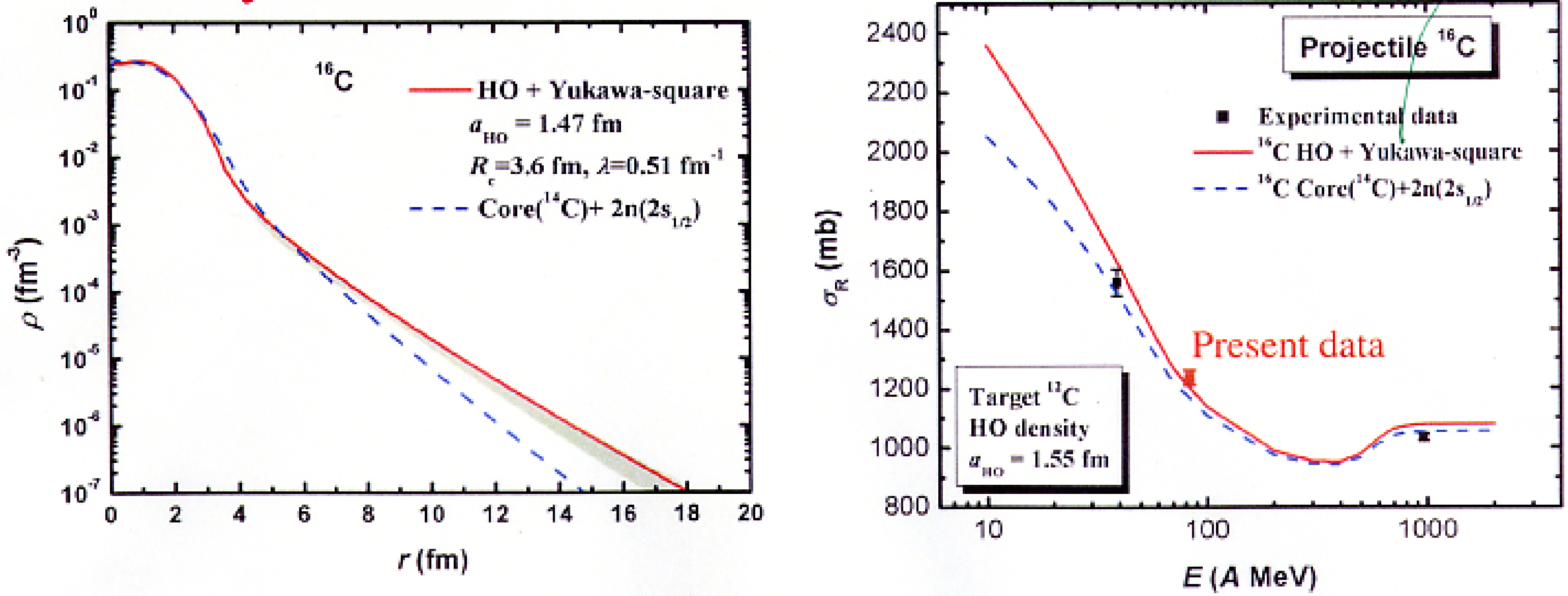
Energy dependence

Effective density distributions for ^{16}C

S_n = 4.25 MeV
S_{2n} = 5.47 MeV.

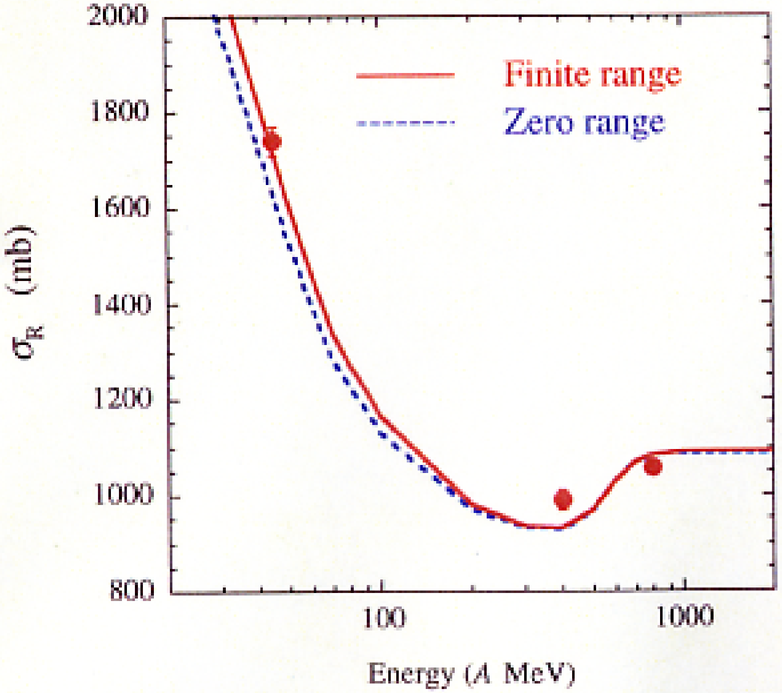
But, ^{16}C is a halo nucleus ····· !?

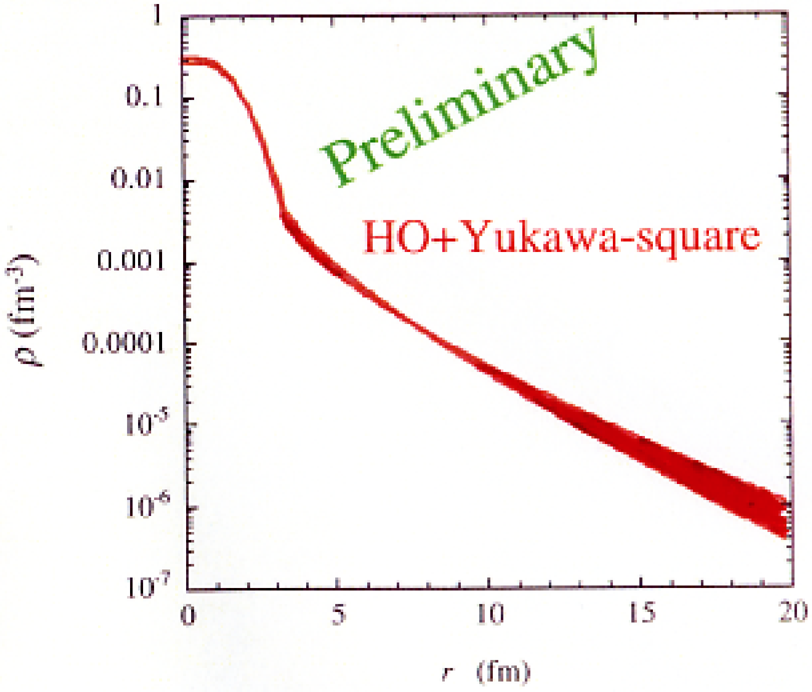
$\frac{exp(-\lambda r)}{r^2}$



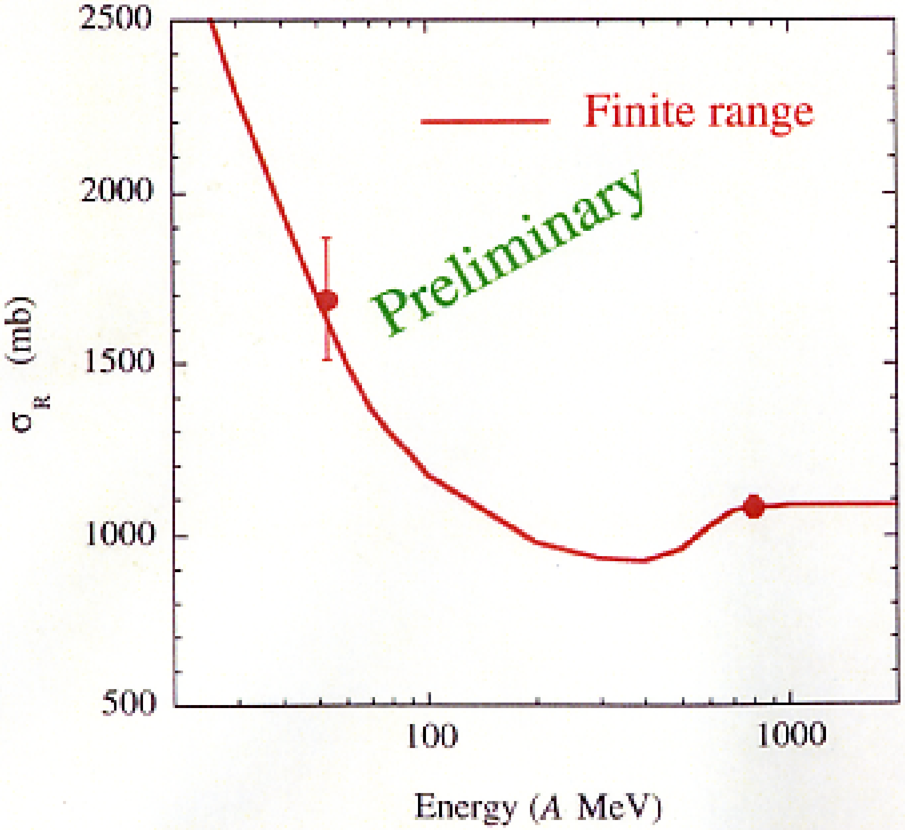
Effective density distributions for ^{11}Li

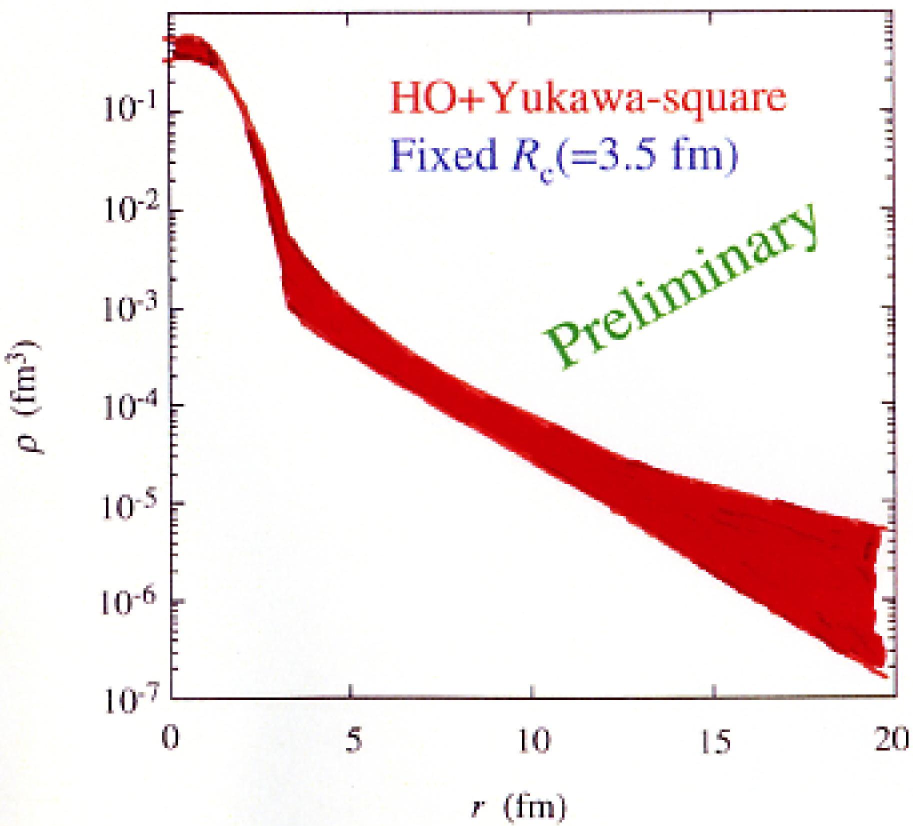
σ_R with C target





Effective density distributions for ^{14}Be





New measurements for $p_{//}$ of fragments

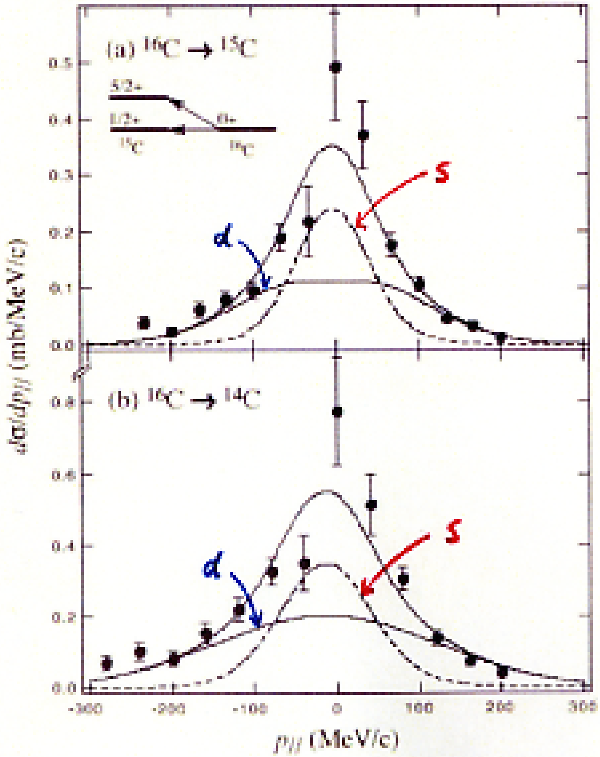
- Precise measurement TOF ➡ $p_{//}$
- Triplet Q magnets after reaction target

➡ { No momentum-acceptance cut
  $p_{//}$ of several fragments at the same time

- New results;

$^{23}O \rightarrow ^{21,22}O$	PRL 88(2002)142502
$^{17}B \rightarrow ^{15}B$	PRL 89(2002)012501
$^{16}C \rightarrow ^{14,15}C$	In preparation

$p_{//}$ for $^{16}C \rightarrow ^{14,15}C$ at 83 *A* MeV



Glauber model analysis

~30% *s*-wave in ^{16}C

Summary

- Energy dependence of σ_R ➡ ρ

  Glauber model finite range

- We can also deduce effective ρ for other light unstable nuclei if we measure σ_R at low energy.
- $p_{//}$ of fragments ➡ information of valence nucleon(s)

  ⇩

  A pigmy halo structure for ^{16}C

- We will extend these measurements to heavier mass system (Z<50) in RIBF……

Nuclear radii determined from σ_R at ~1 *A* GeV

(Radius of ^{4}He (1.47 fm) is subtracted.)