Extracting the electric dipole breakup cross section of one-neutron halo nuclei from inclusive breakup observables

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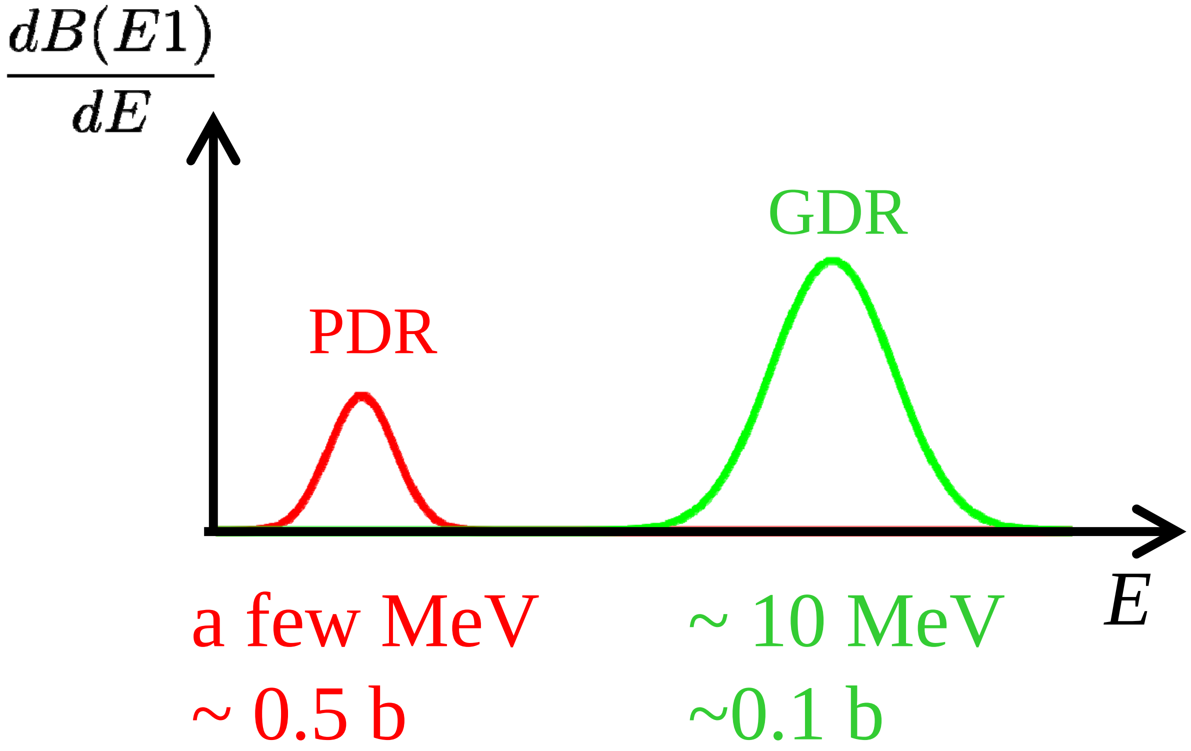
Probing halo structure

Halo nucleus can be probed with Electric Dipole (E1) break up cross section $\sigma(E1)$.

$$\sigma(E1) \propto \int_{S_n}^{\infty} n_{E1}(E) \frac{dB(E1)}{dE} dE$$

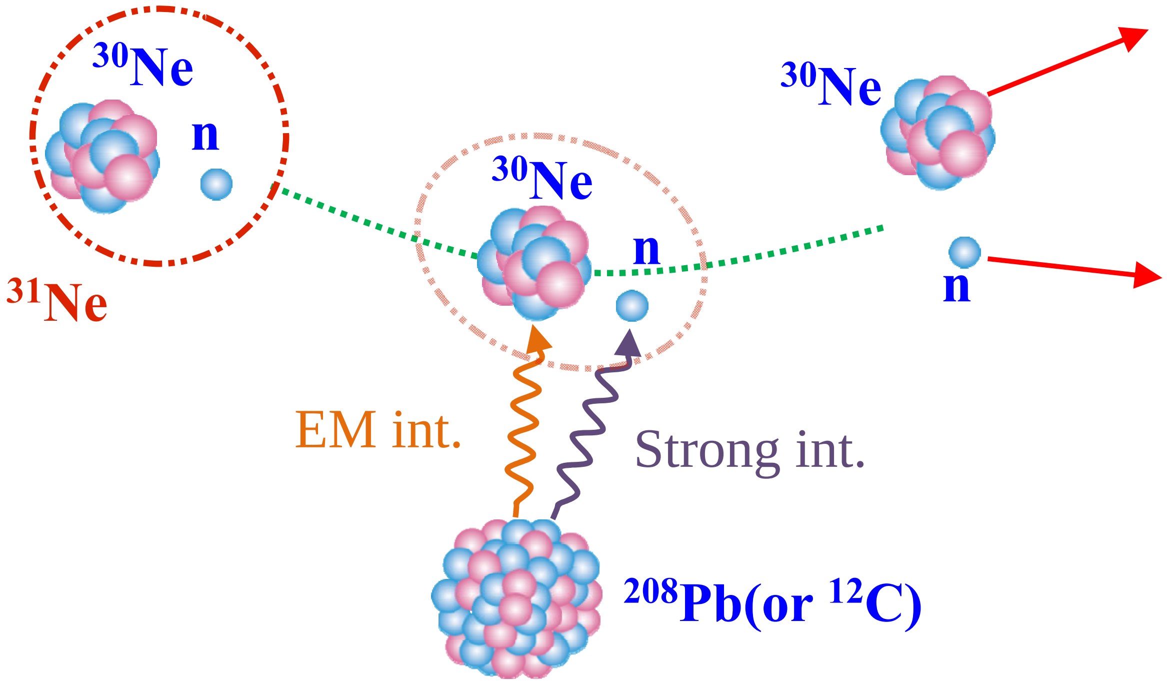
C. A. Bertulani, G. Baur, Phys. Rep. **163**, 299(1988).

$n_{E1}(E)$: exponentially decreasing function of E.



Probing halo structure

One-neutron removal cross sections from ^{31}Ne on Pb and C, $\sigma_{\mathrm{Pb}}^{-1n}$ and $\sigma_{\mathrm{C}}^{-1n}$ were measured at RIBF, RIKEN. T. Nakamura *et al.*, PRL **103**, 262501 (2009).



but, $\sigma(E1)$ is not observable.

<u>E1 cross section formula</u>

$$\sigma(E1) = \sigma_{\mathrm{Pb}}^{-1n} - \Gamma\sigma_{\mathrm{C}}^{-1n}$$

Purpose and method

E1 cross section formula

$$\sigma(E1) = \sigma_{\mathrm{Pb}}^{-1n} - \Gamma\sigma_{\mathrm{C}}^{-1n}$$

1. Justify the validity of E1 cross section formula
2. Find the value of the scaling factor Γ

We aim to establish a quantitatively reliable method of extracting the E1 breakup cross section from observables.

- CDCC (Continuum-Discretized Coupled-Channel method)
- ERT (Eikonal Reaction Theory)
- Microscopic folding model

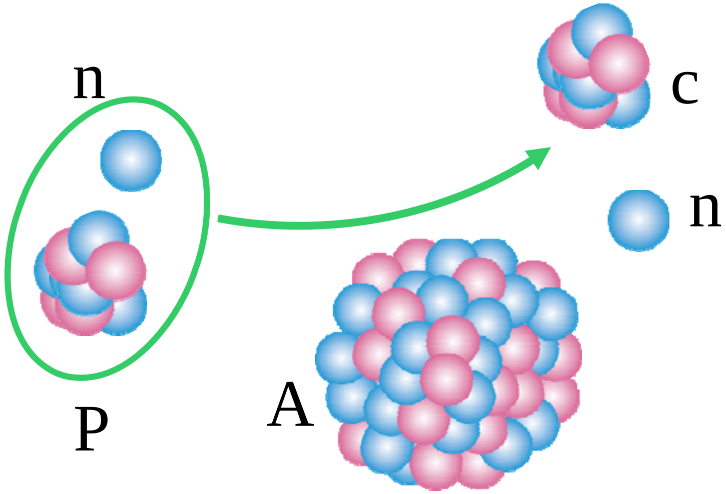
Elastic Breakup (EB) & stripping (STR)

$$\sigma^{-1n} = \sigma^{\text{EB}} + \sigma^{\text{STR}}$$

EB

No target excitation

A(P,c+n)A

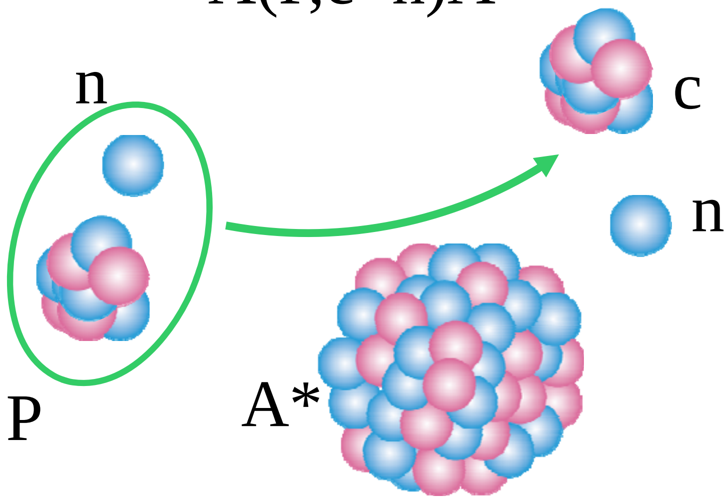


calculated by CDCC

STR

Target excitation

A(P,c+n)A*



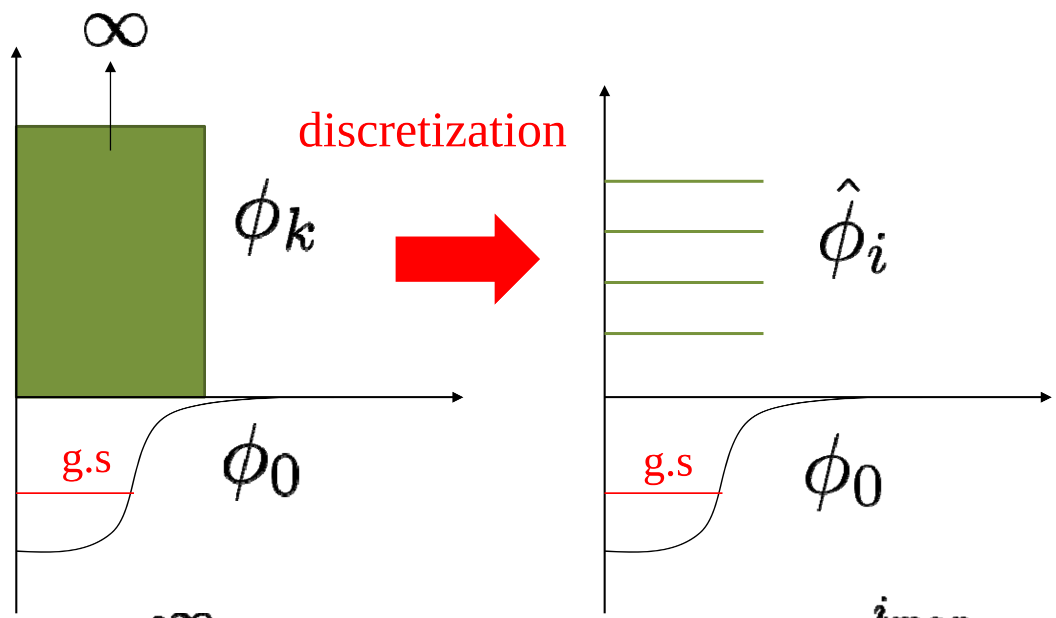
ERT

CDCC

Continuum-Discretized Coupled-Channels method with eikonal approximation (E-CDCC) for exclusive reaction cross sections.

M. Yahiro, K. Ogata, T. Matsumoto, K. Minomo, PTEP **2012,** 01A206 (2012).

Non-perturbative, non-adiabatic description of break up reaction.



$$\psi = \phi_0\chi_0 + \int_0^\infty \phi_k\chi_k dk \;\Longrightarrow\; \psi^{CDCC} = \sum_i^{i_{max}} \hat{\phi}_i\hat{\chi}_i$$

ERT

Eikonal reaction theory (ERT) as an extension of CDCC for inclusive reaction cross section.

M. Yahiro, K. Ogata, K. Minomo, PTP **126**, 167, (2011).

in adiabatic approximation

$$\hat{S} = \hat{S}_c \hat{S}_n$$

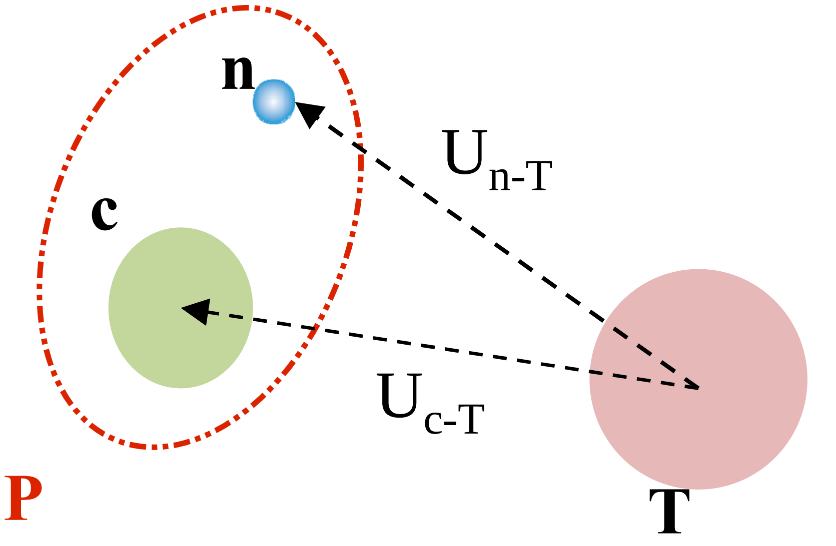
solving Schrödinger equations by CDCC

$$[T + U_c + h - E]\,\Psi = 0 \longrightarrow \quad \hat{S}_c$$

$$[T + U_n + h - E]\,\Psi = 0 \longrightarrow \quad \hat{S}_n$$

$$\sigma_{n:\mathrm{STR}} = \int d\vec{b} \left\langle \phi_0 \left| |\hat{S}_c|^2 (1 - |\hat{S}_n|^2) \right| \phi_0 \right\rangle$$

Microscopic reaction theory



Distorting potential

microscopic folding model for calculating the c-T and n-T potentials.

- HF density for the core and target nuclei.
- Melbourne g-matrix for NN interaction.

K. Amos *et al.*, ANP**25**, 275 (2000).

Reaction systems

- ✓ Projectiles: ^{11}Be, ^{15}C, ^{19}C, ^{31}Ne, ^{29}Ne, ^{33}Mg, ^{35}Mg, ^{37}Mg, ^{39}Si, ^{41}Si
  established 1n-halo   candidates
- ✓ Targets: ^{12}C, ^{16}O, ^{48}Ca, ^{58}Ni, ^{90}Zr, ^{208}Pb
- ✓ Incident energy: 250MeV/nucleon

Validity of E1 cross section formula

Two important assumptions to establish E1 formula.

$$\sigma(E1) = \sigma_{\mathrm{Pb}}^{-1n} - \Gamma\sigma_{\mathrm{C}}^{-1n}$$

- E1 dominance in Coulomb breakup

$$\sigma_{\mathrm{Pb}}^{\mathrm{EB}}(c) \simeq \sigma_{\mathrm{Pb}}^{\mathrm{EB}}(E1)$$

- Small interference between Coulomb and Nuclear interaction

$$\sigma_{\mathrm{Pb}}^{\mathrm{EB}} \simeq \sigma_{\mathrm{Pb}}^{\mathrm{EB}}(n) + \sigma_{\mathrm{Pb}}^{\mathrm{EB}}(c)$$

We examine

- these two assumptions
- Validity of E1 formula
- Values of Γ factors

Validity of E1 cross section formula

E1 dominance in Coulomb breakup

$$\sigma^{\rm EB}_{\rm Pb}(c) \simeq \sigma^{\rm EB}_{\rm Pb}(E1)$$

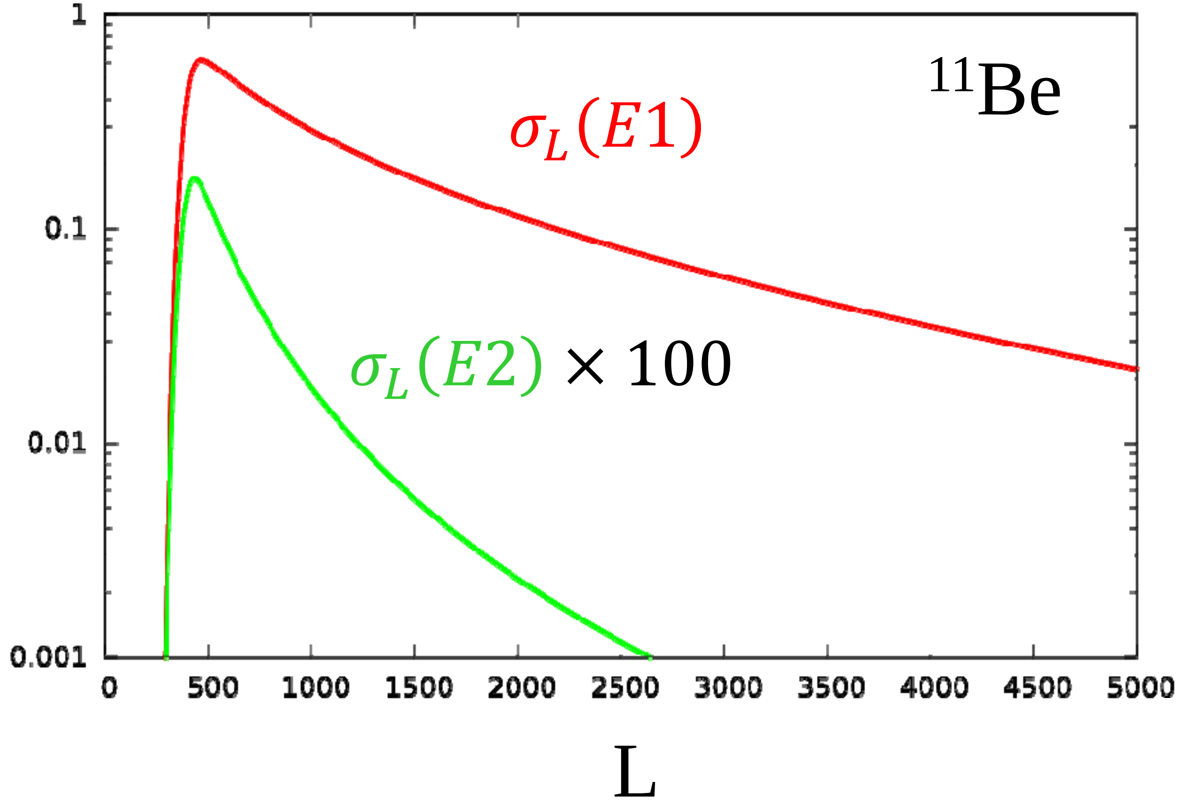
$$e_{E1} = eZ_c \frac{1}{A} \quad e_{E2} = eZ_c \left(\frac{1}{A}\right)^2$$

$$e_{E1} \gg e_{E2}$$

$\sigma(E2)$ damps rapidly for its R^{-3}.

$$\sigma(E1) \propto e_{E1}^2 \frac{r}{R^2}$$

$$\sigma(E2) \propto e_{E2}^2 \frac{r^2}{R^3}$$

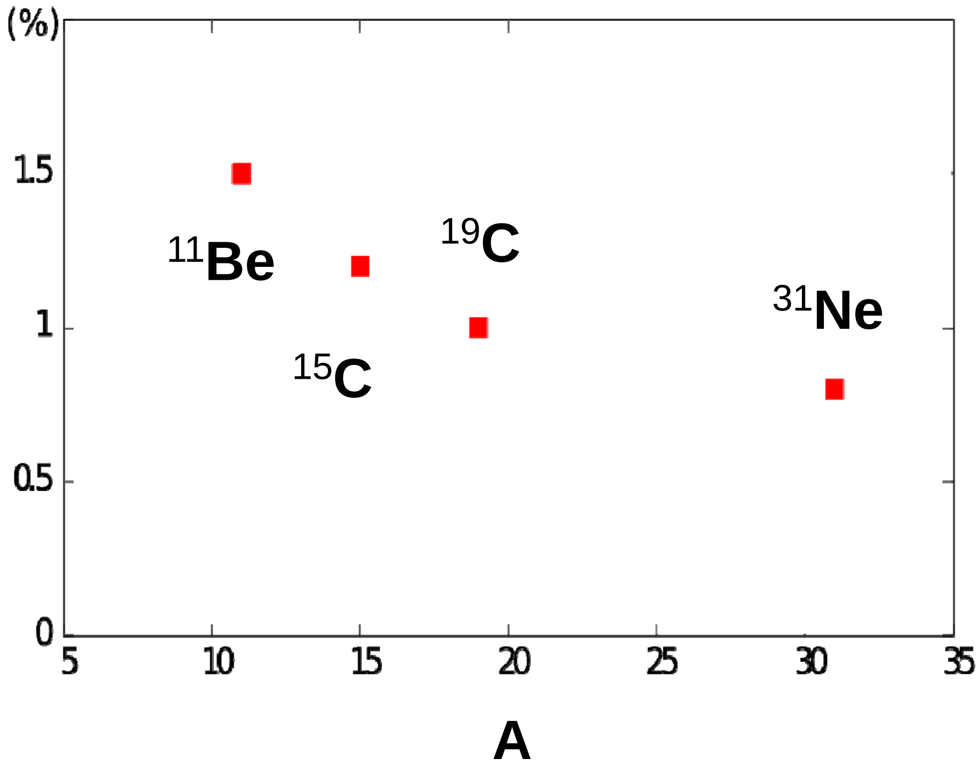


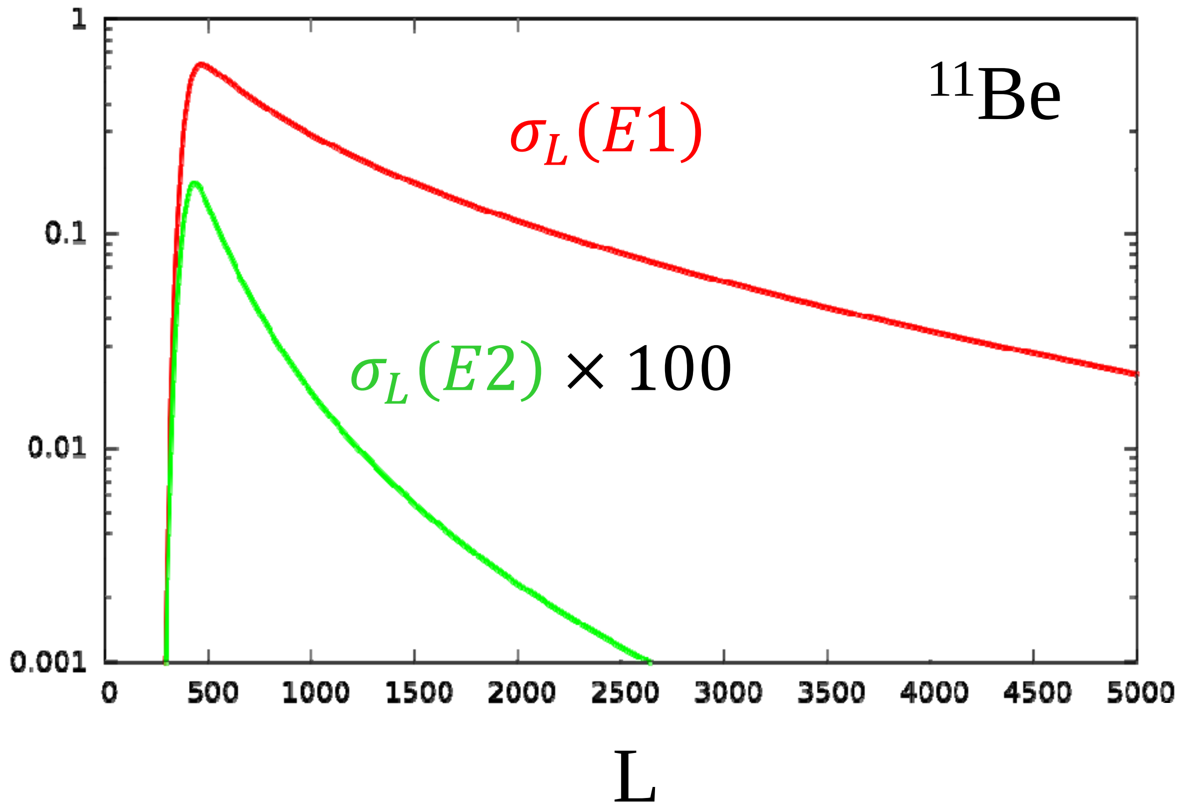
Validity of E1 cross section formula

E1 dominance in Coulomb breakup

$$\sigma^{\rm EB}_{\rm Pb}(c) \simeq \sigma^{\rm EB}_{\rm Pb}(E1)$$

$$1 - \frac{\sigma^{\rm EB}_{\rm Pb}(c)}{\sigma^{\rm EB}_{\rm Pb}(E1)}$$



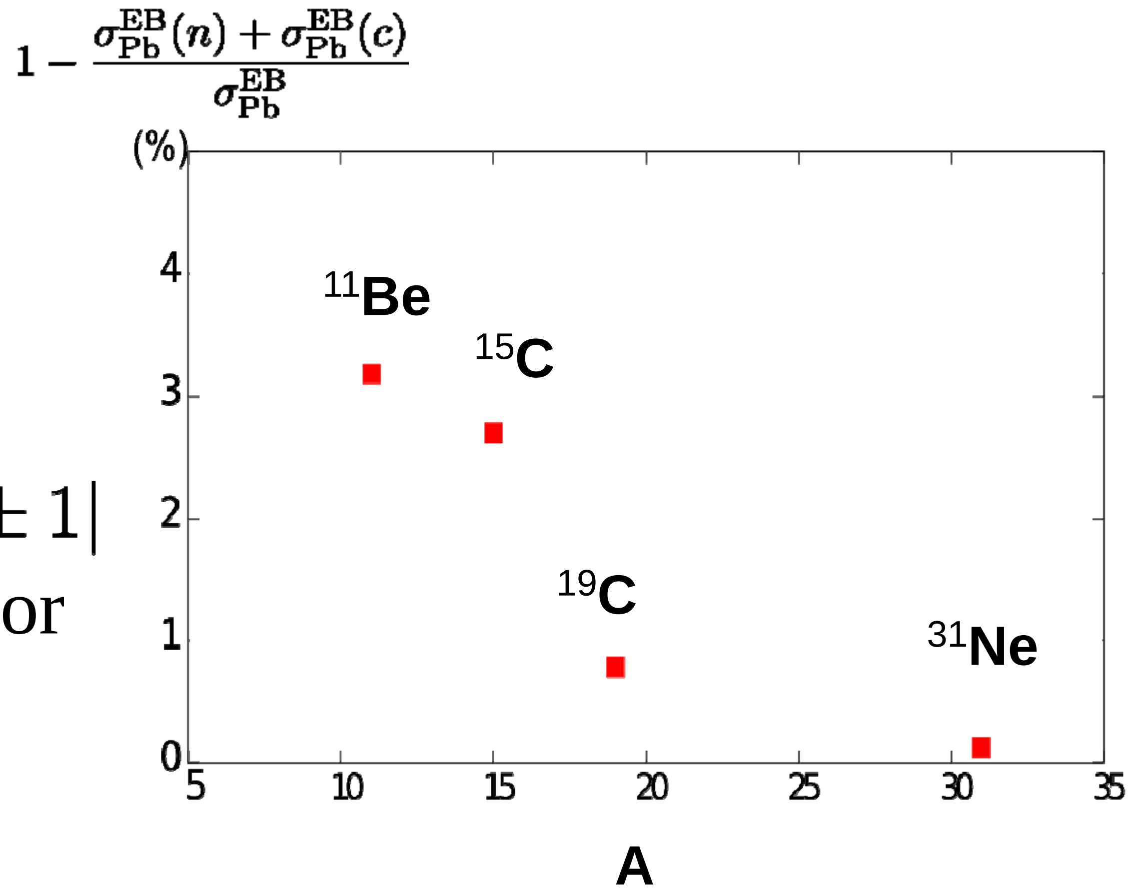


Validity of E1 cross section formula

Small interference between Coulomb and Nuclear interaction

$$\sigma_{\rm Pb}^{\rm EB} \simeq \sigma_{\rm Pb}^{\rm EB}(n) + \sigma_{\rm Pb}^{\rm EB}(c)$$

1. Nuclear breakup at surface, while Coulomb breakup amplitude has a long tail.
2. Angular momentum $\ell \rightarrow |\ell_0 \pm 1|$ by E1, but no such selection for the nuclear breakup.



Validity of E1 cross section formula

Two important assumptions to establish E1 formula.

- Small interference between Coulomb and Nuclear interaction

$$\sigma_{\rm Pb}^{\rm EB} \simeq \sigma_{\rm Pb}^{\rm EB}(n) + \sigma_{\rm Pb}^{\rm EB}(c)$$

- E1 dominance in Coulomb breakup

$$\sigma_{\rm Pb}^{\rm EB}(c) \simeq \sigma_{\rm Pb}^{\rm EB}(E1)$$

$$\begin{aligned} \sigma_{\rm Pb}^{\rm EB}(E1) &= \sigma_{\rm Pb}^{-1n} - \sigma_{\rm Pb}^{-1n}(n) \\ &= \sigma_{\rm Pb}^{-1n} - \Gamma\sigma_{\rm C}^{-1n}(n) \\ &\simeq \sigma_{\rm Pb}^{-1n} - \Gamma\sigma_{\rm C}^{-1n} \end{aligned}$$

$$\Gamma = \frac{\sigma_{\rm Pb}^{-1n}(n)}{\sigma_{\rm C}^{-1n}(n)}$$

$$\sigma_{\rm C}^{-1n} \simeq \sigma_{\rm C}^{-1n}(n)$$

Validity of E1 cross section formula

Two important assumptions to establish E1 formula.

- Small interference between Coulomb and Nuclear interaction

$$\sigma_{\rm Pb}^{\rm EB} \simeq \sigma_{\rm Pb}^{\rm EB}(n) + \sigma_{\rm Pb}^{\rm EB}(c)$$

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<u>E1 cross section formula</u>

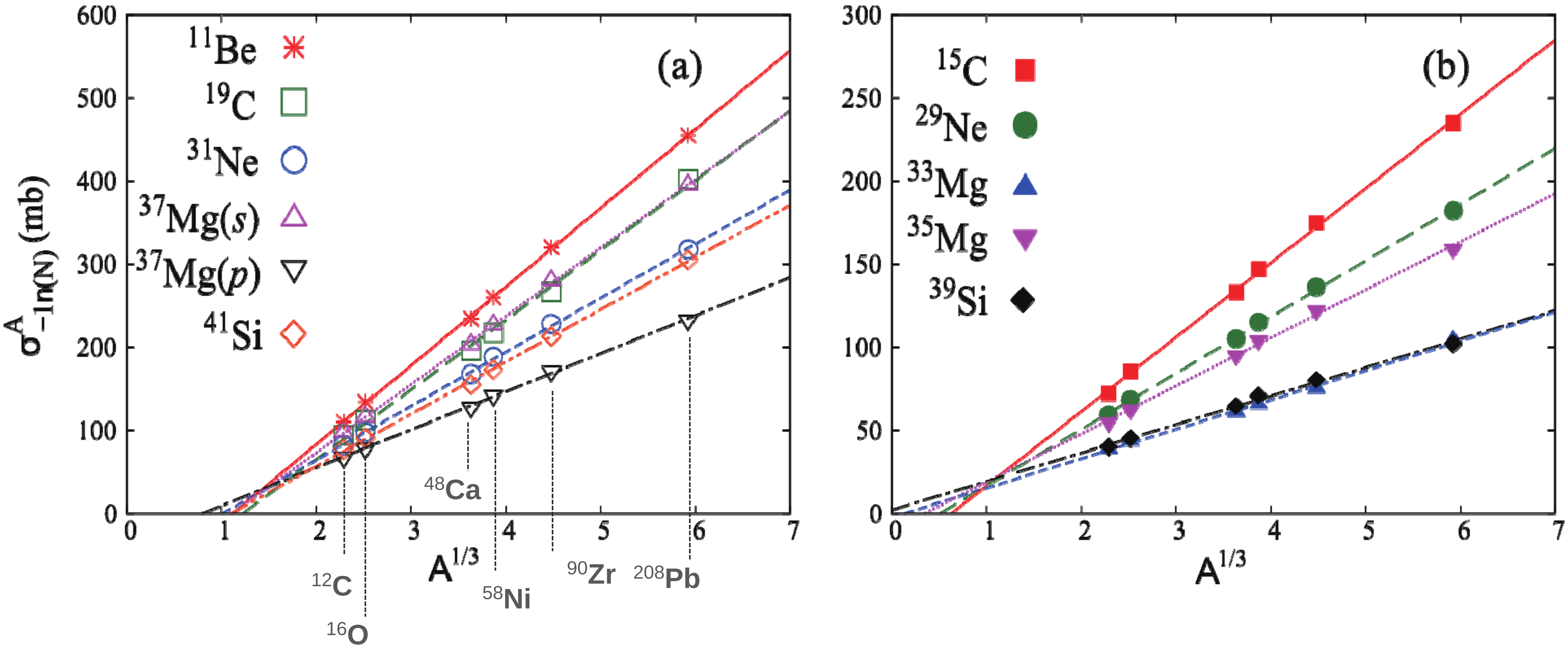
$$\sigma(E1) = \sigma_{\rm Pb}^{-1n} - \Gamma\sigma_{\rm C}^{-1n}$$

where Γ is defined by

$$\Gamma = \frac{\sigma_{\rm Pb}^{-1n}(n)}{\sigma_{\rm C}^{-1n}(n)}$$

about 95% accuracy

Target mass number dependence of $\sigma^{-1n}(n)$



$\sigma^{-1n}(n)$ are proportional to A$^{1/3}$.

scaling factor Γ

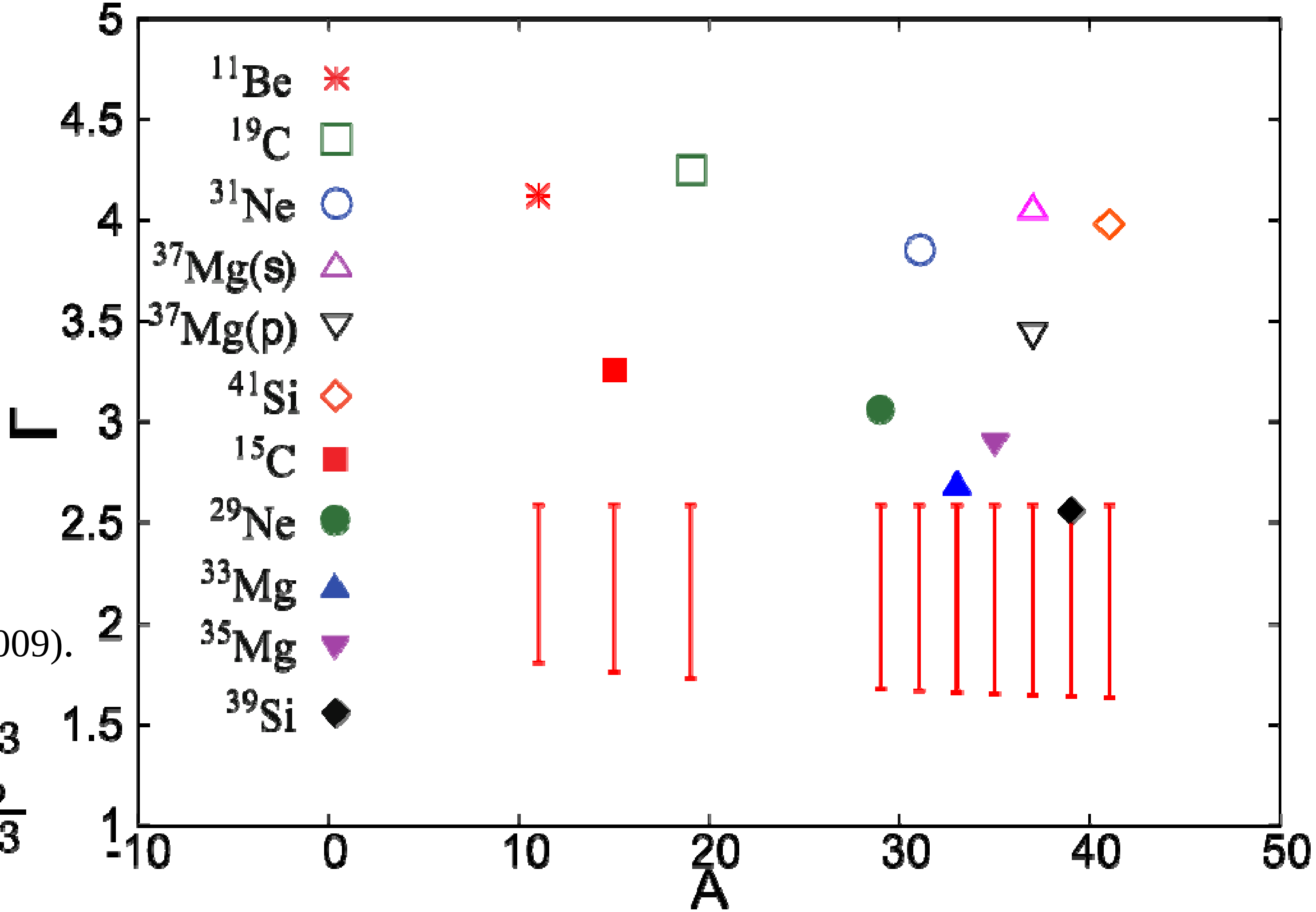
this work

$$\Gamma = \frac{\sigma_{\mathrm{Pb}}^{-1n}(n)}{\sigma_{\mathrm{C}}^{-1n}(n)}$$

previous study

T. Nakamura *et al.*, PRL **103**, 262501 (2009).

$$\frac{A_{\mathrm{Pb}}^{1/3} + A_{pro}^{1/3}}{A_{\mathrm{C}}^{1/3} + A_{pro}^{1/3}} \leq \Gamma \leq \frac{A_{\mathrm{Pb}}^{1/3}}{A_{\mathrm{C}}^{1/3}}$$



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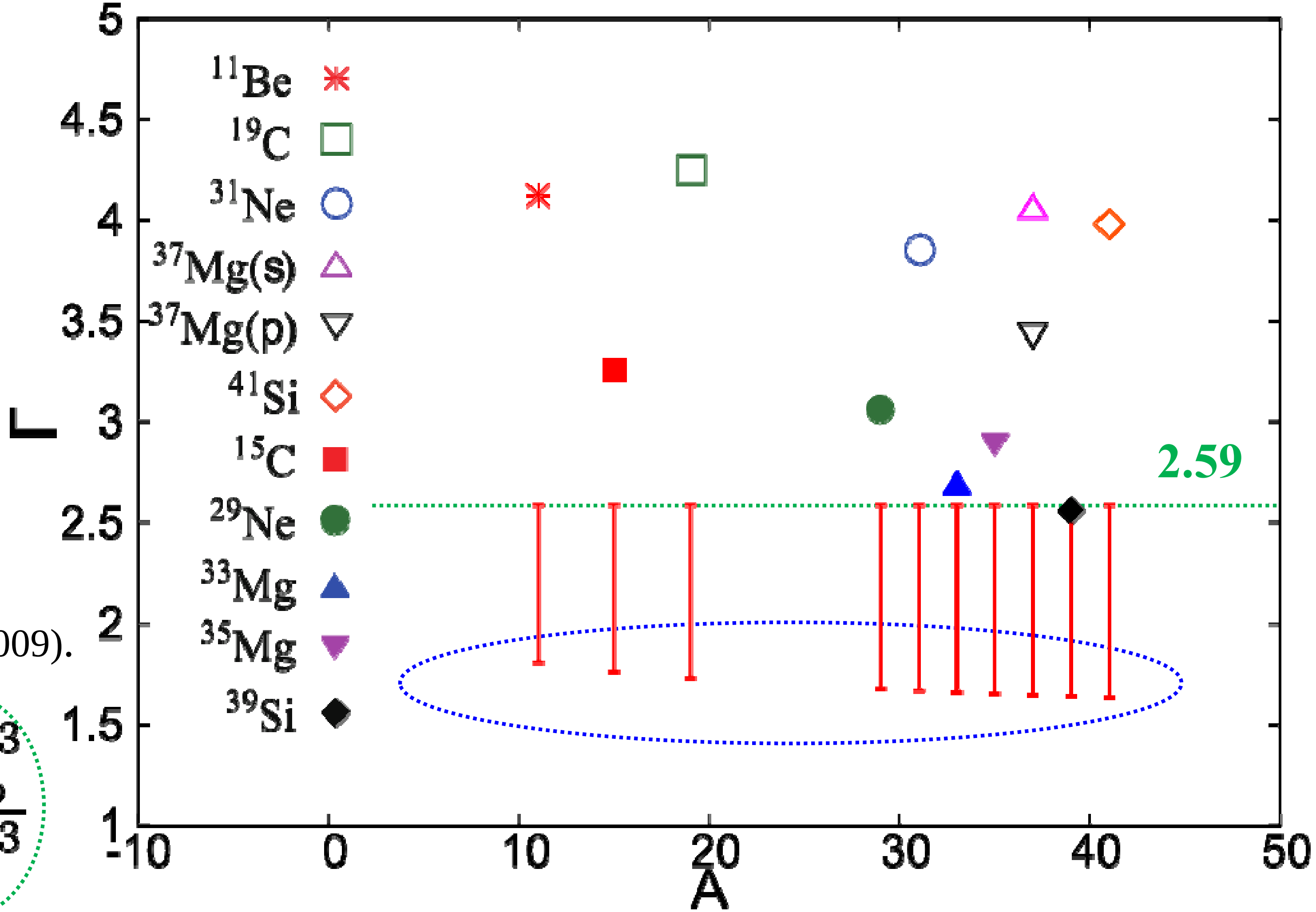

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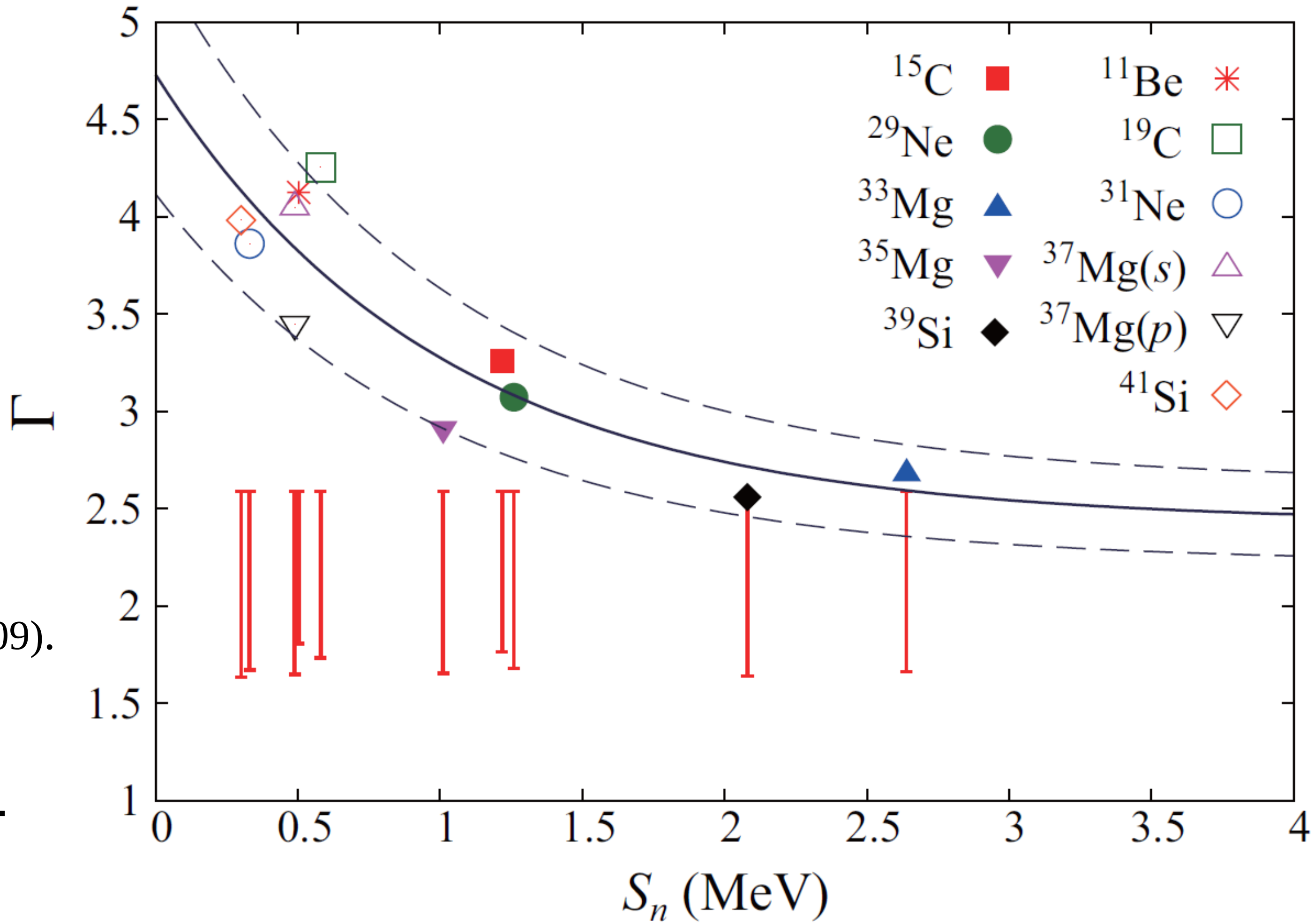


S_n: one-neutron separation energy [MeV]

scaling factor Γ

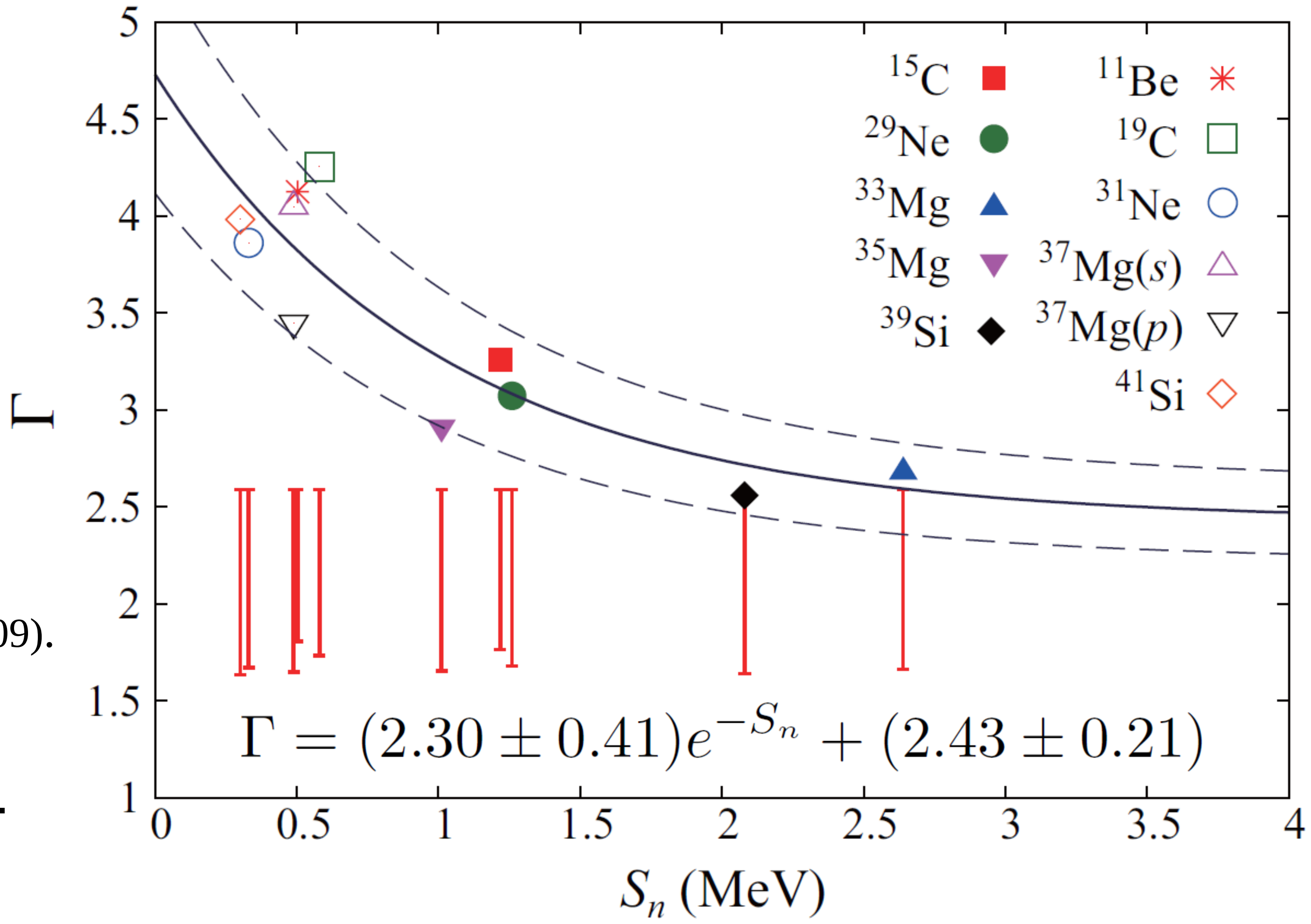
this work

$$\Gamma = \frac{\sigma_{\mathrm{Pb}}^{-1n}(n)}{\sigma_{\mathrm{C}}^{-1n}(n)}$$

previous study

T. Nakamura *et al.*, PRL **103**, 262501 (2009).

$$\frac{A_{\mathrm{Pb}}^{1/3} + A_{pro}^{1/3}}{A_{\mathrm{C}}^{1/3} + A_{pro}^{1/3}} \leq \Gamma \leq \frac{A_{\mathrm{Pb}}^{1/3}}{A_{\mathrm{C}}^{1/3}}$$



S_n: one-neutron separation energy [MeV]

summary

E1 cross section formula

$$\sigma(E1) = \sigma_{\mathrm{Pb}}^{-1n} - \Gamma \sigma_{\mathrm{C}}^{-1n}$$

where Γ is defined by

$$\Gamma = \frac{\sigma_{\mathrm{Pb}}^{-1n}(n)}{\sigma_{\mathrm{C}}^{-1n}(n)}$$

Γ has 1*n* separation energy dependence

$$\Gamma = (2.30 \pm 0.41)e^{-S_n} + (2.43 \pm 0.21)$$

^{31}Ne case

deduced $\sigma(E1)$=540 mb will become 13-20% smaller.

K. Yoshida, T. Fukui, K. Minomo, K. Ogata, PTEP **2014**, 053D03

We confirmed (for 1n halo systems)

- E1 is dominant in Coulomb breakup

$$\sigma_{\mathrm{Pb}}^{\mathrm{EB}}(c) \simeq \sigma_{\mathrm{Pb}}^{\mathrm{EB}}(E1)$$

- Interference between Coulomb and Nuclear interaction is negligible

$$\sigma_{\mathrm{Pb}}^{\mathrm{EB}} \simeq \sigma_{\mathrm{Pb}}^{\mathrm{EB}}(n) + \sigma_{\mathrm{Pb}}^{\mathrm{EB}}(c)$$

- Stripping reaction is caused by nuclear interaction

$$\sigma_{\mathrm{Pb}}^{\mathrm{STR}} \simeq \sigma_{\mathrm{Pb}}^{\mathrm{STR}}(n)$$

- In case of ^{12}C target, Nuclear interaction is dominant

$$\sigma_{\mathrm{C}}^{-1n} \simeq \sigma_{\mathrm{C}}^{-1n}(n)$$

E1 cross section formula

$$\sigma(E1) = \sigma_{\mathrm{Pb}}^{-1n} - \Gamma\sigma_{\mathrm{C}}^{-1n}$$

about 95% accuracy

where Γ is defined by $$\Gamma = \frac{\sigma_{\mathrm{Pb}}^{-1n}(n)}{\sigma_{\mathrm{C}}^{-1n}(n)}$$

$$\sigma_{\mathrm{Pb}}^{-1n} = \sigma_{\mathrm{Pb}}^{\mathrm{STR}} + \sigma_{\mathrm{Pb}}^{\mathrm{EB}}$$

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$$\sigma_{\mathrm{Pb}}^{\mathrm{STR}} \simeq \sigma_{\mathrm{Pb}}^{\mathrm{STR}}(n)$$

$$\sigma_{\mathrm{Pb}}^{\mathrm{EB}} \simeq \sigma_{\mathrm{Pb}}^{\mathrm{EB}}(n) + \sigma_{\mathrm{Pb}}^{\mathrm{EB}}(c)$$

$$\sigma_{\mathbf{Pb}}^{-1n} = \sigma_{\mathbf{Pb}}^{\mathbf{STR}}(n) + \sigma_{\mathbf{Pb}}^{\mathbf{EB}}(n) + \sigma_{\mathbf{Pb}}^{\mathbf{EB}}(c)$$

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$$\sigma_{\mathrm{Pb}}^{\mathrm{EB}}(c) = \sigma_{\mathrm{Pb}}^{-1n} - \sigma_{\mathrm{Pb}}^{-1n}(n)$$

$$\sigma_{\mathrm{Pb}}^{-1n} = \sigma_{\mathrm{Pb}}^{\mathrm{STR}} + \sigma_{\mathrm{Pb}}^{\mathrm{EB}}$$

$$\sigma_{\mathrm{Pb}}^{\mathrm{STR}} \simeq \sigma_{\mathrm{Pb}}^{\mathrm{STR}}(n)$$

$$\sigma_{\mathrm{Pb}}^{\mathrm{EB}} \simeq \sigma_{\mathrm{Pb}}^{\mathrm{EB}}(n) + \sigma_{\mathrm{Pb}}^{\mathrm{EB}}(c)$$

$$\sigma_{\mathrm{Pb}}^{-1n} = \sigma_{\mathrm{Pb}}^{\mathrm{STR}}(n) + \sigma_{\mathrm{Pb}}^{\mathrm{EB}}(n) + \sigma_{\mathrm{Pb}}^{\mathrm{EB}}(c)$$

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$$\sigma_{\mathrm{Pb}}^{\mathrm{EB}}(c) = \sigma_{\mathrm{Pb}}^{-1n} - \sigma_{\mathrm{Pb}}^{-1n}(n)$$

$$\sigma_{\mathrm{Pb}}^{\mathrm{EB}}(c) \simeq \sigma_{\mathrm{Pb}}^{\mathrm{EB}}(E1)$$

$$\sigma_{\mathrm{Pb}}^{\mathrm{EB}}(E1) = \sigma_{\mathrm{Pb}}^{-1n} - \sigma_{\mathrm{Pb}}^{-1n}(n)$$

$$\sigma_{\mathrm{Pb}}^{\mathrm{EB}}(c) = \sigma_{\mathrm{Pb}}^{-1n} - \sigma_{\mathrm{Pb}}^{-1n}(n)$$

$$\Big\downarrow \quad \sigma_{\mathrm{Pb}}^{\mathrm{EB}}(c) \simeq \sigma_{\mathrm{Pb}}^{\mathrm{EB}}(E1)$$

$$\sigma_{\mathrm{Pb}}^{\mathrm{EB}}(E1) = \sigma_{\mathrm{Pb}}^{-1n} - \sigma_{\mathrm{Pb}}^{-1n}(n)$$

$$\Big\downarrow \quad \Gamma = \sigma_{\mathrm{Pb}}^{-1n}(n)/\sigma_{\mathrm{C}}^{-1n}(n)$$

$$\sigma_{\mathrm{Pb}}^{\mathrm{EB}}(c) = \sigma_{\mathrm{Pb}}^{-1n} - \Gamma\sigma_{\mathrm{C}}^{-1n}(n)$$

$$
\begin{tikzcd}
\sigma_{\mathrm{Pb}}^{\mathrm{EB}}(c) = \sigma_{\mathrm{Pb}}^{-1n} - \sigma_{\mathrm{Pb}}^{-1n}(n) \arrow[d, "\sigma_{\mathrm{Pb}}^{\mathrm{EB}}(c) \simeq \sigma_{\mathrm{Pb}}^{\mathrm{EB}}(E1)"] \\
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\end{tikzcd}
$$

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$$\Gamma = \sigma_{\mathrm{Pb}}^{-1n}(n)/\sigma_{\mathrm{C}}^{-1n}(n)$$

$$\sigma_{\mathrm{Pb}}^{\mathrm{EB}}(c) = \sigma_{\mathrm{Pb}}^{-1n} - \Gamma\sigma_{\mathrm{C}}^{-1n}(n)$$

$$\sigma_{\mathrm{C}}^{-1n}(n) \simeq \sigma_{\mathrm{C}}^{-1n}$$

$$\underline{\sigma_{\mathrm{Pb}}^{\mathrm{EB}}(E1)} = \underline{\sigma_{\mathrm{Pb}}^{-1n}} - \Gamma\underline{\sigma_{\mathrm{C}}^{-1n}}$$

we want experiment

We confirmed (for 1n halo systems)

- E1 is dominant in Coulomb breakup

$$\sigma_{\mathrm{Pb}}^{\mathrm{EB}}(c) \simeq \sigma_{\mathrm{Pb}}^{\mathrm{EB}}(E1)$$

- Interference between Coulomb and Nuclear interaction is negligible

$$\sigma_{\mathrm{Pb}}^{\mathrm{EB}} \simeq \sigma_{\mathrm{Pb}}^{\mathrm{EB}}(n) + \sigma_{\mathrm{Pb}}^{\mathrm{EB}}(c)$$

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- In case of ^{12}C target, Nuclear interaction is dominant

$$\sigma_{\mathrm{C}}^{-1n} \simeq \sigma_{\mathrm{C}}^{-1n}(n)$$

E1 cross section formula

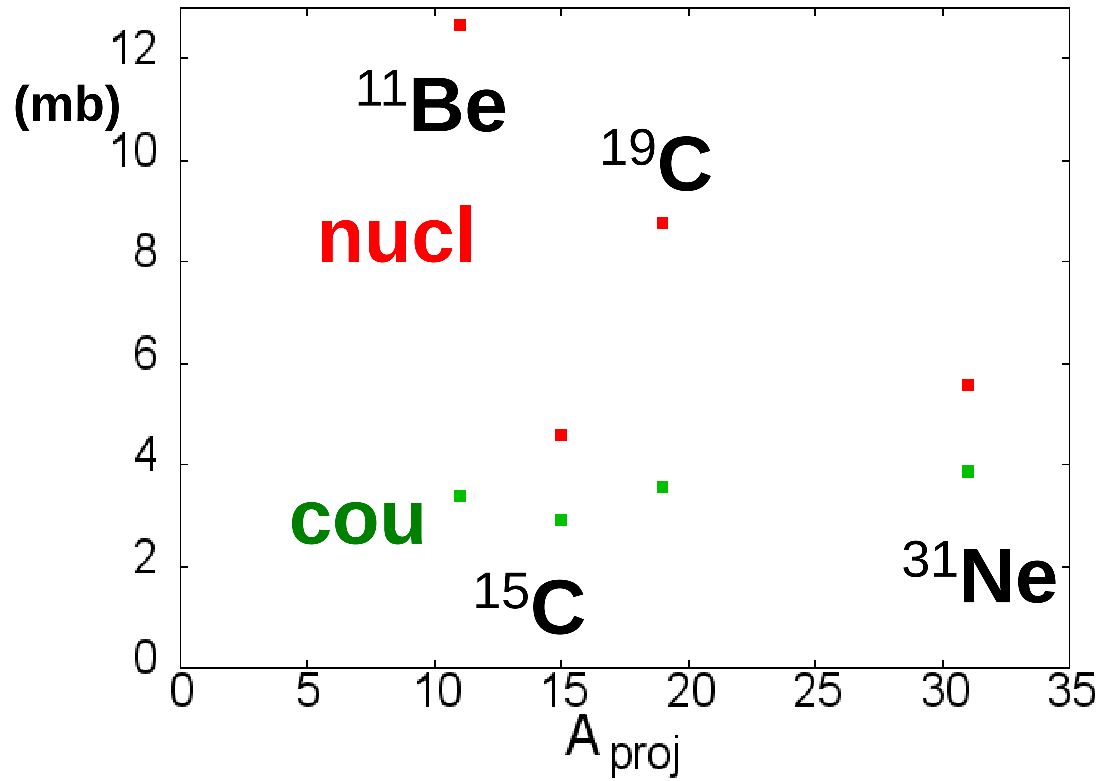
$$\sigma(E1) = \sigma_{\mathrm{Pb}}^{-1n} - \Gamma\sigma_{\mathrm{C}}^{-1n}$$

about 95% accuracy

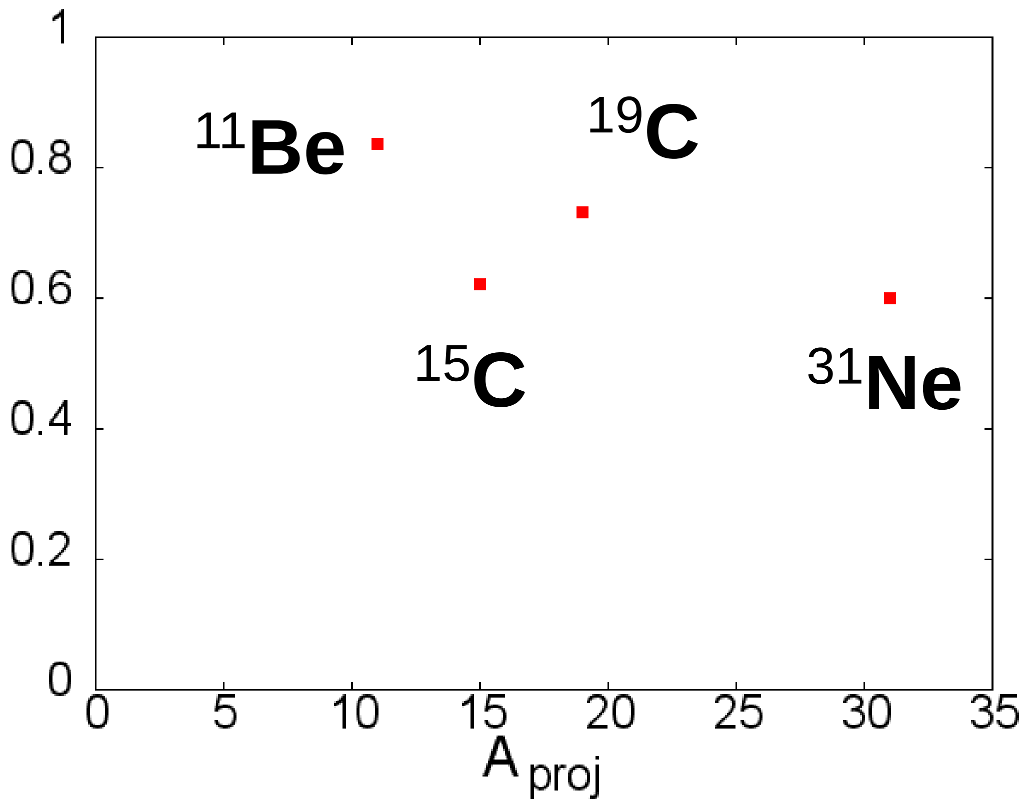
where Γ is defined by $$\Gamma = \frac{\sigma_{\mathrm{Pb}}^{-1n}(n)}{\sigma_{\mathrm{C}}^{-1n}(n)}$$

$$\sigma_{\mathrm{C}}^{\mathrm{EB}} \simeq \sigma_{\mathrm{C}}^{\mathrm{EB}}(n) \ \ ?$$

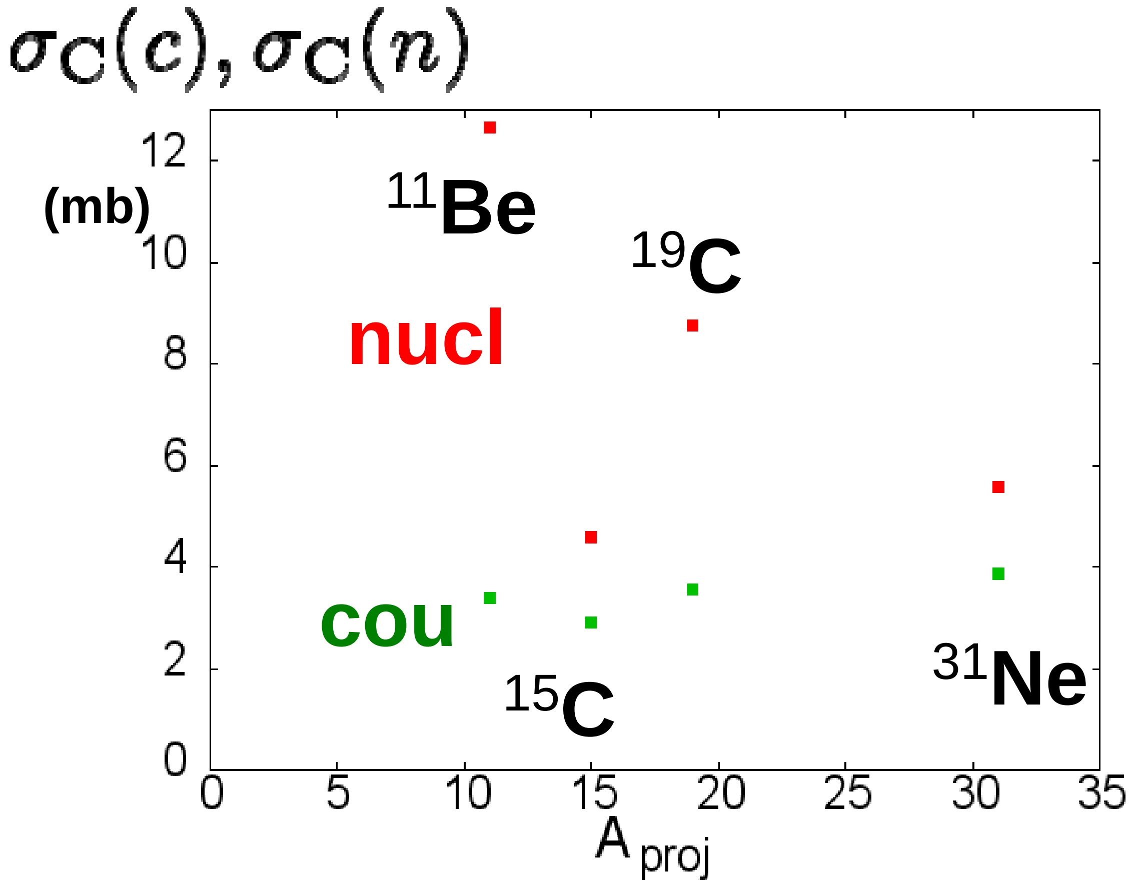
$\sigma_{\mathrm{C}}(c), \sigma_{\mathrm{C}}(n)$

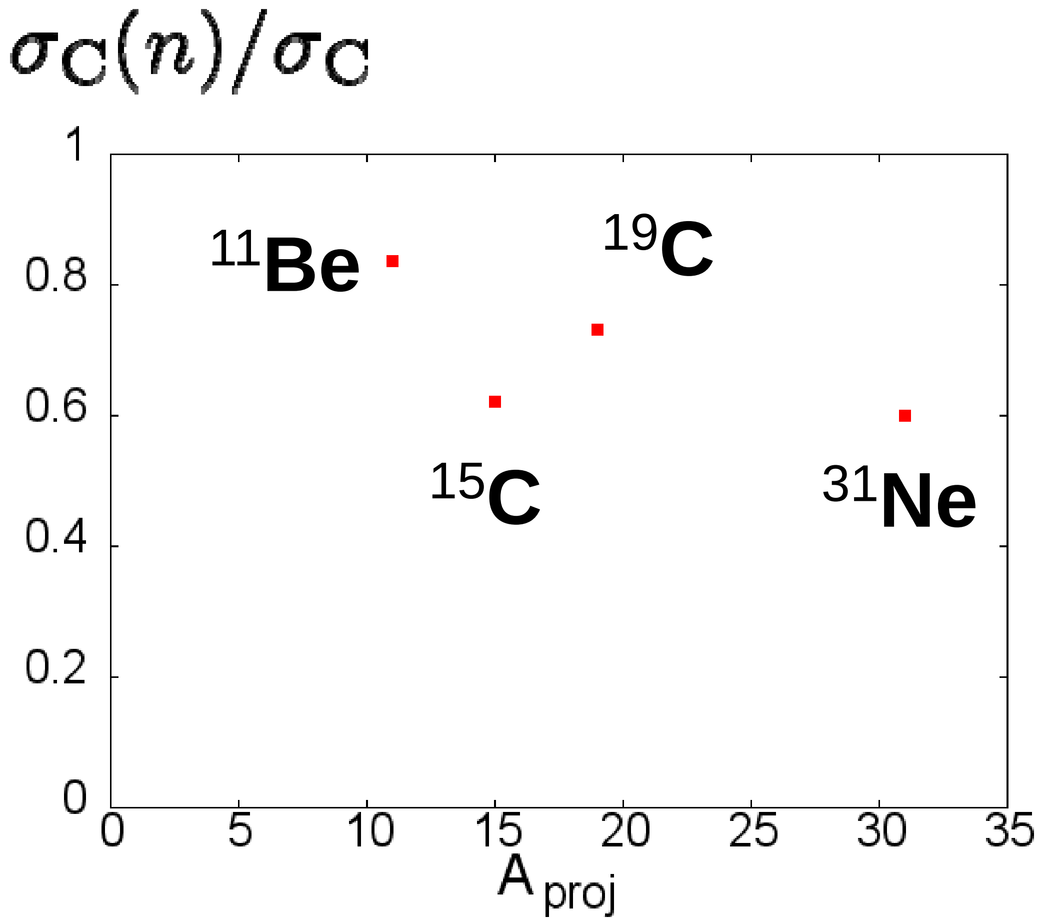


$\sigma_{\mathrm{C}}(n)/\sigma_{\mathrm{C}}$

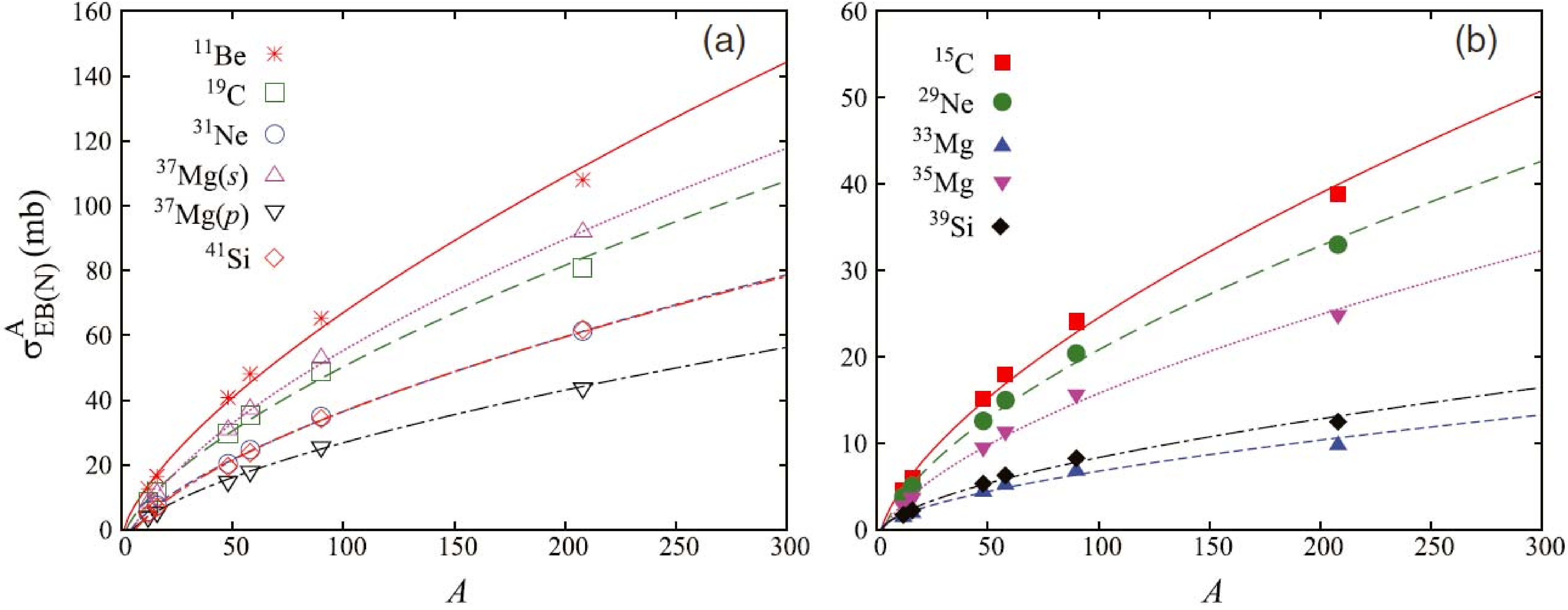


$$\sigma_C^{EB} \not\simeq \sigma_C^{EB}(n)$$

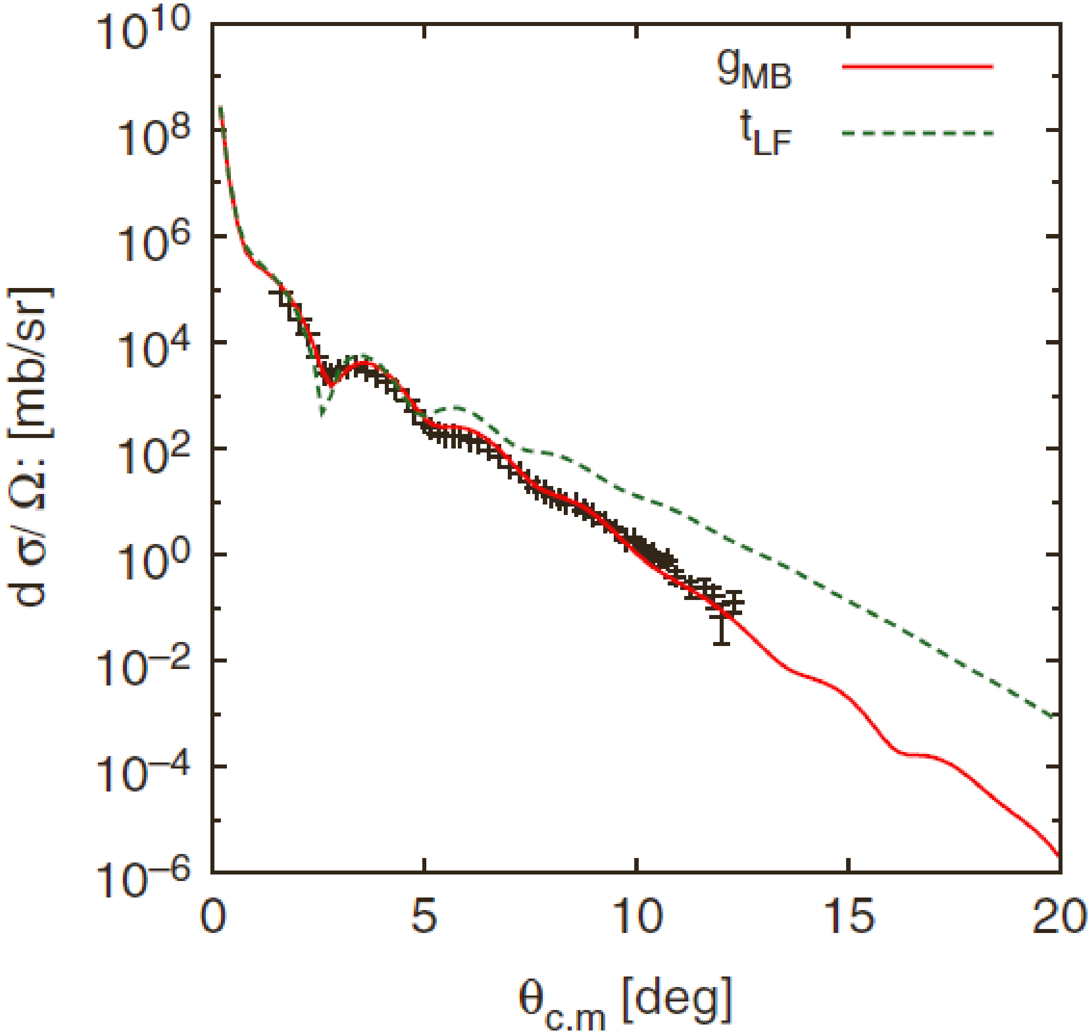




Target mass number dependence of $\sigma^{\mathrm{EB}}(n)$

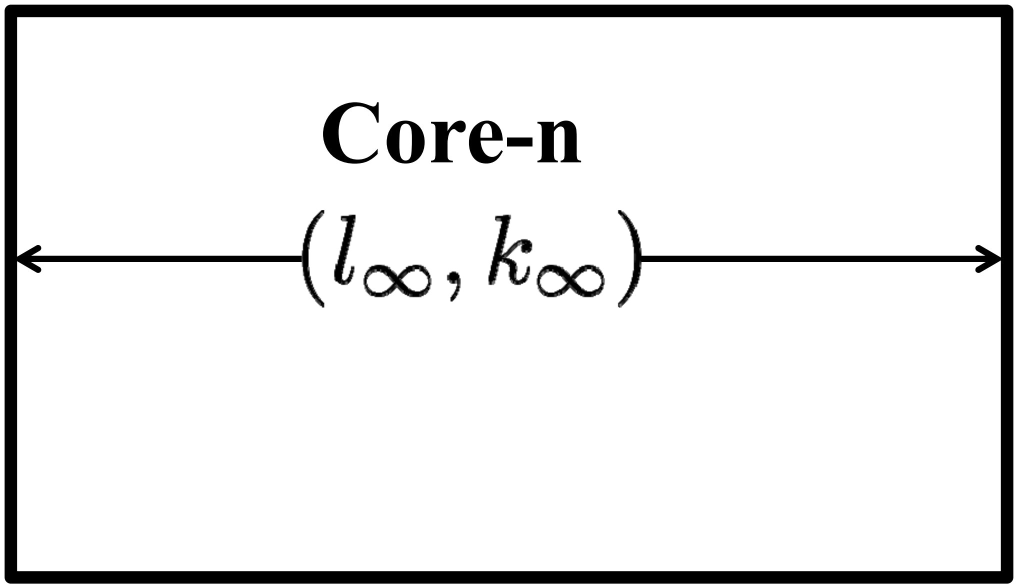


$^{12}C+^{12}C$ elastic cross section at 135MeV/nucleon



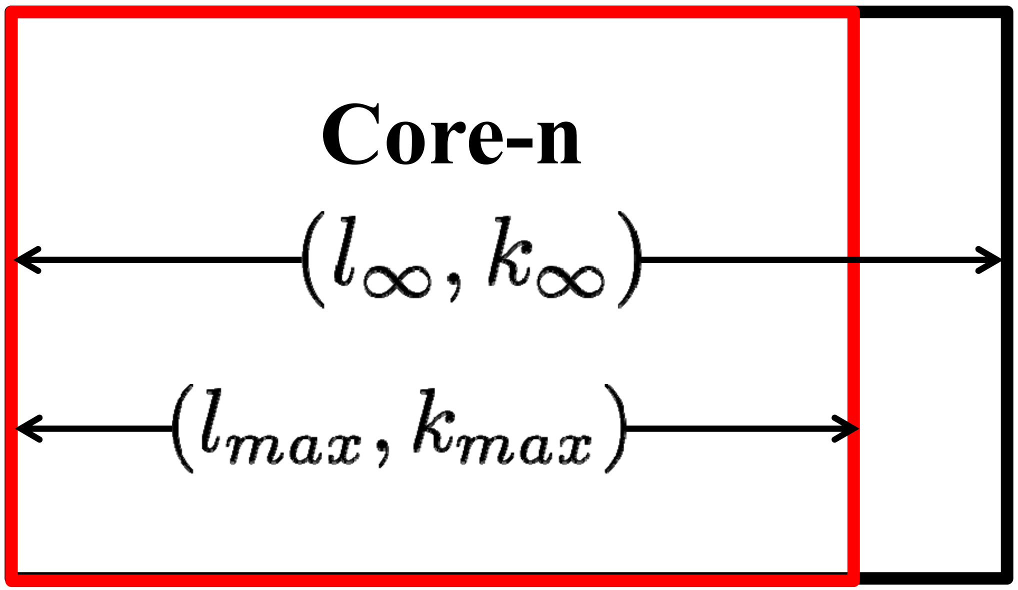
M. Yahiro, K. Ogata, T. Matsumoto, K. Minomo, PTEP**2012**, 01A206 (review)

$$\sigma^{-1n}_{\mathrm{A=1}} = \sigma^{\mathrm{EB}}_{\mathrm{A=1}}$$
$$\left(\sigma^{\mathrm{STR}}_{\mathrm{A=1}} = 0\right)$$



CDCC model space
(this work)

$$\sigma^{-1n}_{\mathrm{A}=1} = \sigma^{\mathrm{EB}}_{\mathrm{A}=1}$$
$$\left(\sigma^{\mathrm{STR}}_{\mathrm{A}=1} = 0\right)$$



CDCC model space
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$$\sigma^{-1n}_{\mathrm{A}=1} = \sigma^{\mathrm{EB}}_{\mathrm{A}=1}$$

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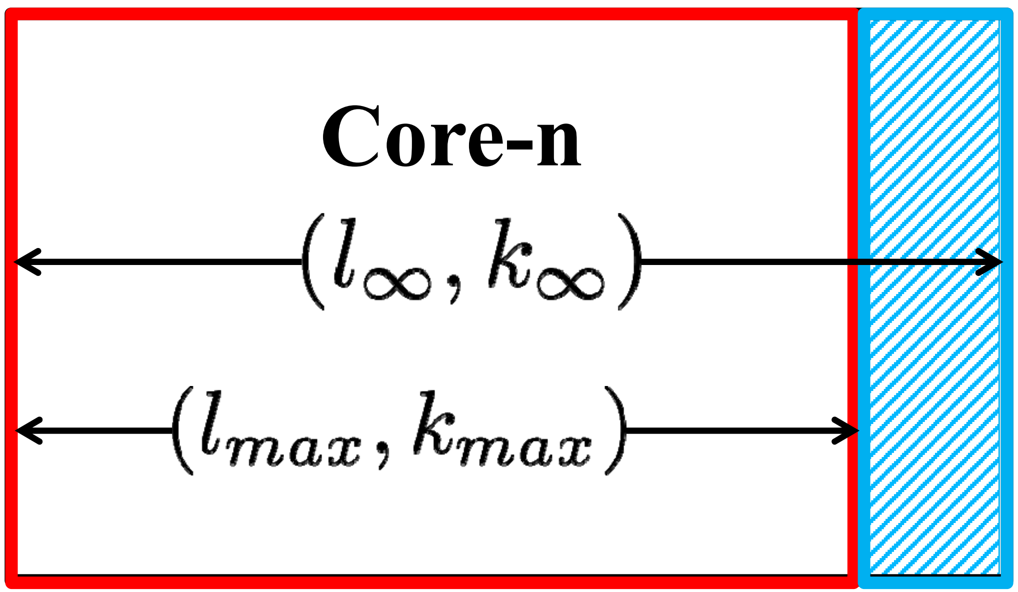
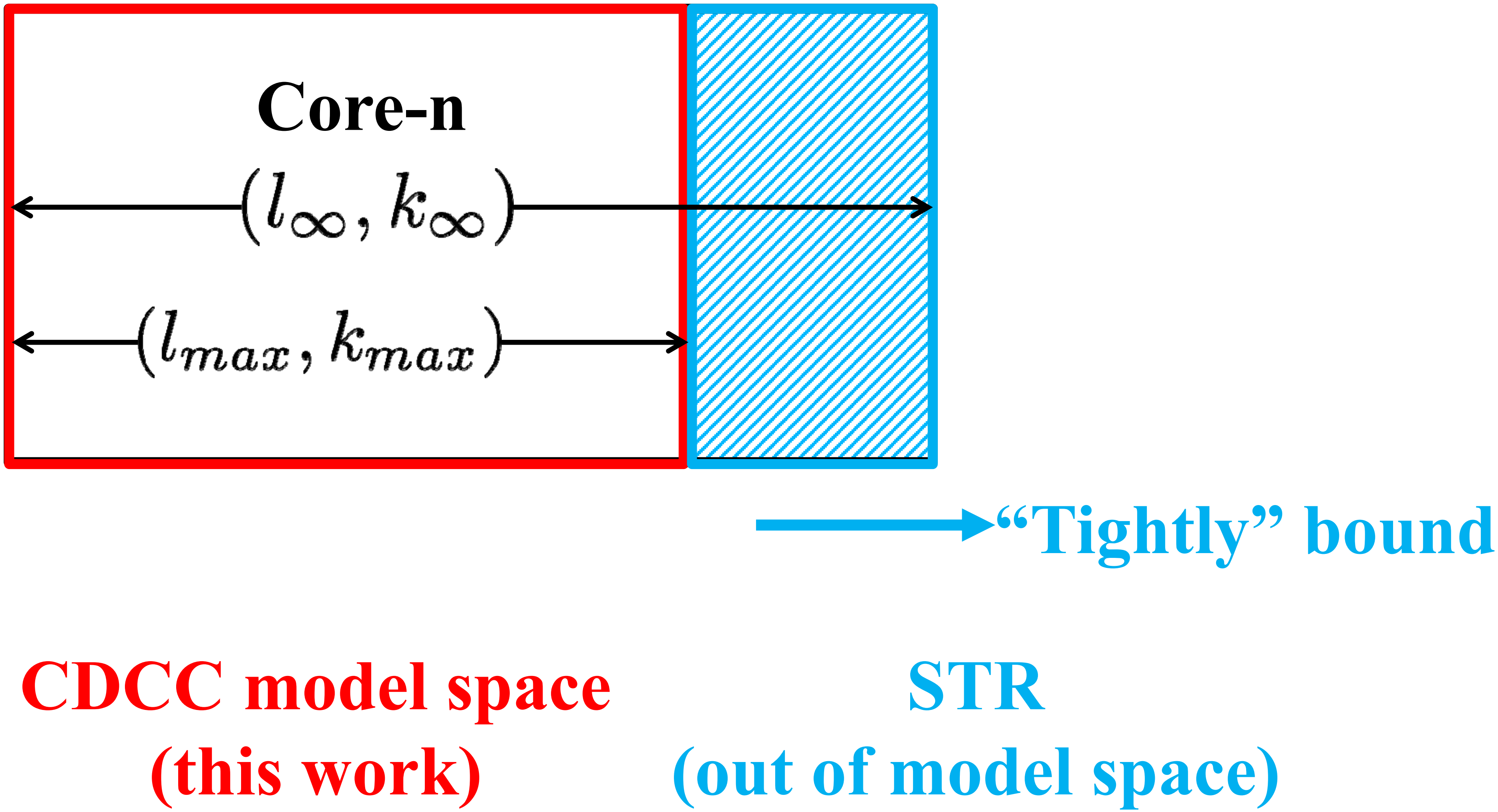


$$\sigma_{\mathrm{A=1}}^{-1n} = \sigma_{\mathrm{A=1}}^{\mathrm{EB}}$$
$$(\sigma_{\mathrm{A=1}}^{\mathrm{STR}} = 0)$$



$$\sigma_{\mathrm{A=1}}^{-1n} = \sigma_{\mathrm{A=1}}^{\mathrm{EB}}$$
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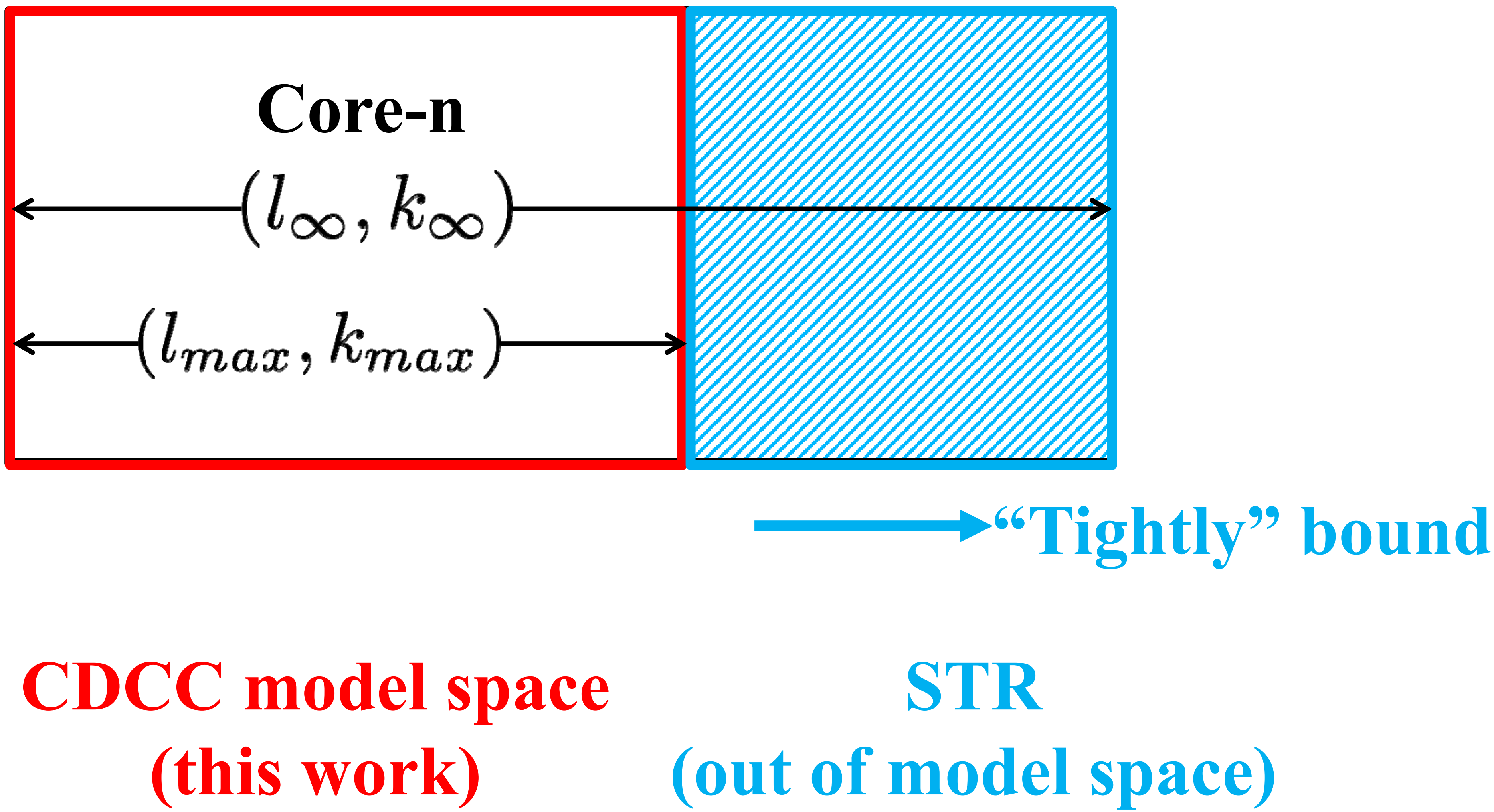
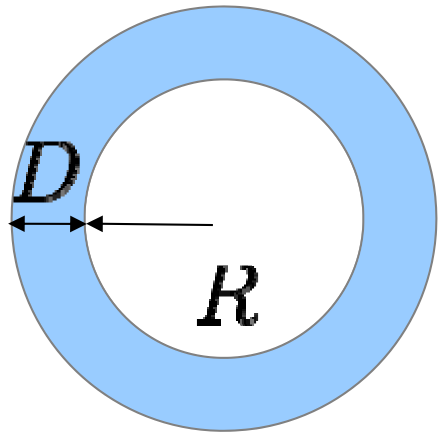


A-R relation

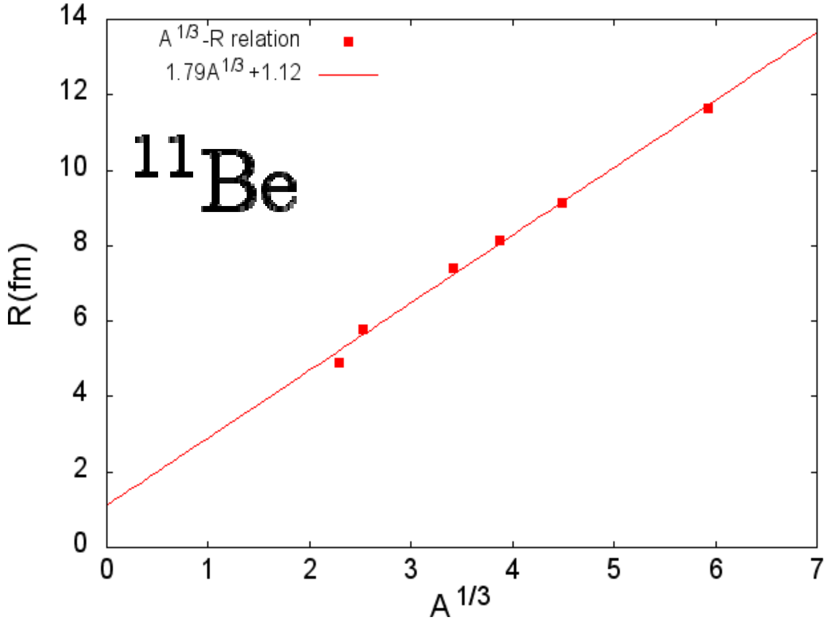
Effective distance $R \equiv (J + 1/2)/K$

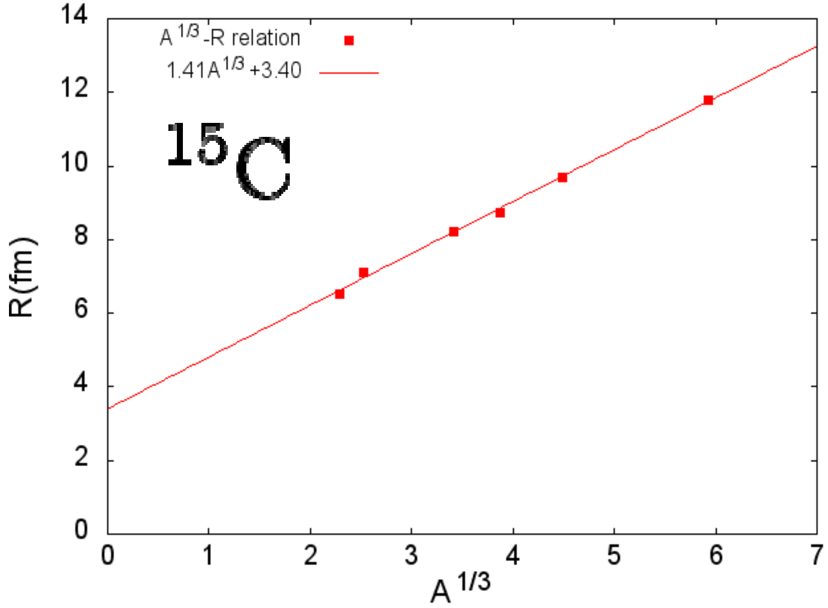
A-D relation

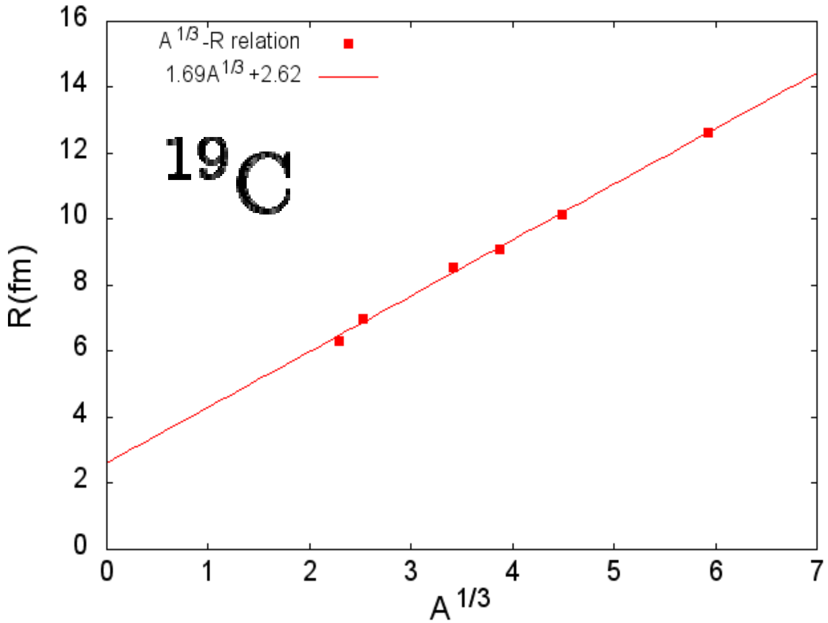
$$2\pi R D = \sigma$$

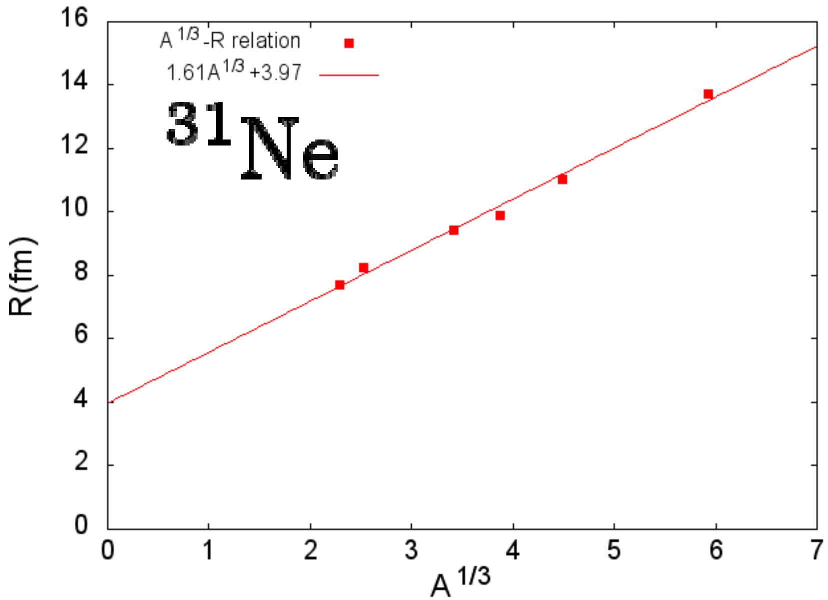


A-R relation


^{11}Be
$A^{1/3}$-R relation
$1.79A^{1/3}+1.12$
R(fm)
$A^{1/3}$

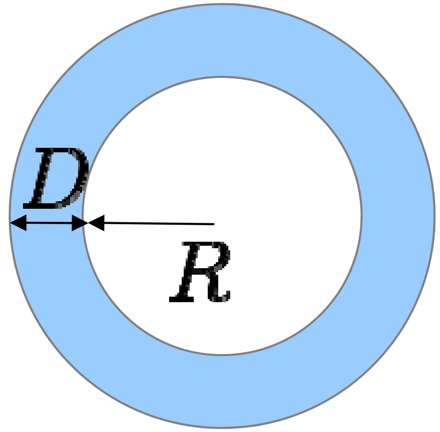

^{15}C
$A^{1/3}$-R relation
$1.41A^{1/3}+3.40$
R(fm)
$A^{1/3}$

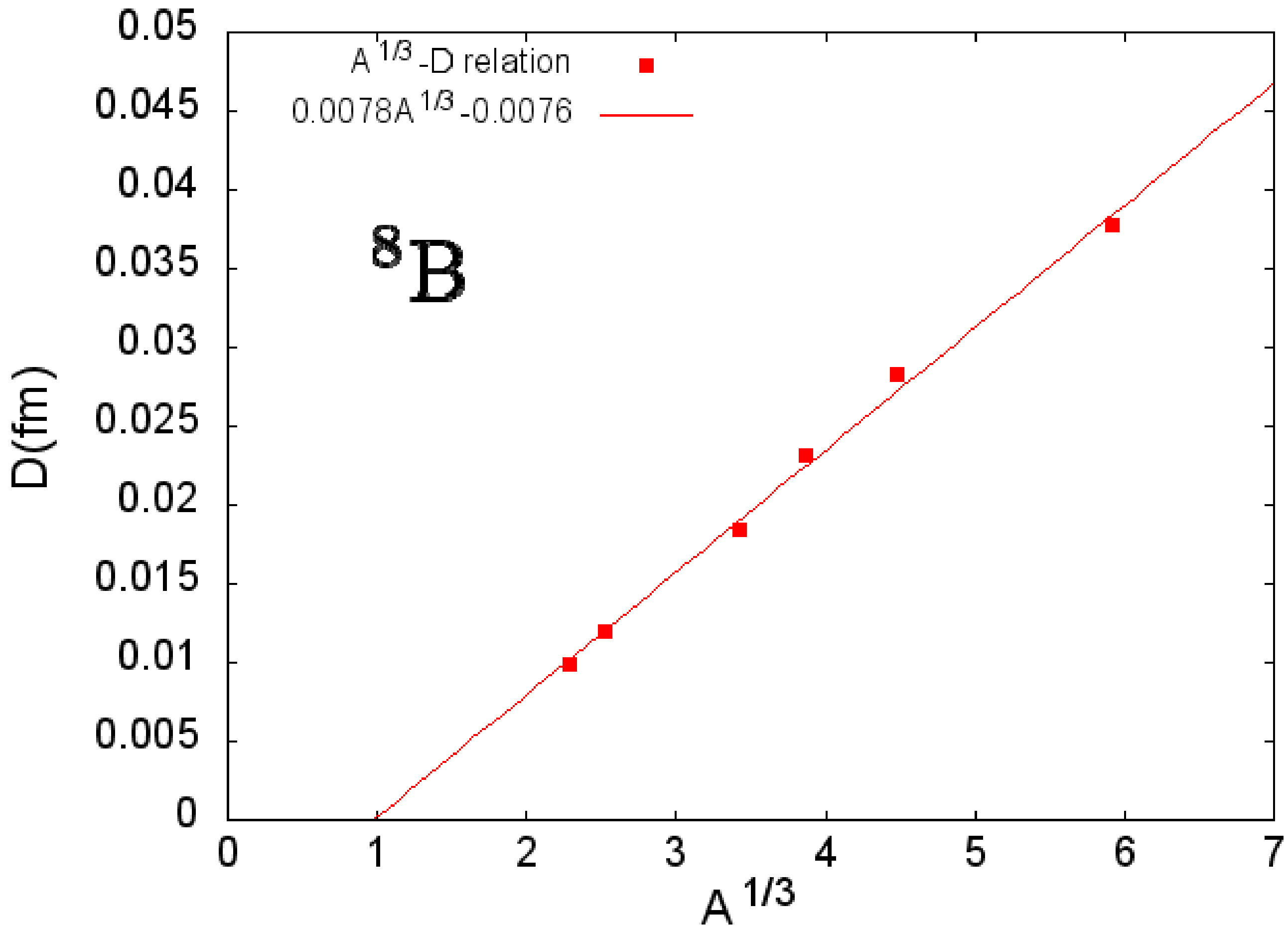

^{19}C
$A^{1/3}$-R relation
$1.69A^{1/3}+2.62$
R(fm)
$A^{1/3}$


^{31}Ne
$A^{1/3}$-R relation
$1.61A^{1/3}+3.97$
R(fm)
$A^{1/3}$

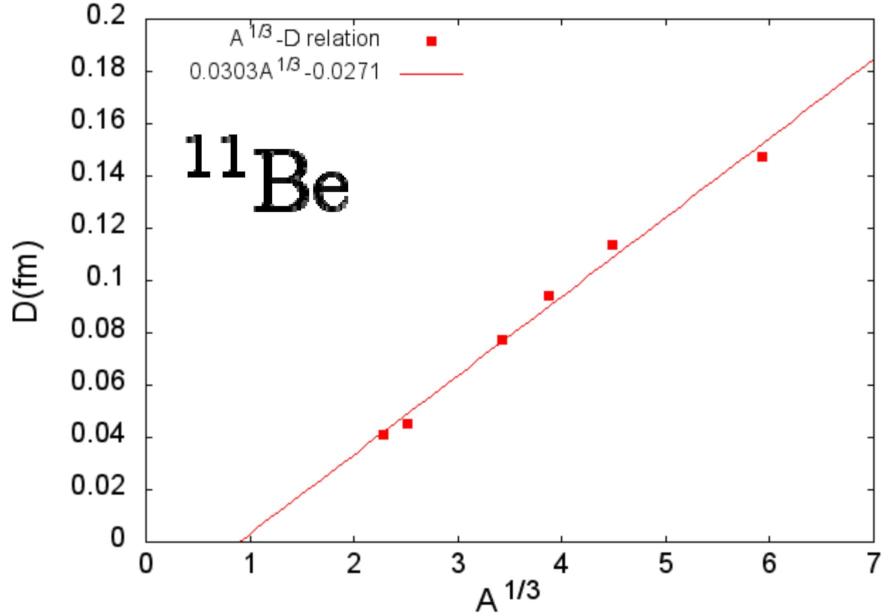
$A - D$ 関係

$$2\pi R D = \sigma$$

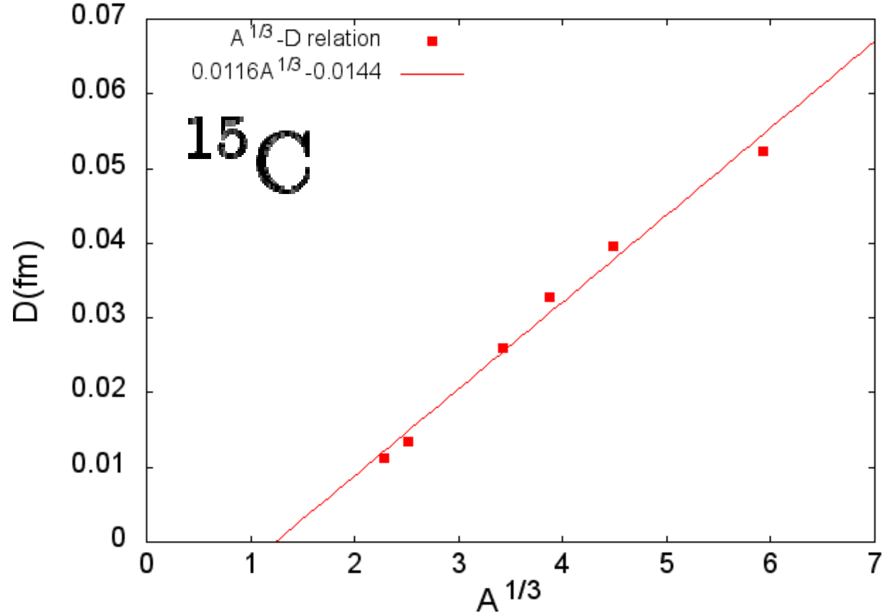




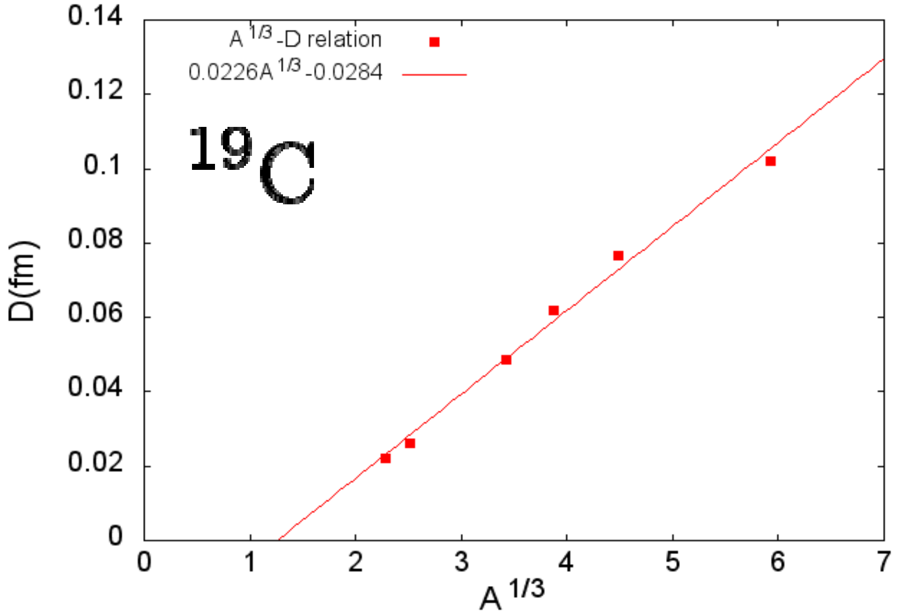
A-D relation



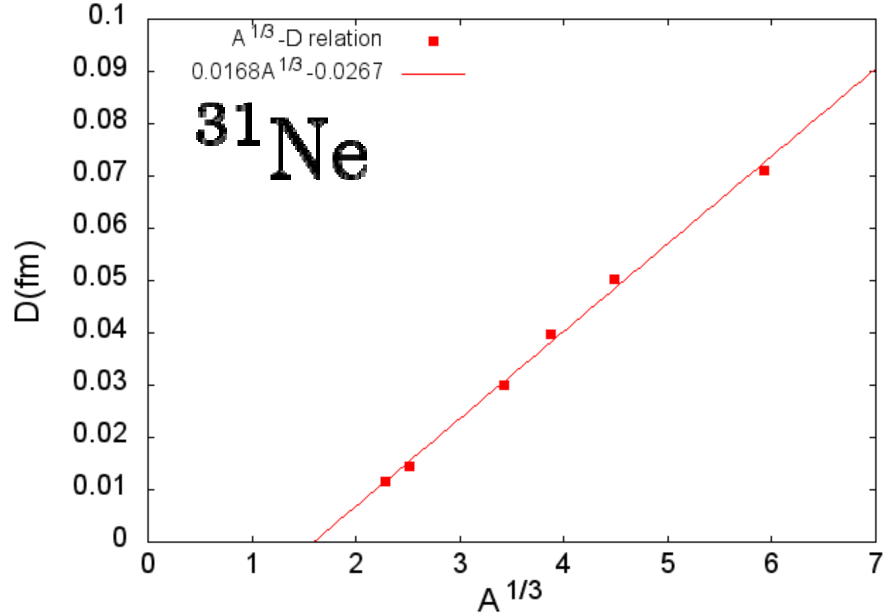
A $^{1/3}$-D relation
$0.0303A^{1/3}-0.0271$
^{11}Be
D(fm)
A $^{1/3}$



A $^{1/3}$-D relation
$0.0116A^{1/3}-0.0144$
^{15}C
D(fm)
A $^{1/3}$



A $^{1/3}$-D relation
$0.0226A^{1/3}-0.0284$
^{19}C
D(fm)
A $^{1/3}$



A $^{1/3}$-D relation
$0.0168A^{1/3}-0.0267$
^{31}Ne
D(fm)
A $^{1/3}$

multipole expansion

$$V_{1A} \propto \frac{1}{R_1} = \sum_{\lambda} \frac{r^{\lambda}}{R^{\lambda+1}} P_{\lambda}(\cos\theta)$$

λ:multipolarity