Search for new halo states in nuclear ground and excited states with fast rare isotope beams

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Our recent studies:

Moderate halo formation in the ground state of ^{29}Ne

* **<u>N. Kobayashi</u>** *et al*., Phys. Rev. C **93**, 014613 (2016).

+ New method:

Measurement of interaction cross sections of excited states with fast rare isotope beams

* **<u>N. Kobayashi</u>**, K. Whitmore, and H. Iwasaki, NIMA **860**, 67 (2016).

Moderate halo formation in the ground state of ^{29}Ne

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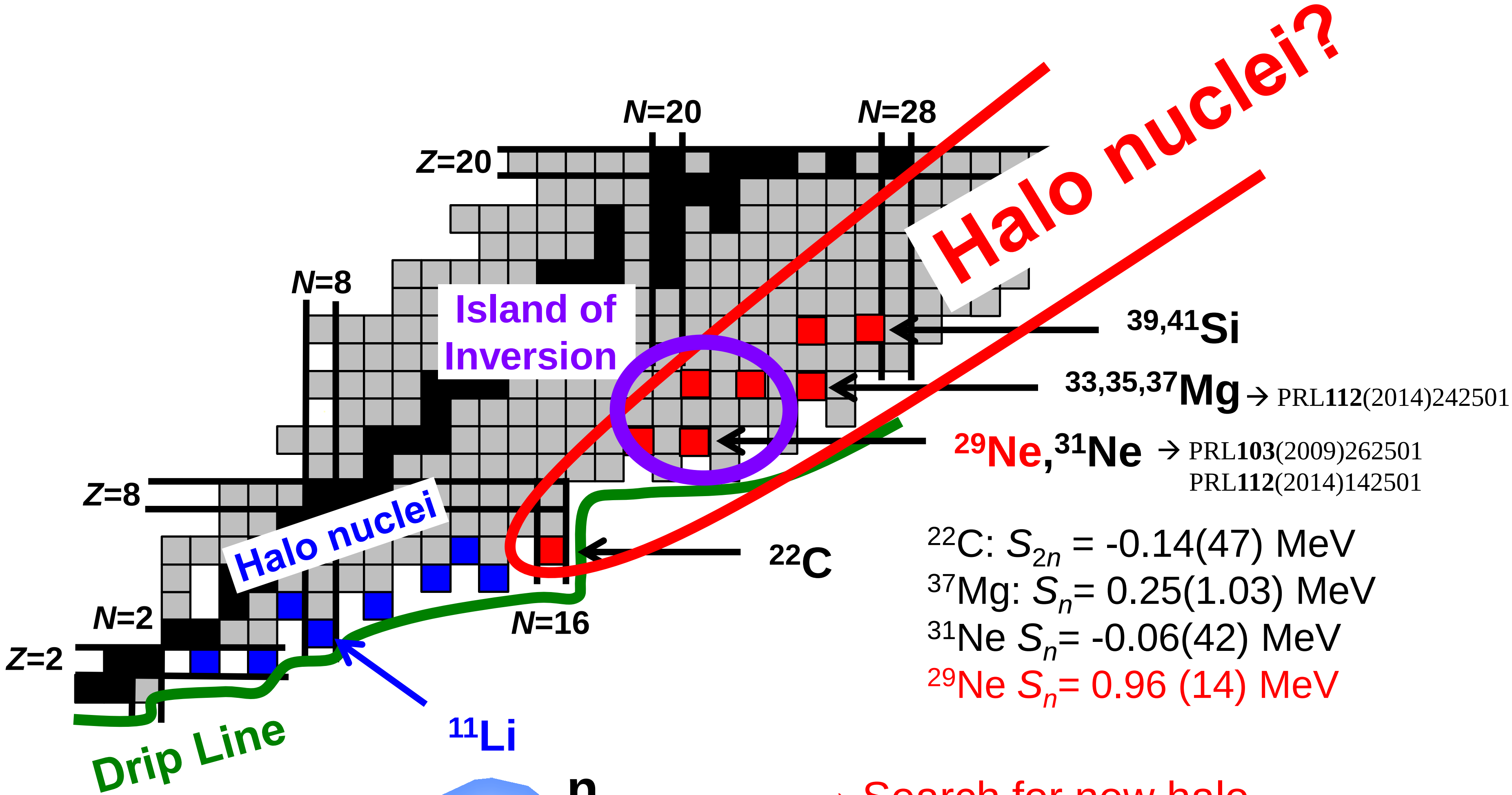
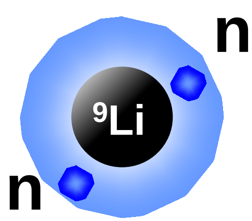
Appearance of halo nuclei in ground states





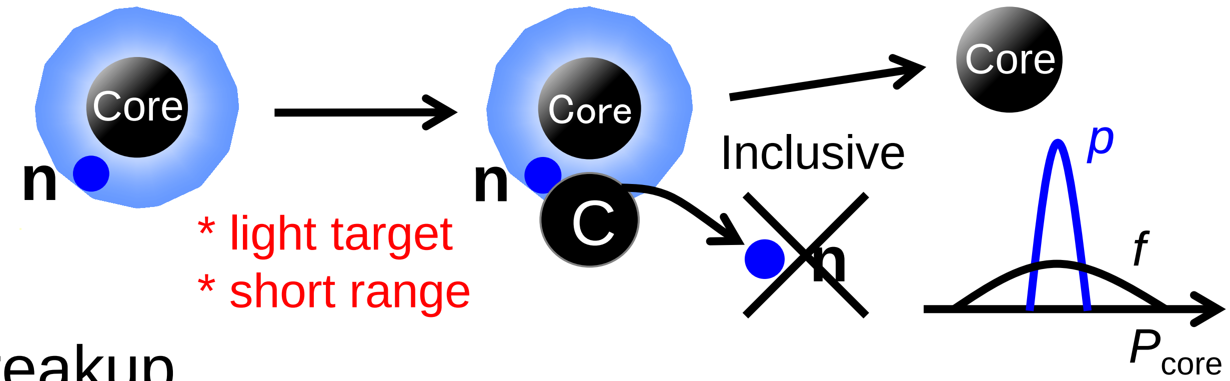
→ Search for new halo
& understand the structure
by Coulomb & nuclear breakup
reactions

Methods to probe halo nuclei

Nuclear breakup

to obtain orbital angular momentum *l*

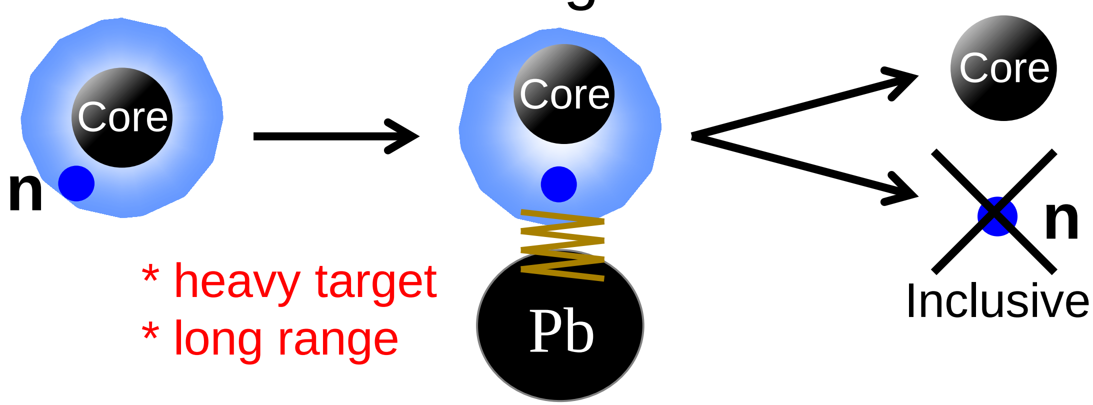
→ *s*-wave and *p*-wave neutrons in halo nuclei



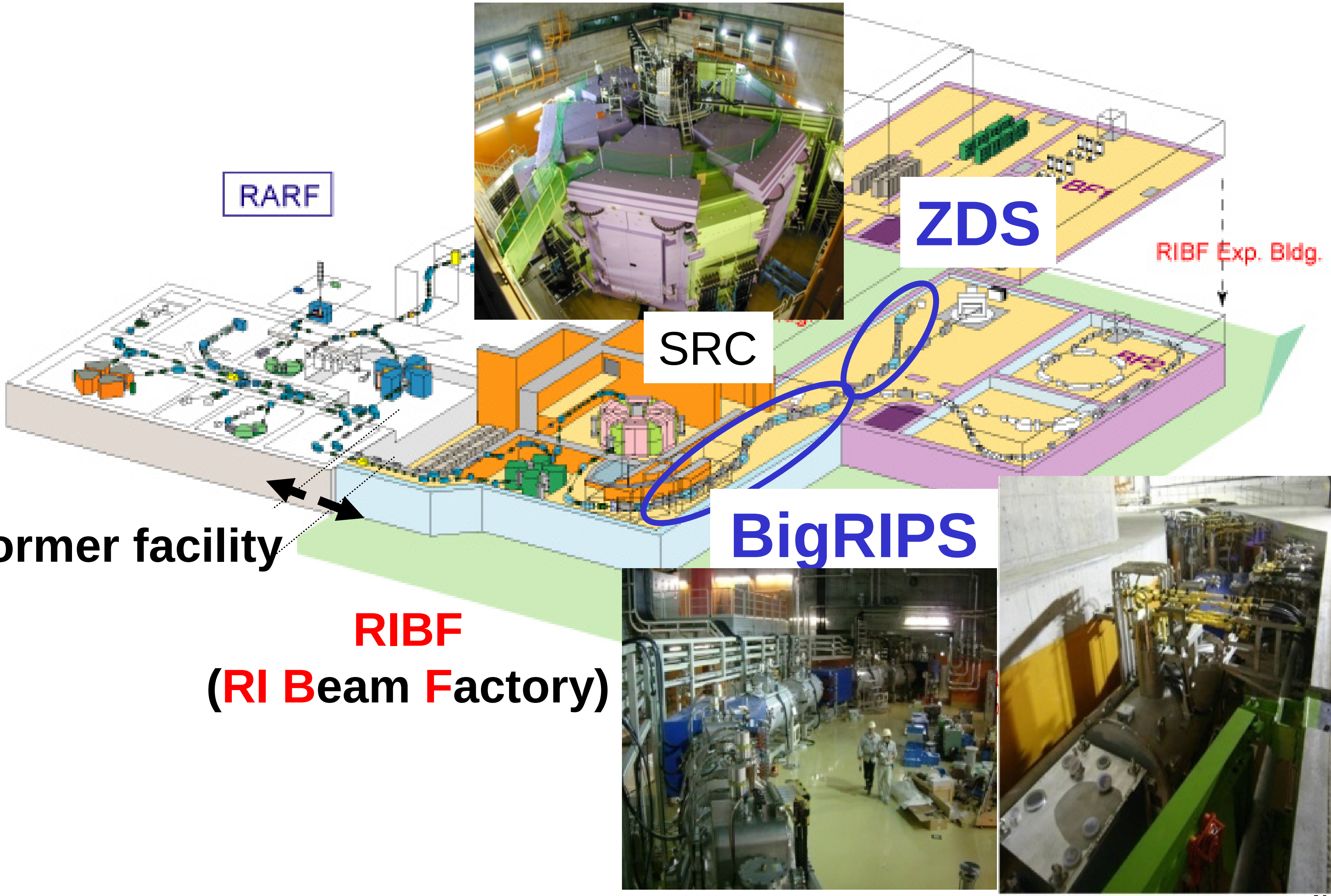
Coulomb breakup

to probe soft E1 excitation

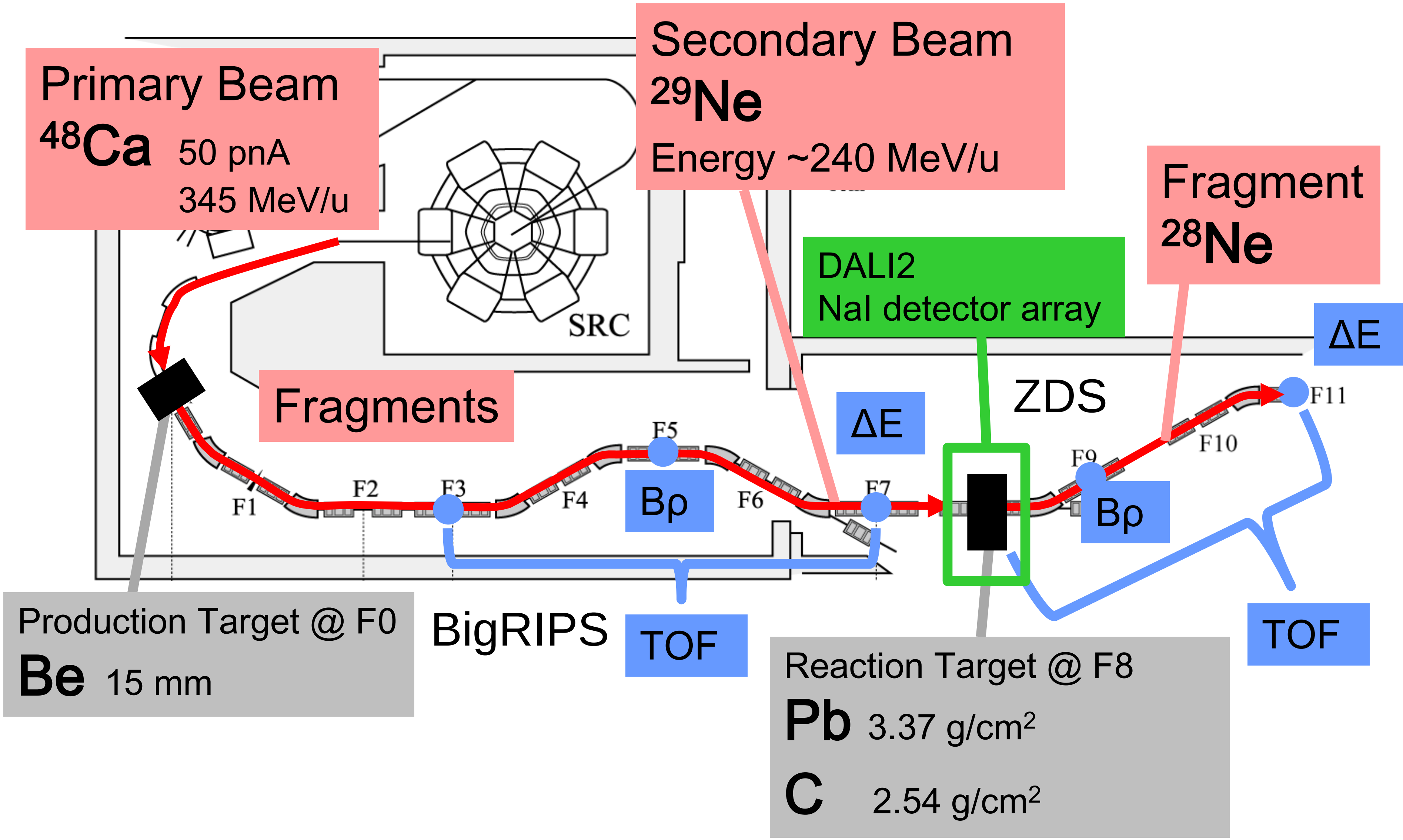
→ signature of halo via the large cross sections σ(E1)



Experiment at RIBF in 2010



Experimental setup



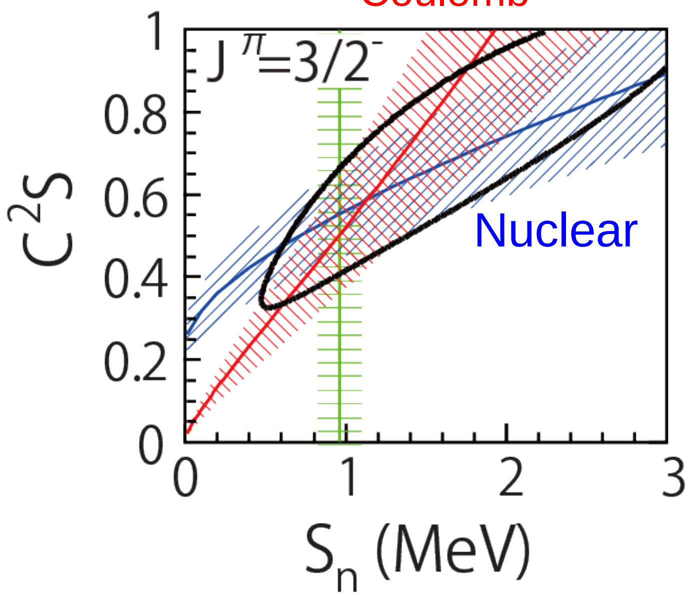
p-wave component in ^{29}Ne (*N*=19, *Z*=20)

	Coulomb breakup	Nuclear breakup	
	Exp.	Exp.	Theo.
Inclusive $^{29}Ne \rightarrow {}^{28}Ne$	222(36) mb	74(2) mb	69.0 mb
Partial $^{29}Ne \rightarrow {}^{28}Ne(0^+_{gs})$	176(50) mb	36(7) mb	31.6 mb

Analysis of Coulomb + Nuclear breakup
→ Spin parity : $3/2^-$
→ $^{28}Ne(0^+_{gs}) \otimes 2p_{3/2}$ ~ 50%
(^{29}Ne S_n= 0.96 (14) MeV)

Moderate *p*-wave halo
coupled with deformed core

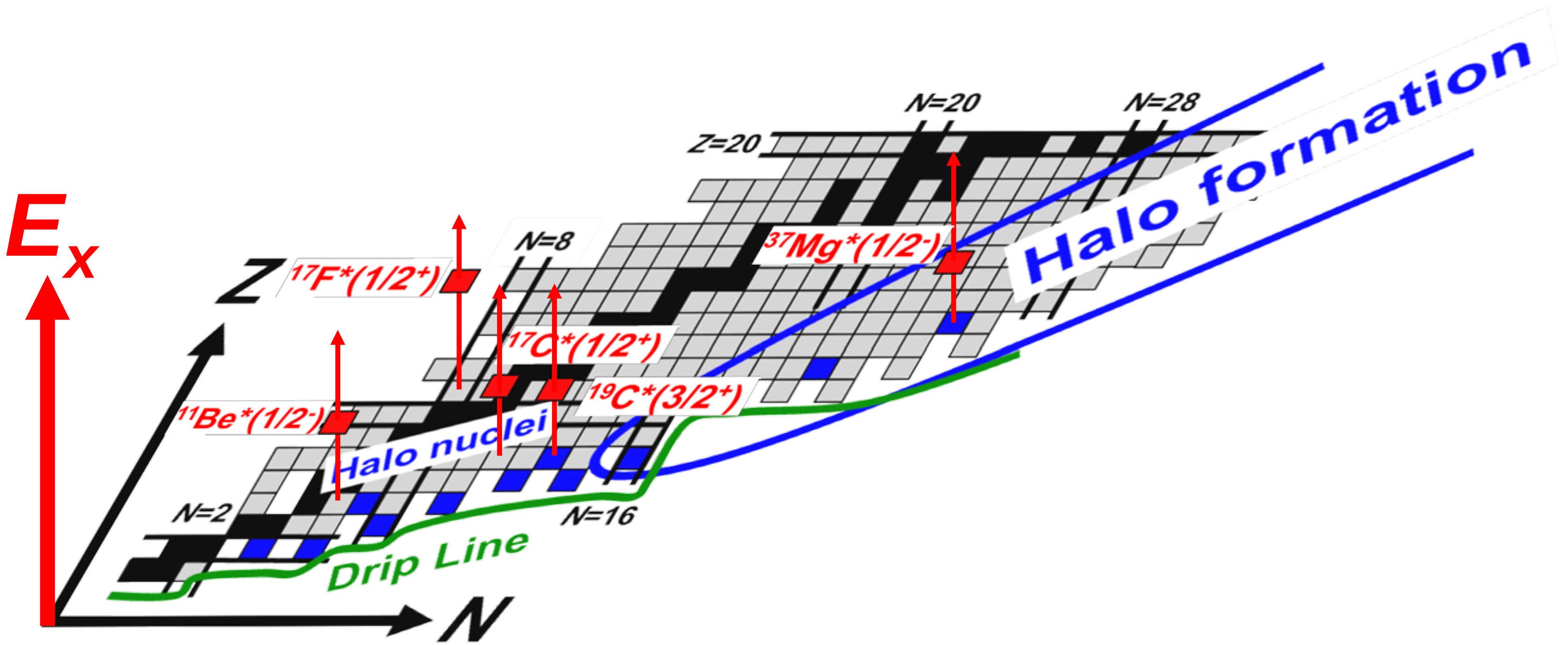
$^{29}Ne(\mathbf{3/2^-}) \rightarrow {}^{28}Ne(0^+) + 2p_{3/2}$



Measurement of interaction cross sections of excited states with fast rare isotope beams

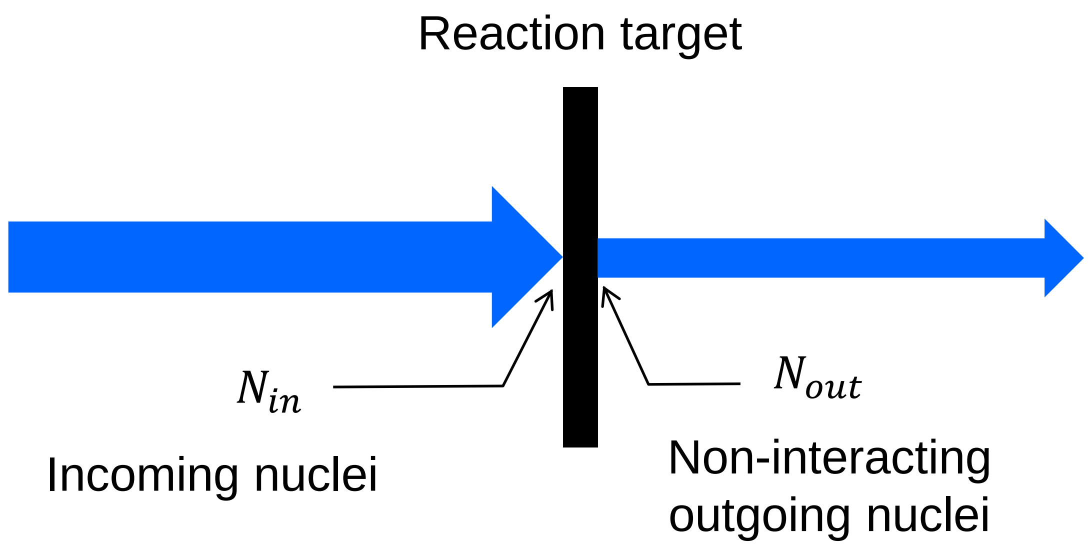
* **N. Kobayashi**, K. Whitmore, and H. Iwasaki, NIMA **860**, 67 (2016).

Next step: halo in excited states



- ☑ Halo formation in the ground states
- ☐ How about in excited states?
  → Recoil Distance transmission method (RDTM)

Transmission Method

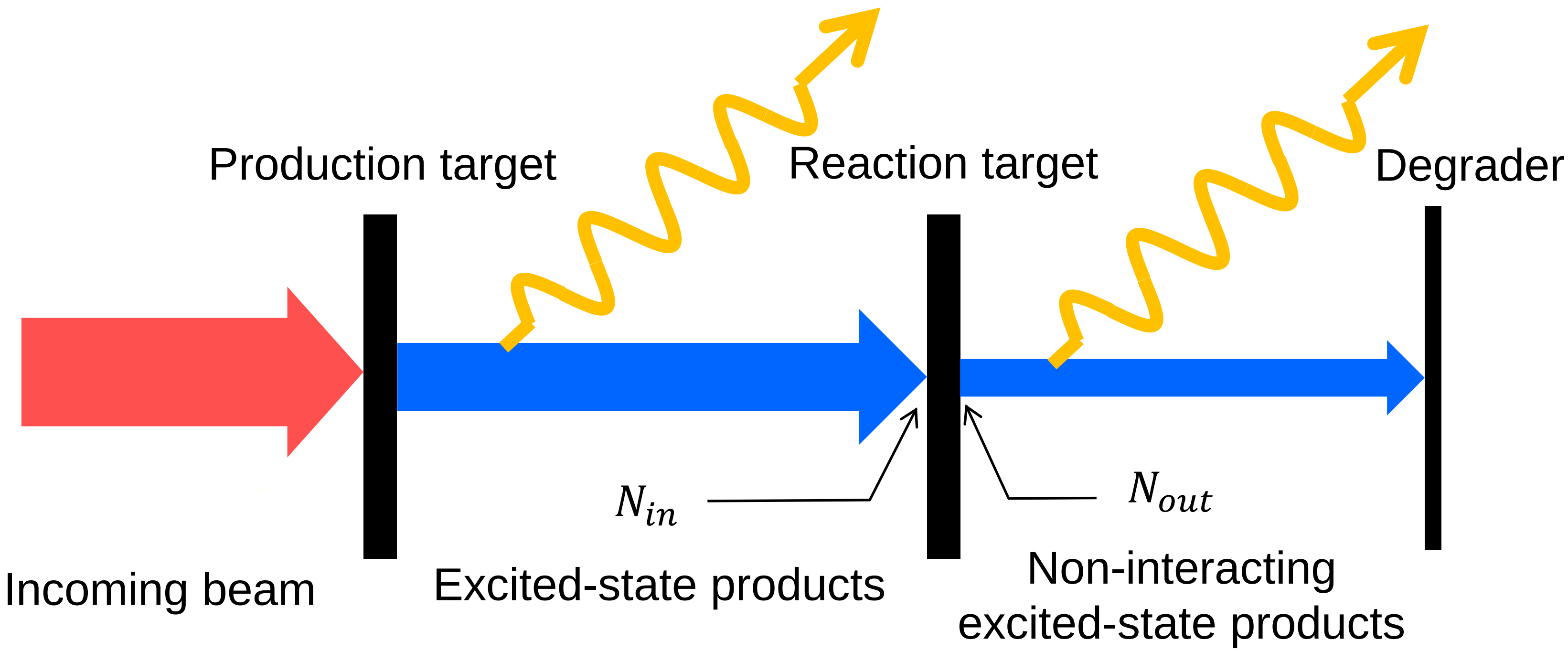


$$\sigma_I^{\mathrm{gs}} = -\frac{A}{N_A \rho x_t} \ln\left(\frac{N_{out}}{N_{in}}\right)$$

σ_I^{gs}: interaction cross section of the ground state

x_t, ρ, A: thickness, density, mass number of the target

Recoil Distance Transmission Method (RDTM)

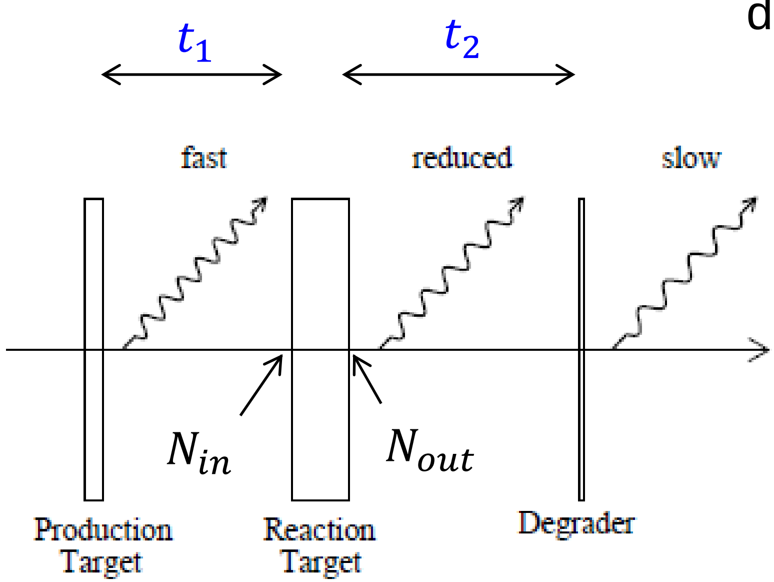


$$\sigma_I^{\mathrm{ex}} = -\frac{A}{N_A \rho x_t} \ln\left(\frac{N_{out}}{N_{in}}\right)$$

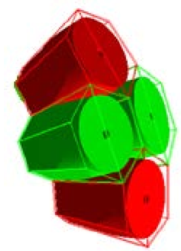
σ_I^{ex}: interaction cross section of the excited state

The number of γ rays → N_{in} & N_{out}

Recoil Distance Transmission Method (RDTM)



Ge tracking detector



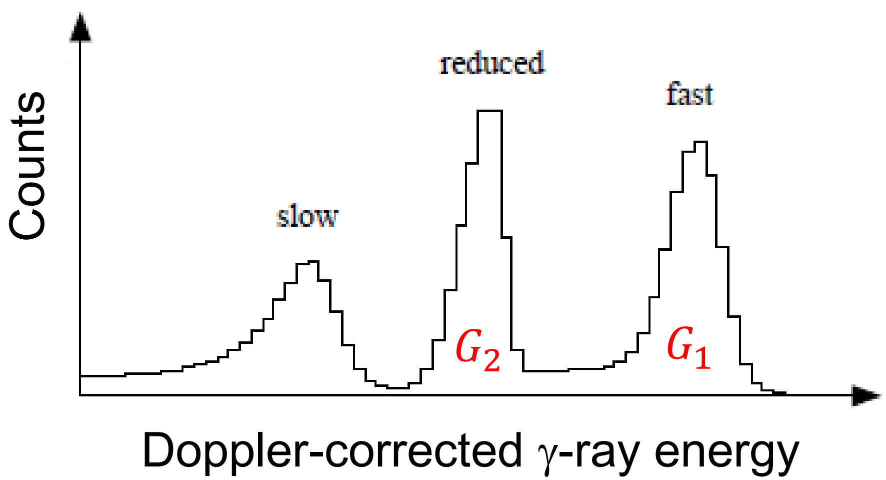
τ: lifetime of the excited state

$$N_{\text{in}} = \frac{G_1 e^{-t_1/\tau}}{1 - e^{-t_1/\tau}}$$

$$N_{\text{out}} = \frac{G_2}{1 - e^{-t_2/\tau}}$$

$$\sigma_I^{\text{ex}} = -\frac{A}{N_A \rho x_t} \ln\left(\frac{N_{\text{out}}}{N_{\text{in}}}\right)$$

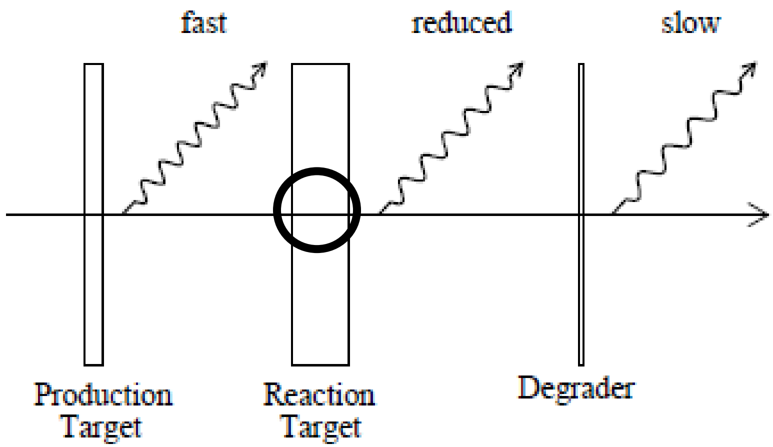
$$= -\frac{A}{N_A \rho x_t} \ln\left(\frac{G_2}{G_1} \frac{1 - e^{-t_1/\tau}}{e^{-t_1/\tau}(1 - e^{-t_2/\tau})}\right)$$

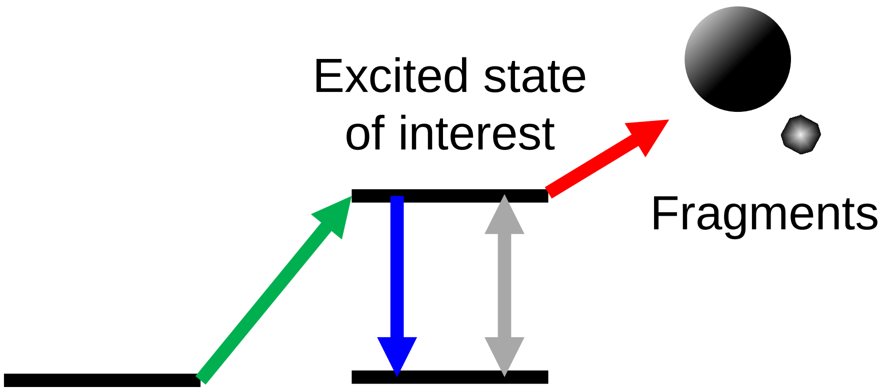


If $t_1 = t_2$,

$$\sigma_I^{\text{ex}} = -\frac{A}{N_A \rho x_t} \ln\left(\frac{G_2}{G_1} e^{t_1/\tau}\right)$$

Additional contributions in the reaction target

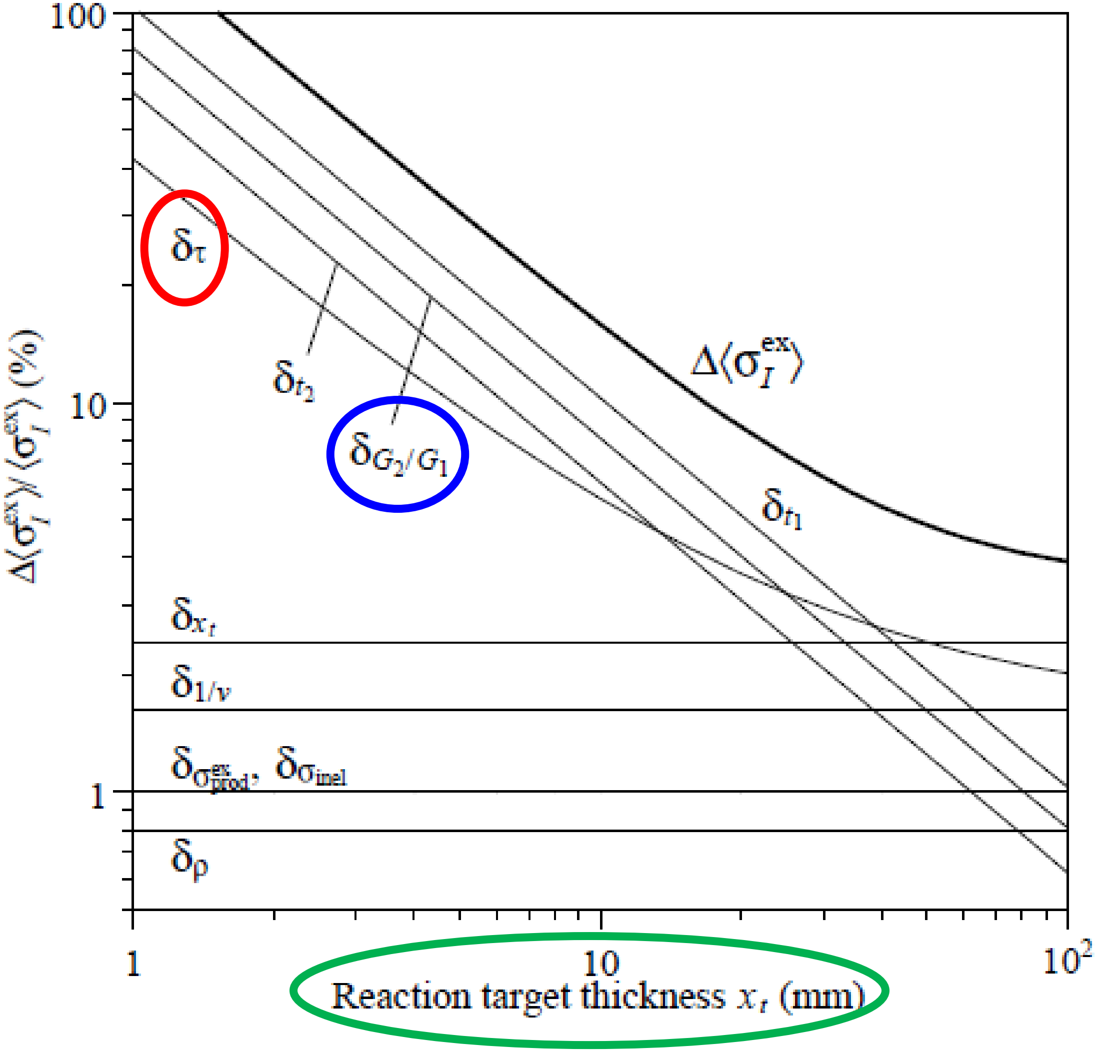




0. reaction of the excited states
1. γ-decay
2. Production of the excited state from incoming beam
3. Production of the excited state from the ground state by inelastic scattering

$$\langle \sigma_I^{\mathrm{ex}} \rangle = -\frac{A}{N_A \rho x_t} \ln\left(\frac{G_2}{G_1}\frac{1-e^{-t_1/\tau}}{e^{-t_1/\tau}(1-e^{-t_2/\tau})}\right) - \frac{A}{N_A \rho \tau}\left\langle\frac{1}{v}\right\rangle + \left\langle \sigma_{\mathrm{prod}}^{\mathrm{ex}} \frac{N_{\mathrm{be}}(x)}{N_{\mathrm{ex}}(x)}\right\rangle + \left\langle \sigma_{\mathrm{inel}} \frac{N_{\mathrm{gs}}(x)}{N_{\mathrm{ex}}(x)}\right\rangle + \ldots$$

Error estimation



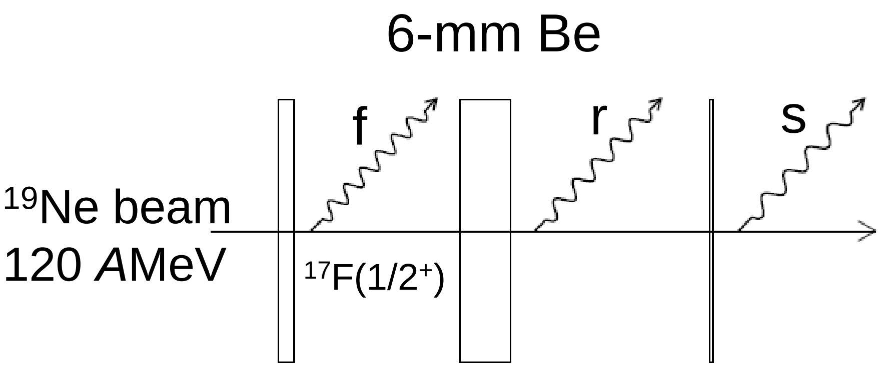
Assumptions

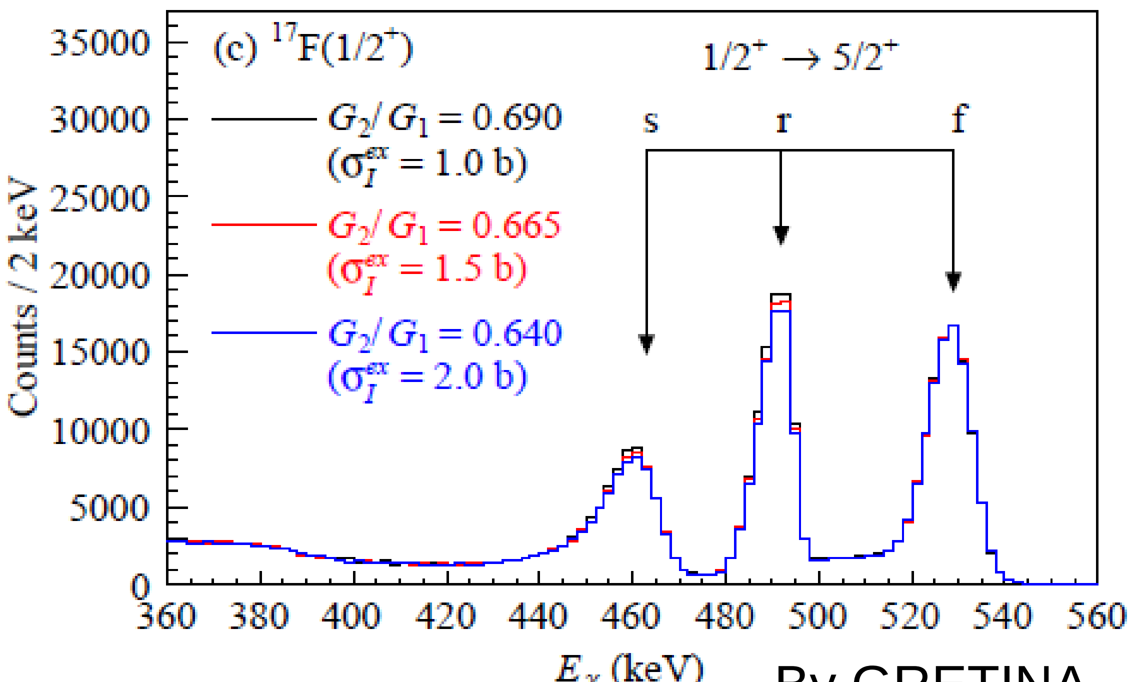
* 1% error for $\rho, x_t, \frac{G_2}{G_1}, \tau, \left\langle\frac{1}{v}\right\rangle, t_1, t_2$

* 0.01-barn error for $\left\langle\sigma_{\text{prod}}^{\text{ex}} \frac{N_{\text{be}}(x)}{N_{\text{ex}}(x)}\right\rangle$ and $\left\langle\sigma_{\text{inel}} \frac{N_{\text{gs}}(x)}{N_{\text{ex}}(x)}\right\rangle$

* Accurate lifetime ~1%
* Precise γ-ray yield ~1%
* Higher energy > 100 MeV/u

Realistic experimental case: ^{17}F(1/2$^+$)





By GRETINA

Experimental data:

- $\tau = 286(6)$ ps (2 % error)

$\langle \sigma_I^{\mathrm{ex}} \rangle = 1.00(28)$ barn
→ 28 % error

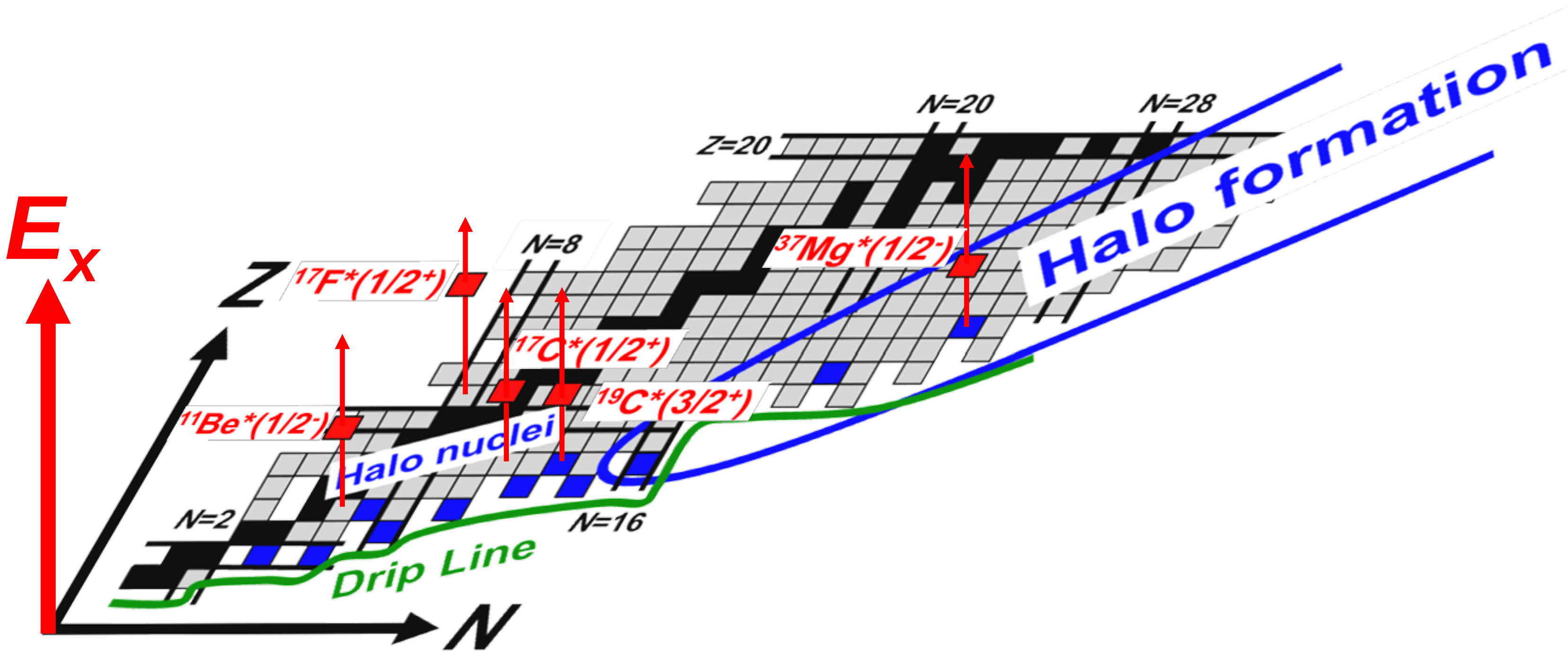
Main contribution:
2 % error in τ : 24% error in $\langle \sigma_I^{\mathrm{ex}} \rangle$

⇩

1 % error in τ : 12% error in $\langle \sigma_I^{\mathrm{ex}} \rangle$

If well-developed halo is suggested, we can confirm it.

Summary



☑ Moderate halo formation in the ground state of ^{29}Ne

☑ RDTM to access halos in excited states

Collaborators

- Moderate halo formation in ground states of ^{29}Ne

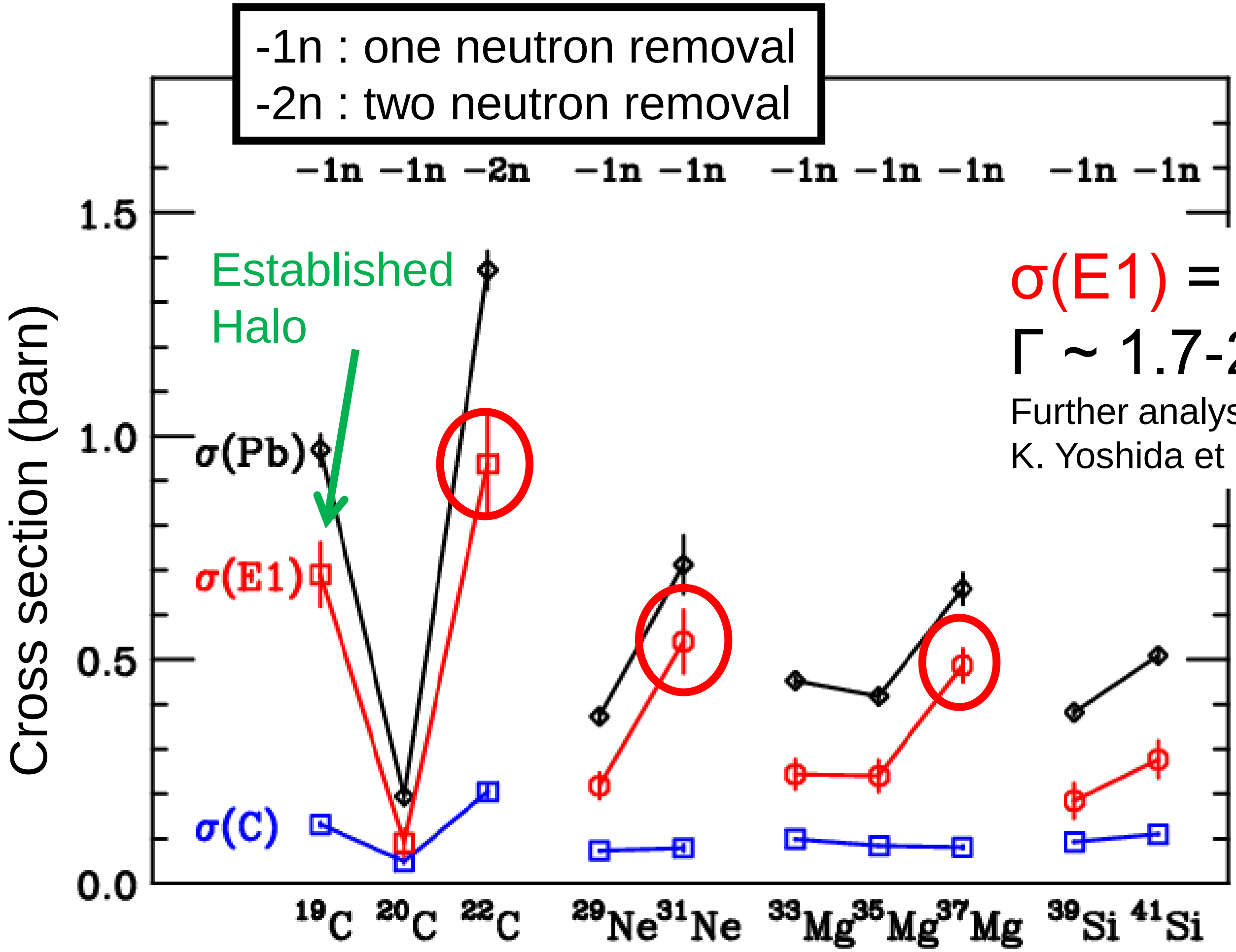
Tokyo Tech: **T. Nakamura, Y. Kondo, Y. Togano, S. Deguchi, Y. Kawada, K. N. Tanaka, N. Tanaka**
SNU : **Y. Satou, S. Kim, H. S. Lee**
JAEA : **Y. Utsuno**
U. of Surrey/Tokyo Tech : **J. A. Tostevin**
RIKEN Nishina Center : **N. Aoi, H. Baba, N. Fukuda, N. Inabe, M. Ishihara, D. Kameda, T. Kubo, K. Kusaka, T. Motobayashi, T. Ohnishi, M. Ohtake, H. Otsu, H. Sakurai, M. Takechi, H. Takeda, E. Takeshita, S. Takeuchi, K. Tanaka, Y. Yanagisawa, K. Yoneda, A. Yoshida, K. Yoshida**
Western Michigan U. : **R. Barthelemy, M. A. Famiano**
LPC-ENSICAEN, IN2P3-CNRS : **J. Gibelin, N. A. Orr**
Saint Mary's U. : **R. Kanungo**
IAEA, NAPC/Nuclear Data Section : **A. Mengoni**
CNS, U. of Tokyo : **M. Matsushita, T. Otsuka, A. Saito, S. Shimoura**
Tohoku U. : **T. Sumikama**

- Measurement of interaction cross sections of excited states with fast rare isotope beams

NSCL/MSU: **K. Whitmore, H. Iwasaki**

Backup

Results



$\sigma(E1) = \sigma(Pb) - \Gamma\sigma(C)$

$\Gamma \sim 1.7\text{-}2.6$

Further analysis:
K. Yoshida et al.,PTEP053D03(2014).

Large σ(E1) of ^{22}C, ^{31}Ne, and ^{37}Mg → halo structure

Interaction cross section
- ^{22}C: K. Tanaka et al., PRL**104**(2010)062701.
- ^{31}Ne : M. Takechi et al., PLB**707**(2012)357.
- ^{37}Mg : M. Takechi et al., PRC**90**(2014)061305.

Error estimation

$$(\Delta\langle\sigma_I^{\mathrm{ex}}\rangle)^2 = \delta_\rho^2 + \delta_{x_t}^2 + \delta_{G_2/G_1}^2 + \delta_{1/v}^2 + \delta_\tau^2 + \delta_{t_1}^2 + \delta_{t_2}^2 + \delta_{\sigma_{\mathrm{prod}}^{\mathrm{ex}}}^2 + \delta_{\sigma_{\mathrm{inel}}}^2$$

$$\delta_\rho = \left[\frac{A}{N_A\rho x_t}\ln\left(\frac{G_2}{G_1}\frac{1-e^{-t_1/\tau}}{e^{-t_1/\tau}(1-e^{-t_2/\tau})}\right) + \frac{A}{N_A\rho\tau}\left\langle\frac{1}{v}\right\rangle\right]\frac{\Delta\rho}{\rho}$$

$$\delta_{x_t} = \frac{A}{N_A\rho x_t}\ln\left(\frac{G_2}{G_1}\frac{1-e^{-t_1/\tau}}{e^{-t_1/\tau}(1-e^{-t_2/\tau})}\right)\frac{\Delta x_t}{x_t}$$

$$\delta_{G_2/G_1} = -\frac{A}{N_A\rho x_t}\frac{\Delta(G_2/G_1)}{G_2/G_1}$$

$$\delta_{1/v} = -\frac{A}{N_A\rho\tau}\left\langle\frac{1}{v}\right\rangle\frac{\Delta\langle 1/v\rangle}{\langle 1/v\rangle}$$

$$\delta_\tau = \frac{A}{N_A\rho}\left[\frac{1}{\tau}\left\langle\frac{1}{v}\right\rangle + \frac{1}{x_t}\frac{t_1/\tau}{1-e^{-t_1/\tau}} - \frac{1}{x_t}e^{-t_2/\tau}\frac{t_2/\tau}{1-e^{-t_2/\tau}}\right]\frac{\Delta\tau}{\tau}$$

$$\delta_{t_1} = -\frac{A}{N_A\rho x_t}\frac{t_1/\tau}{1-e^{-t_1/\tau}}\frac{\Delta t_1}{t_1}$$

$$\delta_{t_2} = \frac{A}{N_A\rho x_t}e^{-t_2/\tau}\frac{t_2/\tau}{1-e^{-t_2/\tau}}\frac{\Delta t_2}{t_2}$$

$$\delta_{\sigma_{\mathrm{prod}}^{\mathrm{ex}}} = \Delta\left\langle\sigma_{\mathrm{prod}}^{\mathrm{ex}}\frac{N_{\mathrm{be}}(x)}{N_{\mathrm{ex}}(x)}\right\rangle$$

$$\delta_{\sigma_{\mathrm{inel}}} = \Delta\left\langle\sigma_{\mathrm{inel}}\frac{N_{\mathrm{gs}}(x)}{N_{\mathrm{ex}}(x)}\right\rangle$$

Calculation of Gamma factor

(basically, ratio of radius of lead nucleus to that of carbon nucleus)

$$R \propto A^{1/3}$$

$$R(\mathrm{Pb}) \ : \ \text{radius of lead nucleus}$$

$$\Gamma_{\max} = \frac{R(\mathrm{Pb})}{R(\mathrm{C})} = 2.6$$

$$\Gamma_{\min} = \frac{R(\mathrm{Pb}) + R({}^{37}\mathrm{Mg})}{R(\mathrm{C}) + R({}^{37}\mathrm{Mg})} = 1.7$$

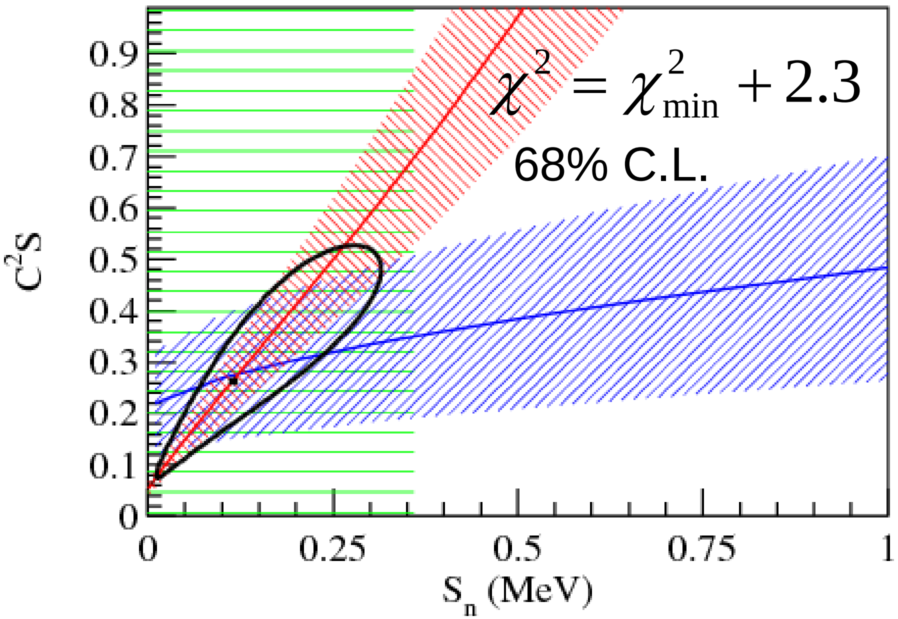
$$\Gamma = \frac{\Gamma_{\max} + \Gamma_{\min}}{2} = \frac{2.6 + 1.7}{2} = 2.2$$

Confidence level of C^2S vs S_n

$\chi2$: sum of three $\chi2$

$$\chi^2 = \left(\frac{C^2S^{exp}(C,S_n) - C^2S}{\sigma(C^2S^{exp}(C,S_n))} \right)^2 + \left(\frac{C^2S^{exp}(E1,S_n) - C^2S}{\sigma(C^2S^{exp}(E1,S_n))} \right)^2 + \left(\frac{S_n^{exp} - S_n}{\sigma(S_n^{exp})} \right)^2$$

^{31}Ne(3/2$^-$) $\rightarrow$ ^{30}Ne(0$^+$) + $p_{3/2}$



$C^2S(C,S_n)$: SF of nuclear breakup

$C^2S(E1,S_n)$: SF of Coulomb breakup

S_n : separation energy

^{exp} : experimental value

σ : error

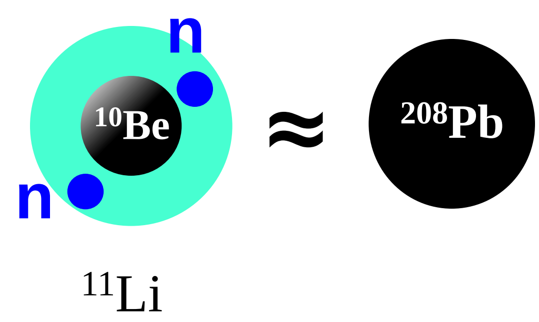
$$C^2S = 0.26^{+0.17}_{-0.14}$$

$$S_n = 0.11^{+0.12}_{-0.08} \text{ MeV}$$

Characteristic features of Halo Nuclei

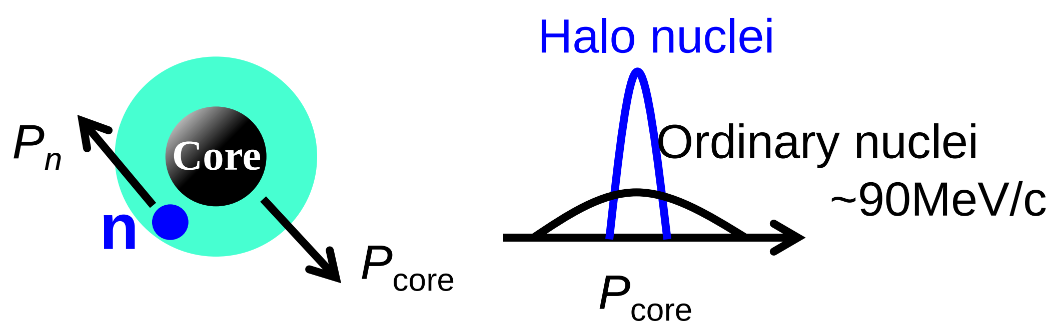
1. Large radius

Spatially extended distribution of one or two valence neutrons
→ Large interaction cross section



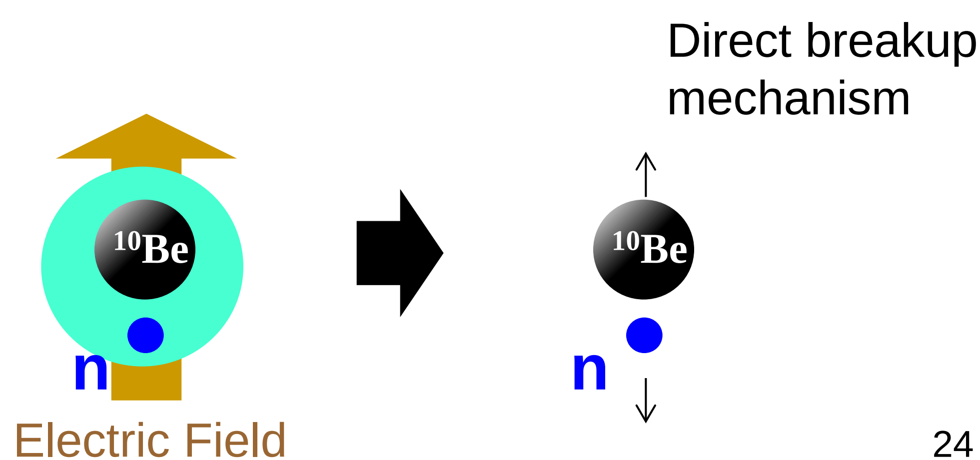
2. Small momentum of the core and valence neutron

← Fourier transform of the wide distribution of the halo neutron



3. Large E1 transition strength

→ Large coulomb breakup cross section



Coulomb breakup -- Method to extract E1 transition strength

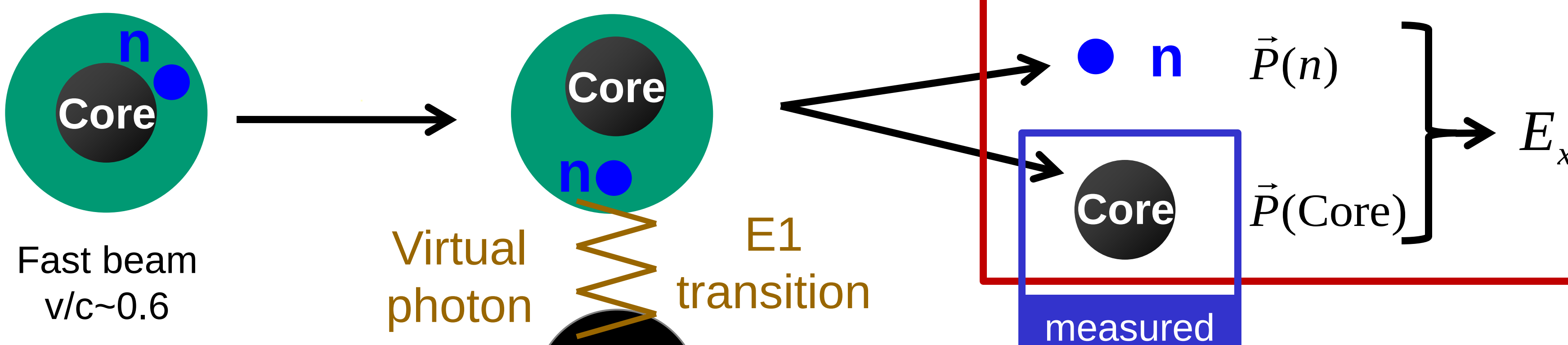
Exclusive Coulomb breakup

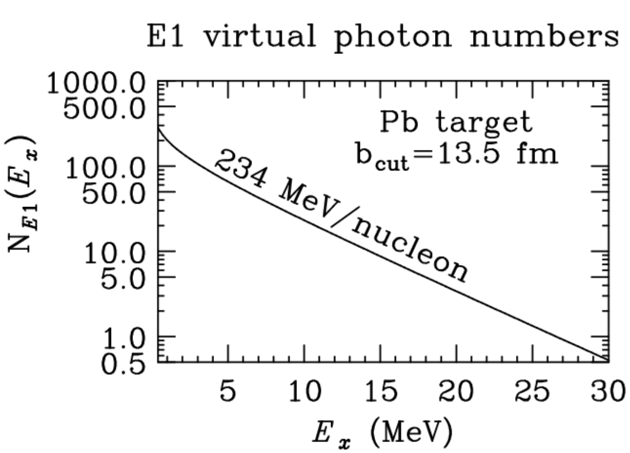
$$\underbrace{\frac{d\sigma(E1)}{dE_x}}_{\text{measured}} = \frac{16\pi^3}{9\hbar c} N_{E1}(E_x) \underbrace{\frac{dB(E1)}{dE_x}}_{\text{extracted}}$$

measured ⟶ extracted

Required beam intensity > ~ 10-100 cps

Invariant mass method





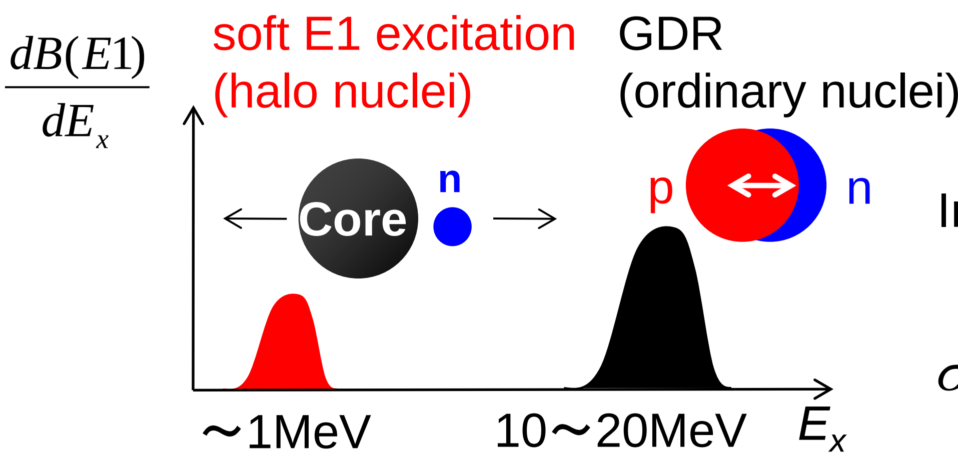
target

Inclusive Coulomb breakup (our work)

$$\underbrace{\sigma_{-1n}(E1)}_{\text{measured}} = \int_{S_{1n}}^{S_{2n}} \frac{16\pi^3}{9\hbar c} N_{E1}(E_x) \frac{dB(E1)}{dE_x} dE_x$$

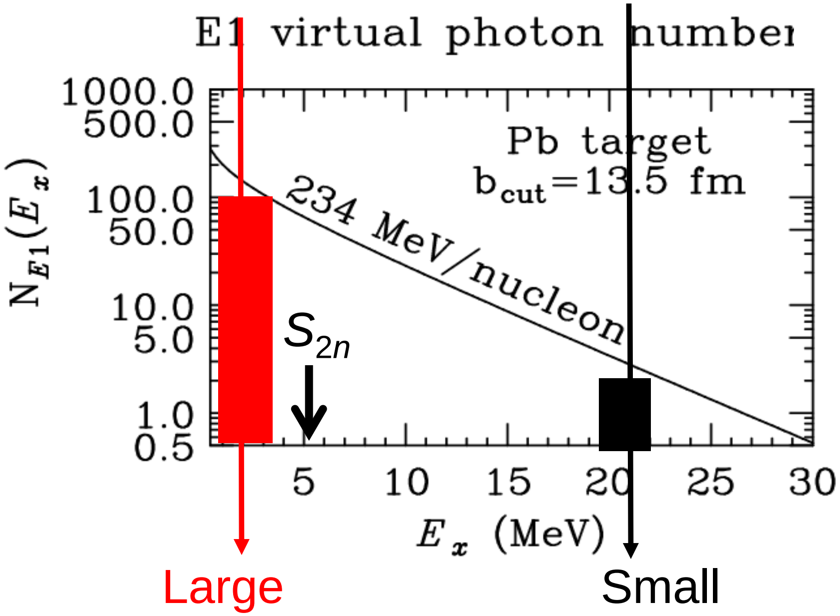
Feasible even with a few cps

Coulomb breakup – sensitive to halo structure



Inclusive Coulomb breakup cross section
(One neutron removal channel)

$$\sigma_{-1n}(E1) = \int_{S_{1n}}^{S_{2n}} \frac{16\pi^3}{9\hbar c} N_{E1}(E_x) \frac{dB(E1)}{dE_x} dE_x$$



$$N_{E1}(E_x) \times \frac{dB(E1)}{dE_x}$$

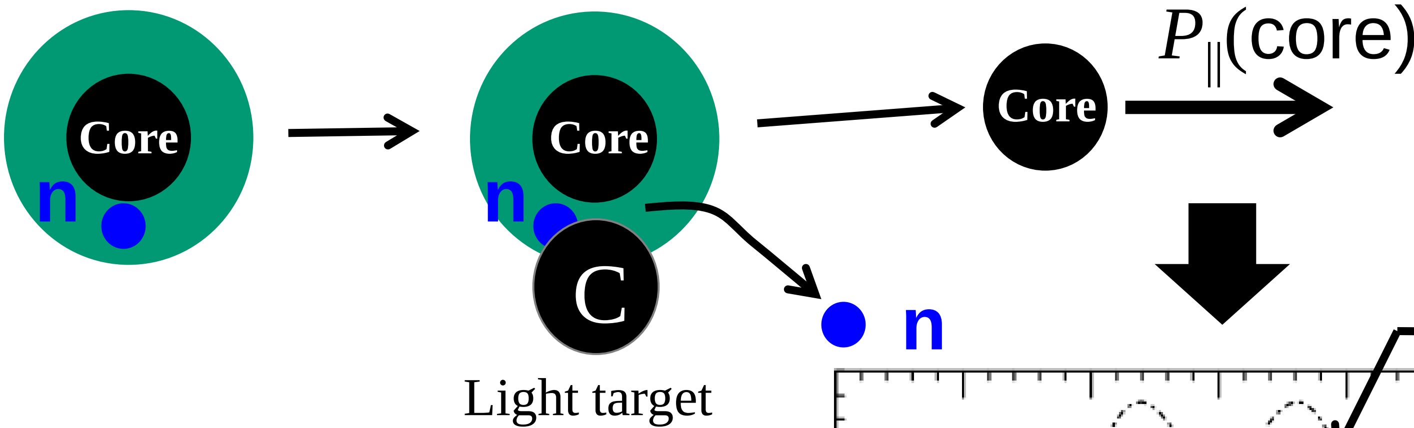
halo nuclei ➡ $\sigma_{-1n}(E1)$ is large ($\gtrsim$ 500 mb)

ordinary nuclei ➡ $\sigma_{-1n}(E1)$ is small ($\approx$ 100 mb)

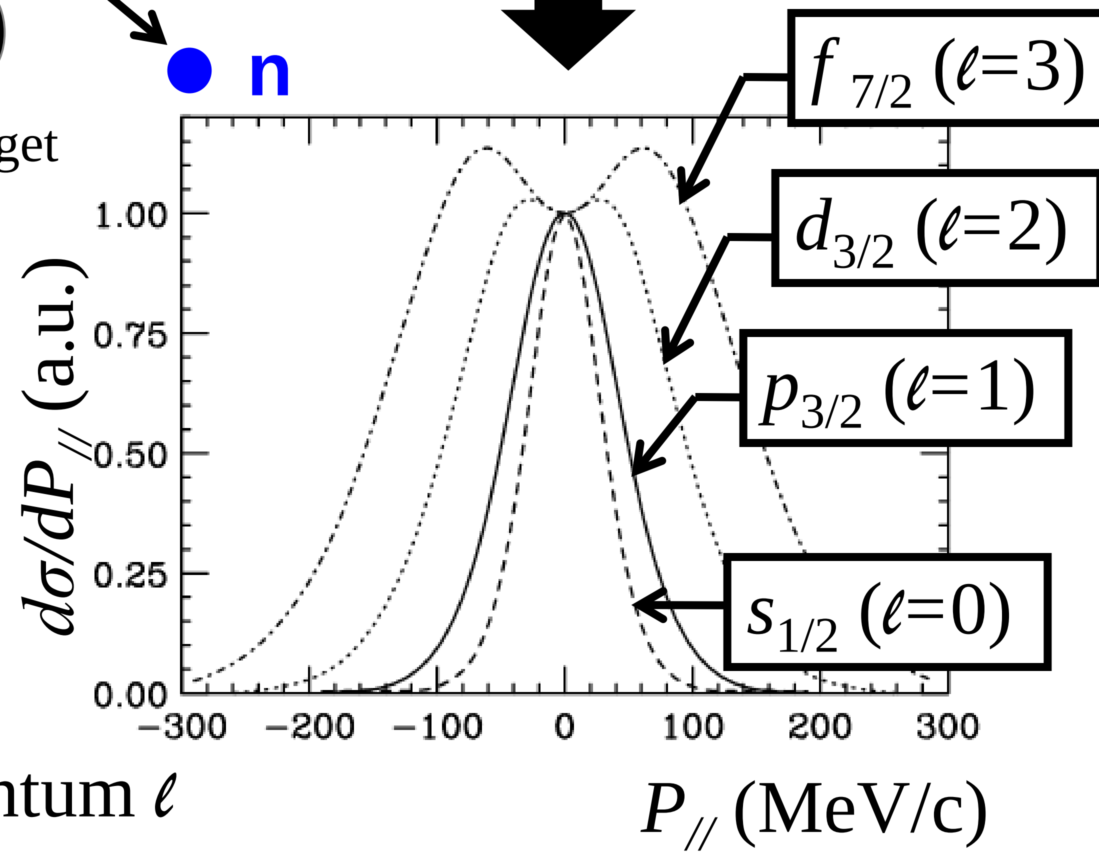
Signature of halo structure from Coulomb breakup

T.Kobayashi *et al.*, PLB **232**, 51 (1989)

Nuclear breakup -- Method to extract the valence neutron ℓ



$$|\mathrm{Init.}\rangle = |\mathrm{Core} \otimes \varphi_{nlj}\rangle$$



$P_{//}$ distribution

→ Orbital angular momentum ℓ of the valence neutrons