

# Eikonal reaction theory for one- and two-neutron removal reactions

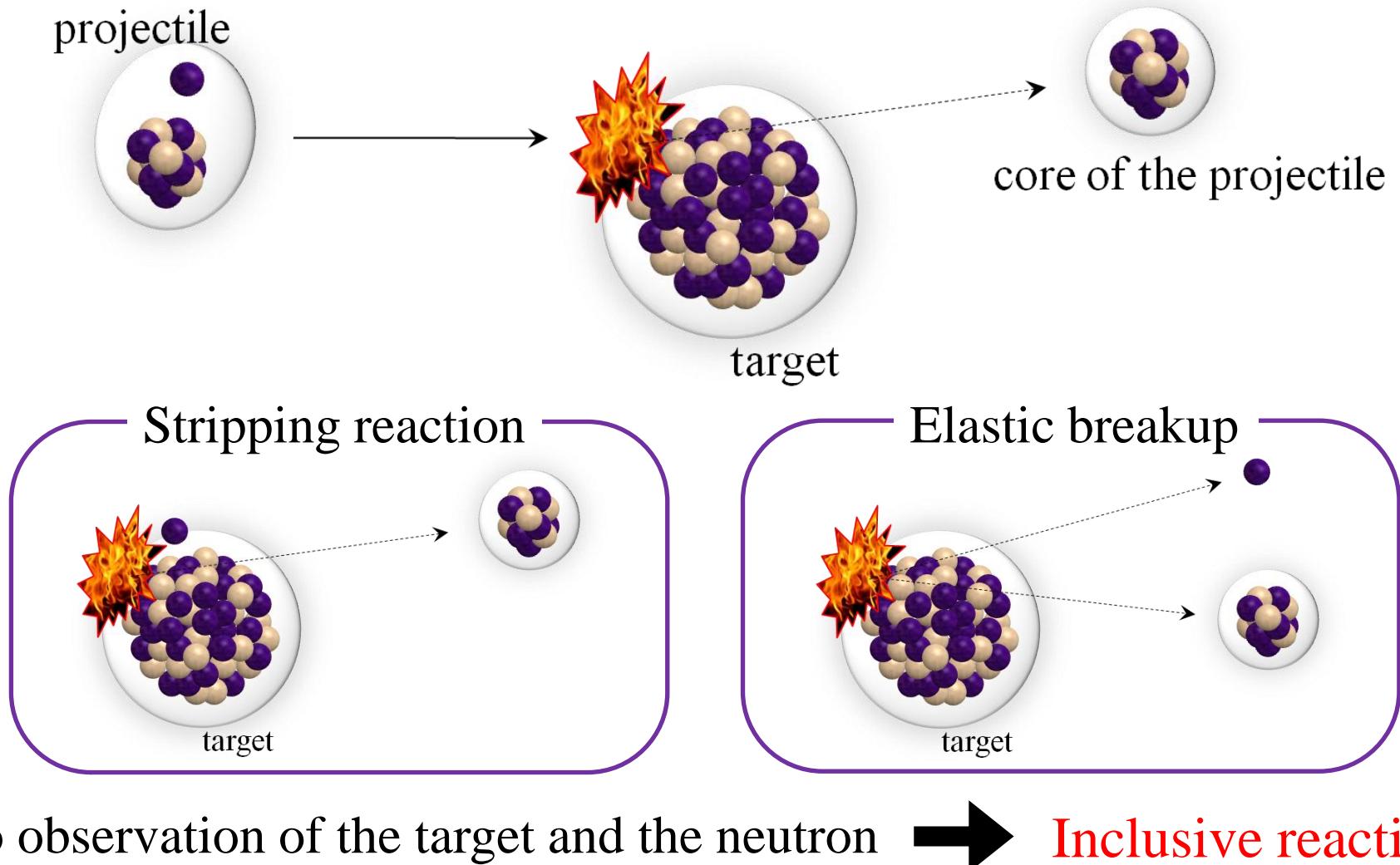
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# One neutron removal

This reaction is an important experimental tool to investigate weakly-bound nuclei.



# Outline

A new theory of treating removal reactions and it's applications  
Eikonal reaction theory (ERT)

I. Introduction ~Studies on “Island of Inversion”

II. Eikonal reaction theory (ERT)

III. Analysis of  $\sigma_{-1n}$  for  $^{31}\text{Ne}$

IV. Analysis of  $\sigma_{-2n}$  for  $^6\text{He}$

V. Summary

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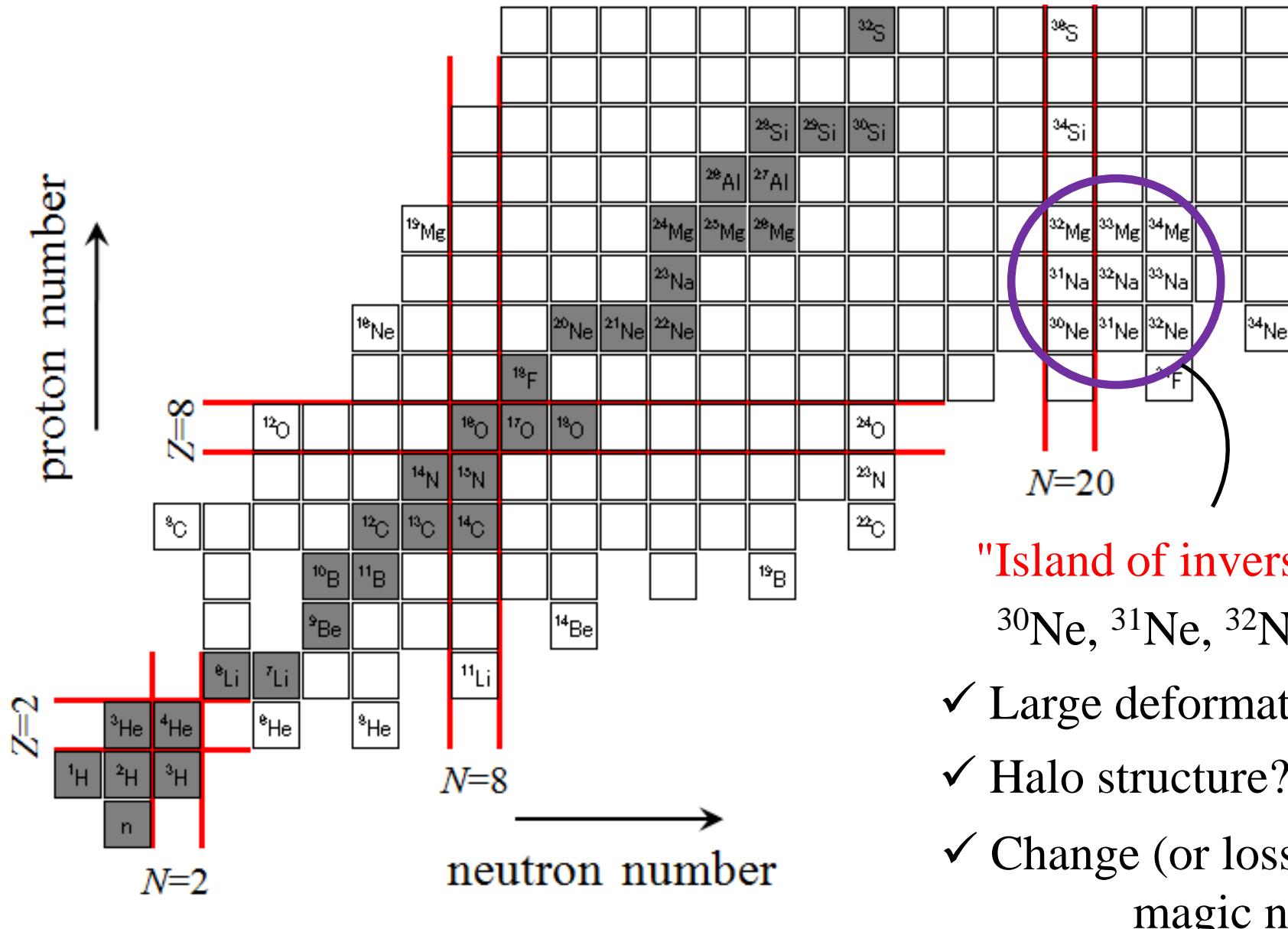
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# Nuclei near the neutron drip line



"Island of inversion"

$^{30}Ne$ ,  $^{31}Ne$ ,  $^{32}Ne$ , ...

- ✓ Large deformation?
- ✓ Halo structure?
- ✓ Change (or loss) of magic number?

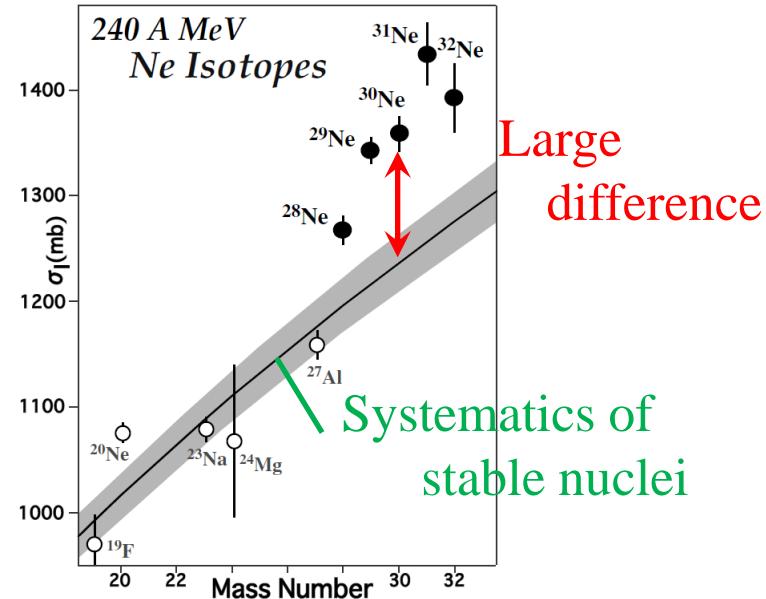
# Studies on “Island of Inversion”

- ✓ Interaction cross sections  
for neutron-rich Ne-isotopes

*M. Takechi, et al., NPA834, 412c (2010).*

$^A\text{Ne} + ^{12}\text{C}$ ,  $E_{\text{lab}} \sim 240$  (MeV/nucleon)

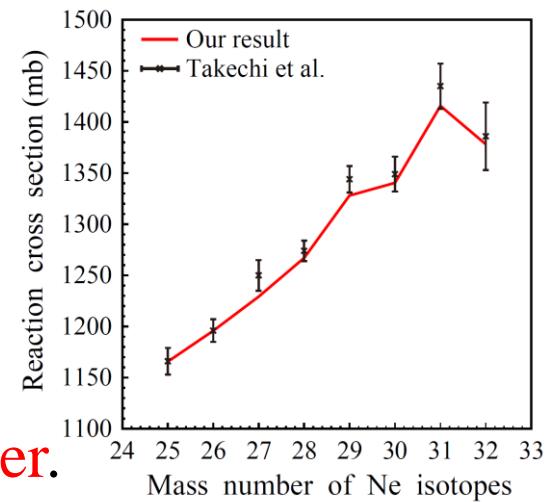
Large interaction cross sections  
→ Deformation and halo?



- ✓ Reaction analysis by a fully microscopic framework  
*K. Minomo, et al., PRL108, 052503 (2012).*

Double folding model

$$U(\mathbf{r}) = \int d\mathbf{r}' d\mathbf{r}'' \frac{\rho_{\text{Ne}}(\mathbf{r}') \rho_{\text{C}}(\mathbf{r}'') g_{\text{NN}}(\rho; \mathbf{r} - \mathbf{r}' + \mathbf{r}'')}{\text{AMD}} \quad \text{Melbourne } g\text{-matrix}$$



The data are reproduced with no adjustable parameter.

# Studies on “Island of Inversion”

- ✓ One-neutron removal cross section for  $^{31}\text{Ne}$

*T. Nakamura, et al., PRL103, 262501 (2009).*

$^{31}\text{Ne} + ^{12}\text{C}$ ,  $E_{\text{lab}} = 230$  (MeV/nucleon)

$^{31}\text{Ne} + ^{208}\text{Pb}$ ,  $E_{\text{lab}} = 234$  (MeV/nucleon)

## Naive shell model

The last neutron of  $^{31}\text{Ne}$  occupies 0f or 1p.

## Measured large Coulomb breakup ( $\sim E1$ )

→ Halo with the 1p3/2 configuration?

- ✓ Theoretical analyses of  $^{31}\text{Ne}$

### Glauber model

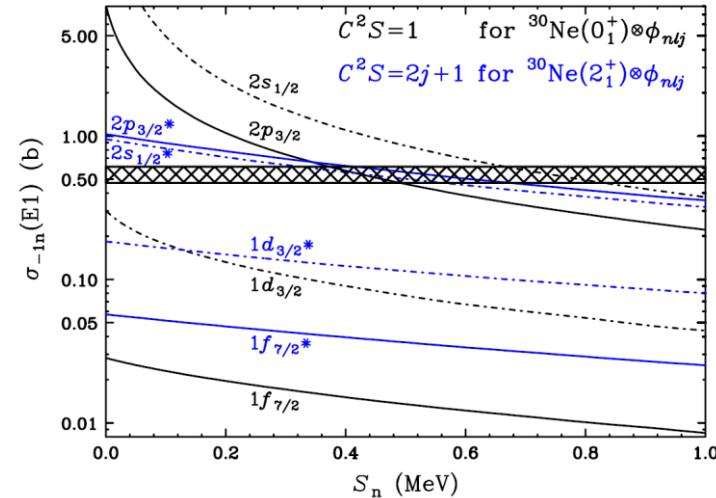
*W. Horiuchi, et al., PRC81, 024606 (2010).*

1p configuration is dominant.

### Virtual photon theory with the particle-rotor model

*Y. Urata, et al., PRC83, 041303(R) (2011).*

Lower angular momentum configurations with deformed core are favorable.



# Reaction theories

We hope systematic analysis of removal reactions for both targets.

✓ Glauber model

○ Exclusive reaction      ○ Inclusive reaction

Eikonal approximation + adiabatic approximation

Breakdown for Coulomb breakup!

✓ The method of Continuum-Discretized Coupled Channels (CDCC)

○ Exclusive reaction      ✗ Inclusive reaction

Reliable calculation

We propose a new theory to treat the inclusive reactions accurately.

Eikonal reaction theory (ERT)

*M. Yahiro, K. Ogata, K. Minomo, PTP126, 167 (2011).*

*S. Hashimoto, K. Ogata, M. Yahiro, K. Minomo, S. Chiba, PRC83, 054617 (2011).*

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**II. Eikonal reaction theory (ERT)**

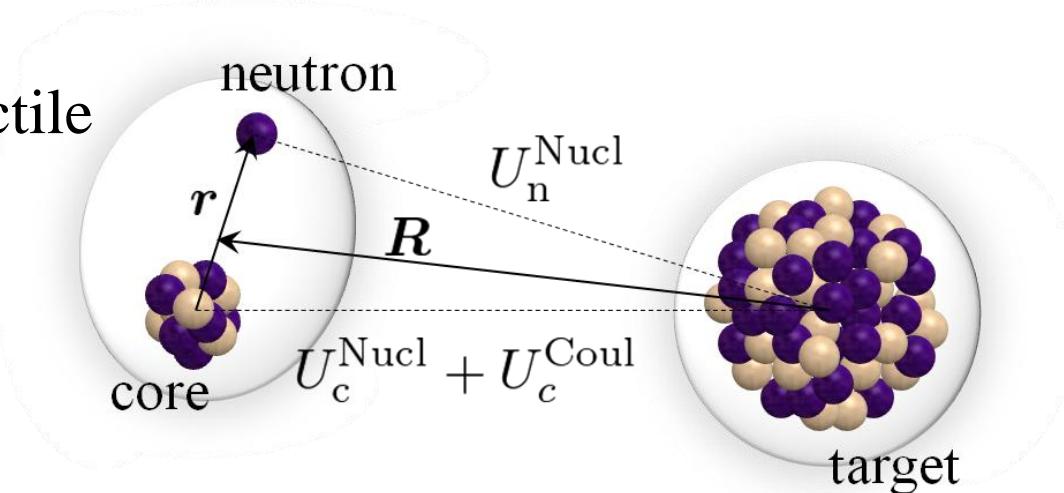
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# Three-body model

One-neutron halo projectile



Three-body Schrödinger equation:

$$\left[ -\frac{\hbar^2}{2\mu} \nabla_{\mathbf{R}}^2 + h_P + U(r_c, r_n) - E \right] \Psi = 0$$

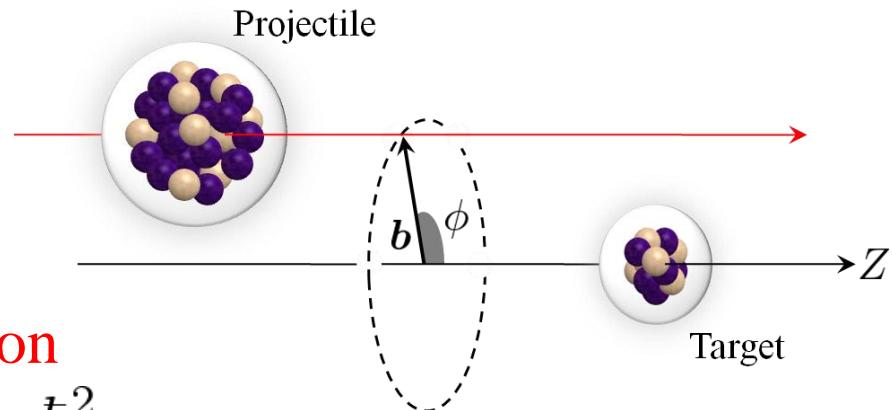
Internal Hamiltonian:  $h_P = -\frac{\hbar^2}{2\mu_P} \nabla_{\mathbf{r}}^2 + V(\mathbf{r})$

Potentials:  $U(r_c, r_n) = U_c^{\text{Nucl}}(r_c) + U_c^{\text{Coul}}(r_c) + U_n^{\text{Nucl}}(r_n)$

# Eikonal reaction theory

✓ Product assumption

$$\Psi = \hat{O}\psi(\mathbf{R}, \mathbf{r}) \quad \hat{O} = \frac{1}{\sqrt{\hbar v}} e^{i\hat{K} \cdot Z}$$



The eikonal approximation

(Neglect of  $\hat{O}\nabla_{\mathbf{R}}^2\psi$  in  $-\frac{\hbar^2}{2\mu}\nabla_{\mathbf{R}}^2\Psi$ )

$$i\frac{d\psi}{dZ} = \hat{O}^\dagger U \hat{O}\psi \quad (\text{cf. Eikonal-CDCC})$$

The S-matrix as a formal solution to the equation

$$S = \exp \left[ -i\mathcal{P} \int_{-\infty}^{\infty} dZ \hat{O}^\dagger \left( U_c^{\text{Nucl}} + U_c^{\text{Coul}} + U_n^{\text{Nucl}} \right) \hat{O} \right]$$

$\mathcal{P}$ : Path ordering operator  
(Z ordering)

# Eikonal reaction theory

$$S = \exp \left[ -i\mathcal{P} \int_{-\infty}^{\infty} dZ \hat{O}^\dagger \left( U_c^{\text{Nucl}} + U_c^{\text{Coul}} + U_n^{\text{Nucl}} \right) \hat{O} \right]$$

We apply **the adiabatic approximation** to only  $\hat{O}^\dagger U_n^{\text{Nucl}} \hat{O}$ .

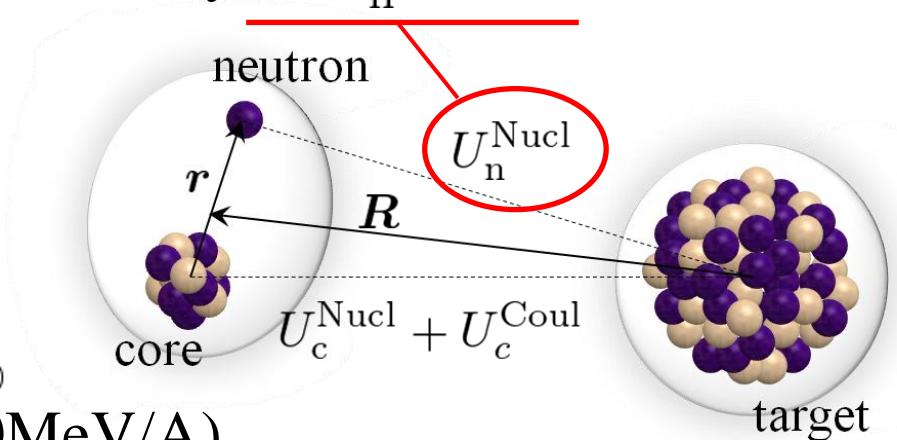
$$\hat{O}^\dagger U_n^{\text{Nucl}} \hat{O} \rightarrow \frac{U_n^{\text{Nucl}}}{\hbar v_0}$$

The error coming

from this approximation  $\sim 3\%$

( $\sigma_R, \sigma_{bu}, \sigma_{str}$  for  $^{31}\text{Ne} + ^{12}\text{C}$  @ 240 MeV/A)

**Very good!**



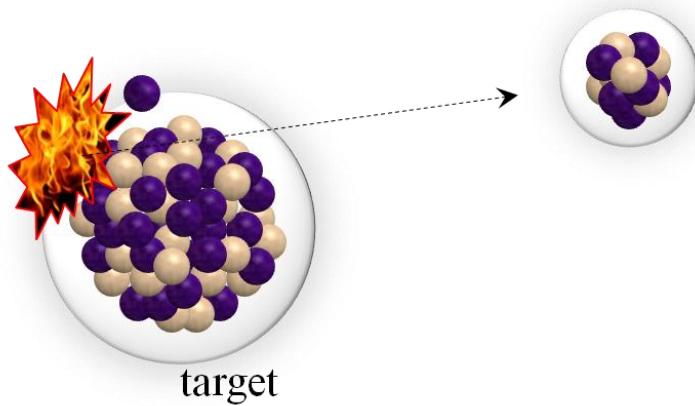
$$S \approx \exp \left[ -i\mathcal{P} \int_{-\infty}^{\infty} dZ \hat{O}^\dagger \left( U_c^{\text{Nucl}} + U_c^{\text{Coul}} \right) \hat{O} \right] \exp \left[ -\frac{i}{\hbar v_0} \int_{-\infty}^{\infty} dZ U_n^{\text{Nucl}} \right]$$

$$= S_c S_n$$

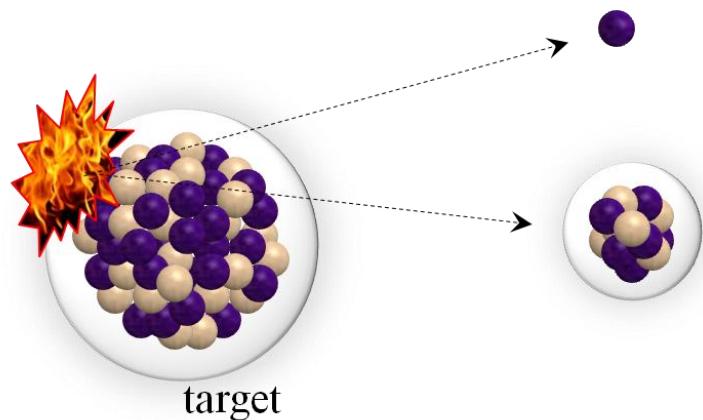
# Cross sections

✓ One-neutron removal cross section  $\sigma_{-n} = \sigma_{\text{str}} + \sigma_{\text{bu}}$

Stripping reaction



Elastic breakup



$$\sigma_{\text{str}} = \int d^2\mathbf{b} \langle \varphi_0 | |S_c|^2 (1 - |S_n|^2) | \varphi_0 \rangle$$

$$\sigma_{\text{bu}} = \sum_{\beta} \int d^2\mathbf{b} |\langle \varphi_{\beta} | S_c S_n | \varphi_0 \rangle|^2$$

✓ How to get  $S_c$

$S_c$  is a formal solution to the below equation.

$$\left[ -\frac{\hbar^2}{2\mu} \nabla_{\mathbf{R}}^2 + h_P + U_c^{\text{Nucl}}(r_c) + U_c^{\text{Coul}}(r_c) - E \right] \Psi_c = 0$$

No  $U_n^{\text{Nucl}}$  !

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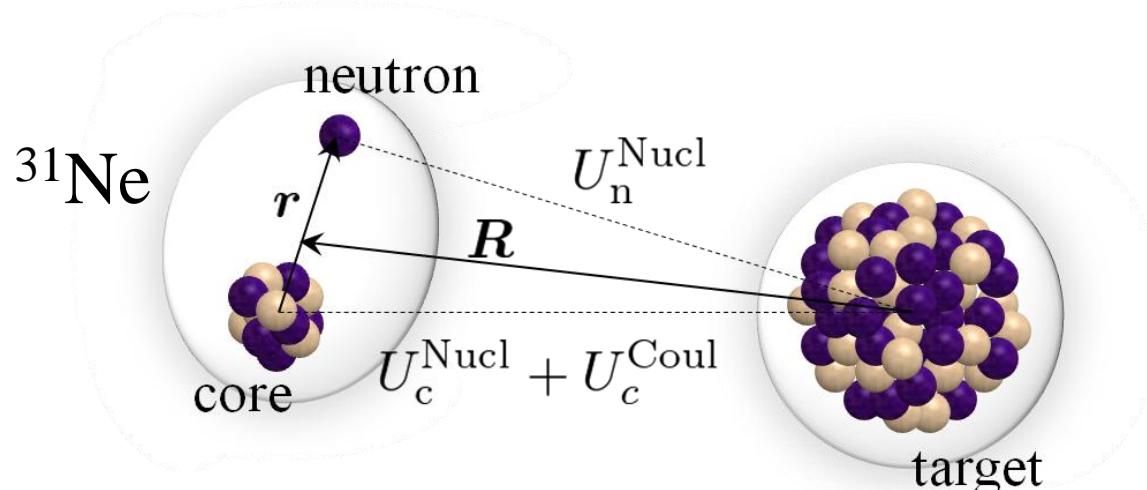
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# Model setting



$$U_n^{\text{Nucl}}(\mathbf{r}_n) = \int d\mathbf{r}' \rho_T(\mathbf{r}') t_{\text{NN}}(\mathbf{r}_n - \mathbf{r}')$$

$$U_c^{\text{Nucl}}(\mathbf{r}_c) = \int d\mathbf{r}' d\mathbf{r}'' \rho_c(\mathbf{r}') \rho_T(\mathbf{r}'') t_{\text{NN}}(\mathbf{r}_c - \mathbf{r}' + \mathbf{r}'')$$

t-matrix interaction

*B. Abu-Ibrahim, et al., PRC77, 034607 (2008).*

Mean-field model

*W. Horiuchi, et al., PRC81, 024606 (2010).*

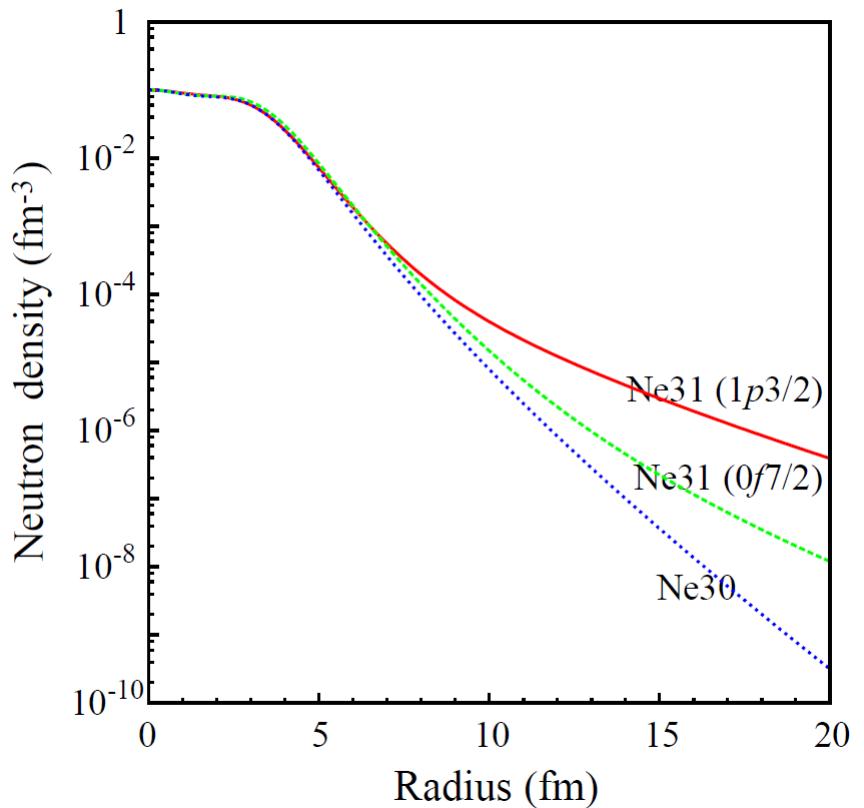
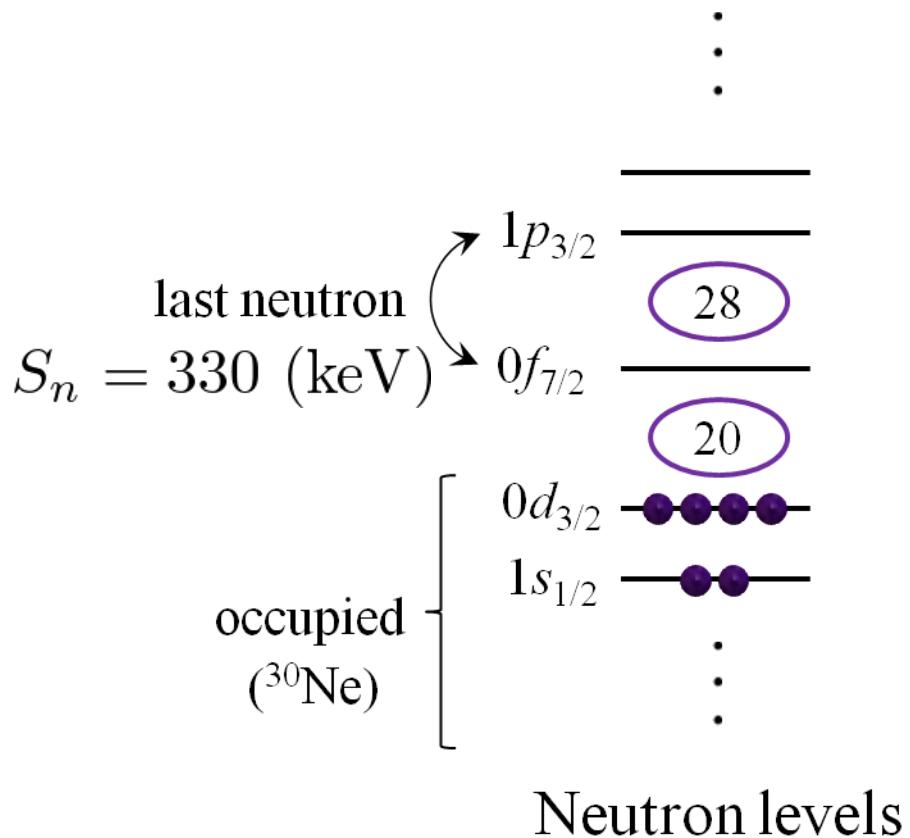
→ Follow the work by Niigata group

# Structure of $^{31}\text{Ne}$

Core  $^{30}\text{Ne}(0^+)$  + valence neutron  $0f_{7/2}$  or  $1p_{3/2}$

Single particle levels in Woods-Saxon potential

*W. Horiuchi, et al., PRC81, 024606 (2010).*



# Numerical results

	1p3/2 orbit		0f7/2 orbit	
	$^{12}\text{C}$	$^{208}\text{Pb}$	$^{12}\text{C}$	$^{208}\text{Pb}$
$\sigma_{\text{str}}$	90	244	29	53
$\sigma_{\text{bu}}$	23.3	799.5	3.3	73.0
$\sigma_{-\text{n}}$	114	1044	32	126
Exp.	$79 \pm 7$	$712 \pm 65$	$79 \pm 7$	$712 \pm 65$
$S$	0.693	0.682	2.47	5.65

# Good consistency!

$S_{\text{AMD}} \sim 0.6$  by M. Kimura

*cf. The results with the Glauber model*

W. Horiuchi, et al., PRC81, 024606 (2010).

$$\text{For } 1p3/2, \quad \sigma_{-n}^{(^{12}\text{C})} = 96 \text{ (mb)} \quad (\mathcal{S} = 0.823) \quad \sigma_{-n}^{(^{208}\text{Pb})} = 1140 \text{ (mb)} \quad (\mathcal{S} = 0.625)$$

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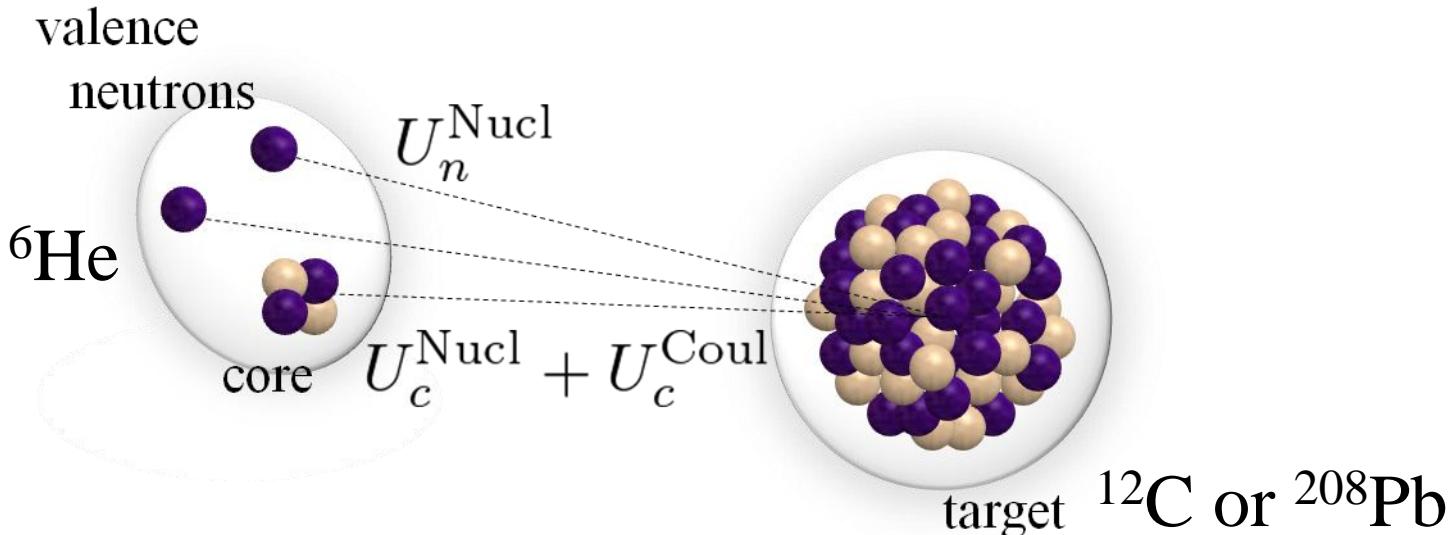
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# ERT for three-body projectile



$$S = \exp \left[ -i\mathcal{P} \int_{-\infty}^{\infty} dZ \hat{O}^\dagger \left( U_c^{\text{Nucl}} + U_c^{\text{Coul}} + U_n^{\text{Nucl}} + U_n^{\text{Nucl}} \right) \hat{O} \right]$$
$$\approx S_c S_n S_n$$

✓ Stripping cross sections

$$\sigma_{1n \text{ str}} = 2 \int d^2 \mathbf{b} \langle \varphi_0 | |S_c|^2 |S_n|^2 (1 - |S_n|^2) | \varphi_0 \rangle$$

$$\sigma_{2n \text{ str}} = \int d^2 \mathbf{b} \langle \varphi_0 | |S_c|^2 (1 - |S_n|^2) (1 - |S_n|^2) | \varphi_0 \rangle$$

# Model setting

- ✓ Four-body CDCC with the pseudostate method

*T. Matsumoto, et al., PRC70, 061601(R) (2004).*

*M. Rodriguez-Gallardo, et al., PRC 77, 064609 (2008).*

- ✓ A three-body model for  ${}^6\text{He}$

$V_{\alpha n}$ :KKNN interaction

*H. Kanada, et al., PTP61, 1327 (1979).*

$V_{nn}$ :Realistic nucleon-nucleon interaction

*D. Gogny, et al., PLB32, 591 (1970).*

- ✓ Optical potentials

$$U_n^{\text{Nucl}}(\mathbf{r}_n) = \int d\mathbf{r}' \rho_T(\mathbf{r}') g_{\text{NN}}(\rho; \mathbf{r}_n - \mathbf{r}')$$

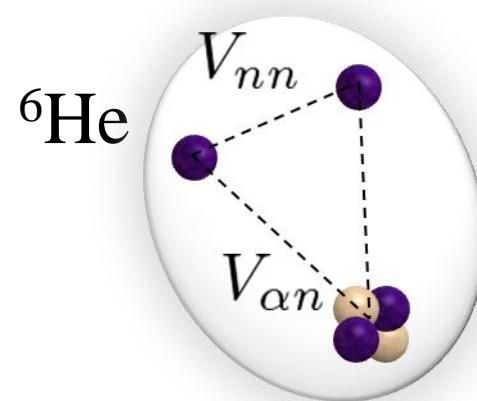
$$U_c^{\text{Nucl}}(\mathbf{r}_c) = \int d\mathbf{r}' d\mathbf{r}'' \rho_c(\mathbf{r}') \rho_T(\mathbf{r}'') g_{\text{NN}}(\rho; \mathbf{r}_c - \mathbf{r}' + \mathbf{r}'')$$

Melbourne  $g$ -matrix

*K. Amos, et al., ANP25, 275 (2000).*

Hartree-Fock calculation with Gogny D1S

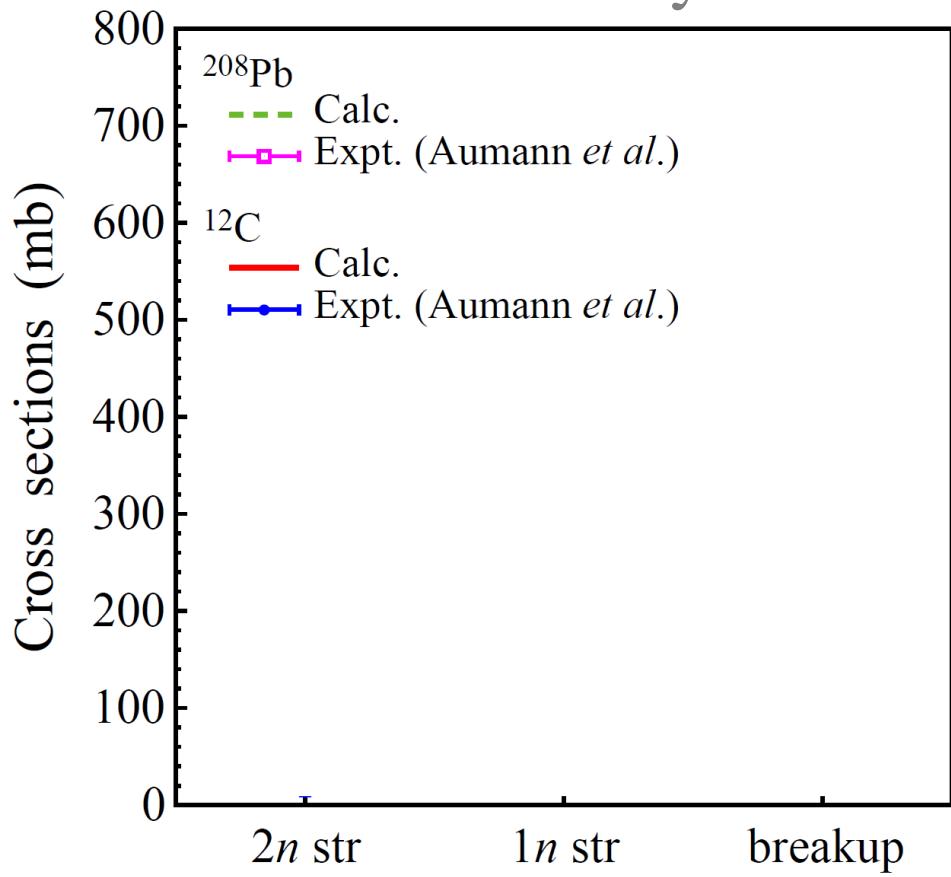
*J. F. Berger, et al., CPC63, 1365 (1991).*



# Two-neutron removal from ${}^6\text{He}$

${}^6\text{He} + {}^{12}\text{C} ({}^{208}\text{Pb}) , \quad E_{\text{lab}} = 240 \text{ (MeV/nucleon)}$

Preliminary



*T. Aumann, et al. PRC59, 1252 (1999).*

## 2n removal

${}^{12}\text{C}$

$$\sigma_{2n \text{ rmv}}^{(\text{calc})} = \quad (\text{mb})$$

$$\sigma_{2n \text{ rmv}}^{(\text{exp})} = \quad (\text{mb})$$

${}^{208}\text{Pb}$

$$\sigma_{2n \text{ rmv}}^{(\text{calc})} = \quad (\text{mb})$$

$$\sigma_{2n \text{ rmv}}^{(\text{exp})} = \quad (\text{mb})$$

Good agreement!

# Summary

- ✓ Eikonal reaction theory

ERT is an accurate method of treating neutron removal reaction.

It's an extension of CDCC.

- ✓ One-neutron removal from  $^{31}\text{Ne}$

The spectroscopic factors estimated by different targets are consistent.

The major component of the  $^{31}\text{Ne}_{\text{g.s.}}$  is  $^{30}\text{Ne}(0^+) \otimes 1p3/2$ .

- ✓ Two-neutron removal from  $^6\text{He}$

Good agreements for  $^{12}\text{C}$  and  $^{208}\text{Pb}$  targets

The applicability of ERT to two-neutron removal was clearly shown.

→ Pair correlation effect for  $^{32}\text{Ne}$ ?