Extraction of ANC via one-neutron removal

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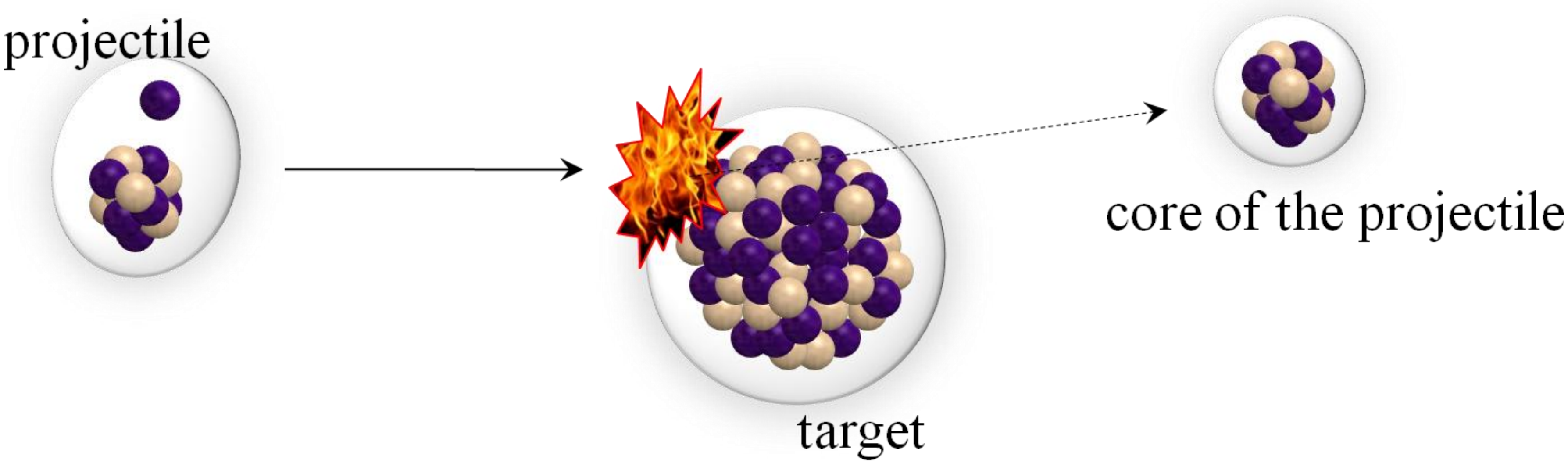
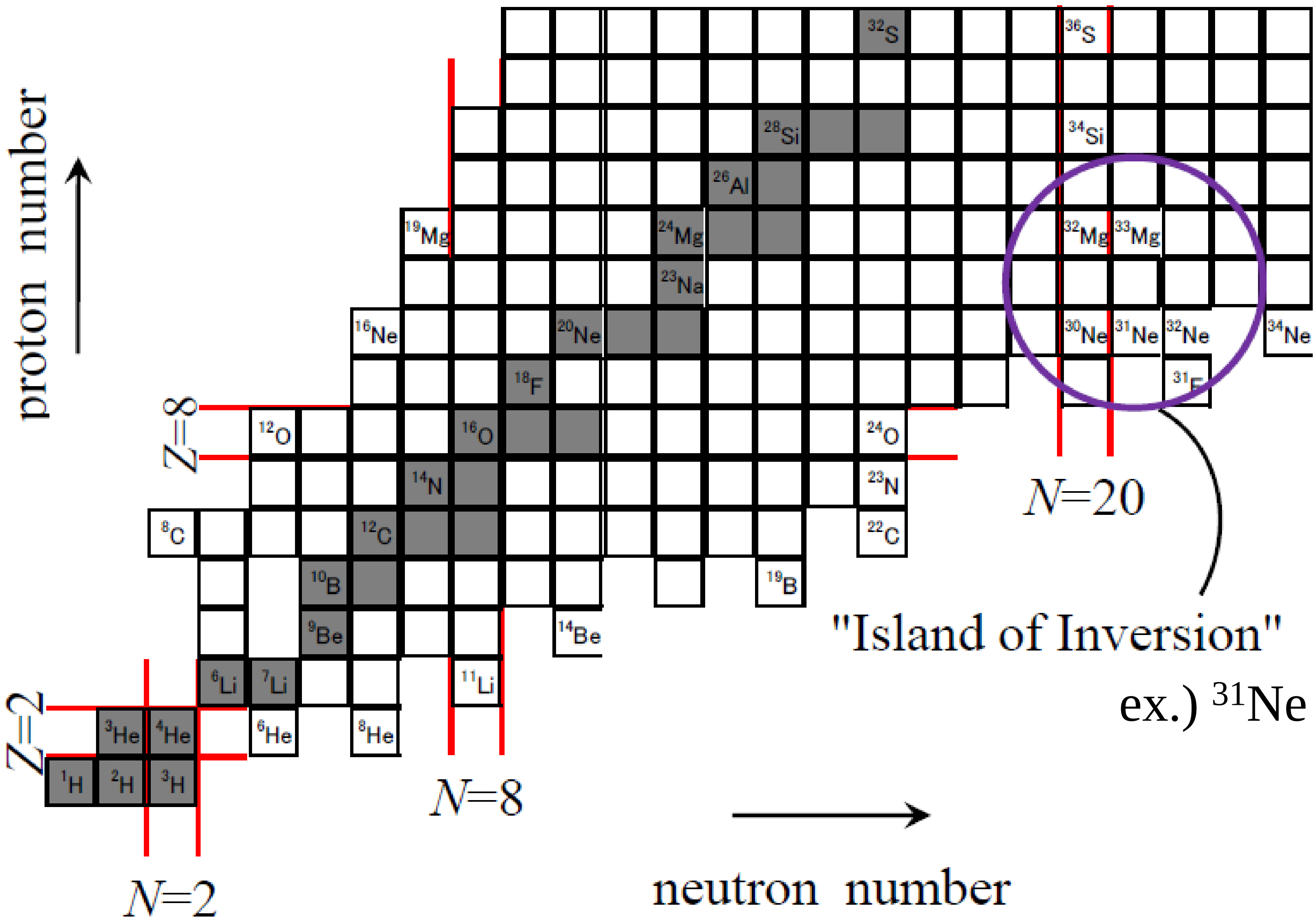
One-neutron removal



Which quantity should be extracted from this reaction?

Both ANC and spectroscopic factor with theoretical error bar

Nuclei near the neutron drip line



Studies on ^{31}Ne

✓ Experiment on one-neutron removal reaction

T. Nakamura *et al.*, Phys. Rev. Lett. **103**, 262501 (2009)

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

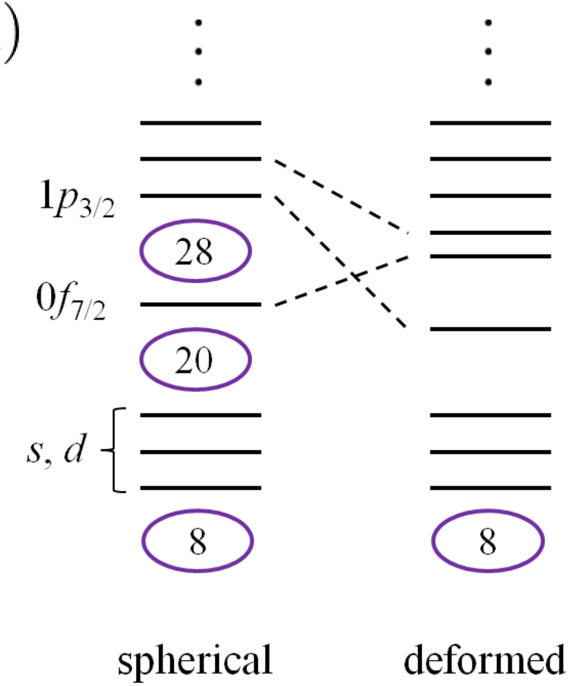
$$^{31}\mathrm{Ne} + {}^{208}\mathrm{Pb}\ , \quad E_{\mathrm{lab}} = 234\ (\mathrm{MeV/nucleon})$$

✓ Reaction analysis with Glauber model

W. Horiuchi *et al.*, Phys. Rev. C **81**, 024606 (2010)

In the naive shell model, $0f_{7/2}$ or $1p_{3/2}$?

They suggested a strong $1p_{3/2}$ configuration.



Reaction theories

✓ Glauber model

〇Exclusive reaction 〇Inclusive reaction

Eikonal approximation + adiabatic approximation

Breakdown for Coulomb breakup!

✓ Continuum-Discretized Coupled Channels (CDCC) method

〇Exclusive reaction ×Inclusive reaction

Reliable calculation

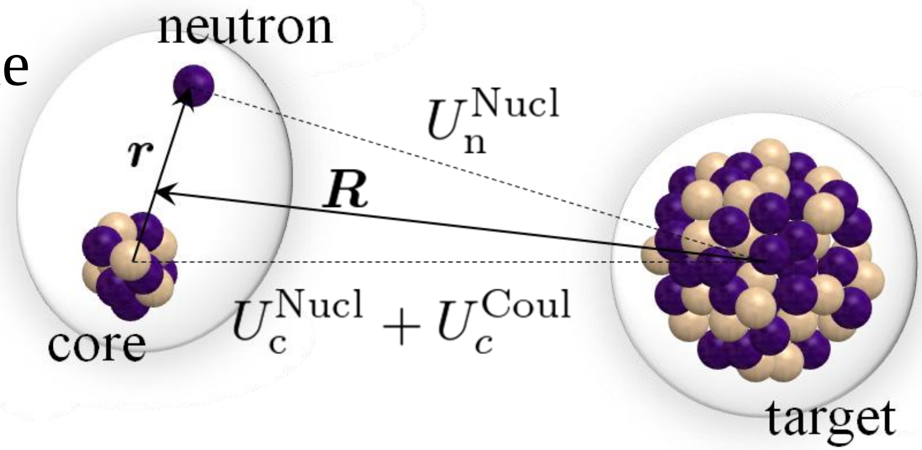
We propose a new theory to treat the inclusive reactions accurately.

Eikonal reaction theory (ERT)

Eikonal reaction theory (ERT)

One-neutron halo projectile

^{31}Ne



^{12}C or ^{208}Pb

Three-body Schrödinger equation

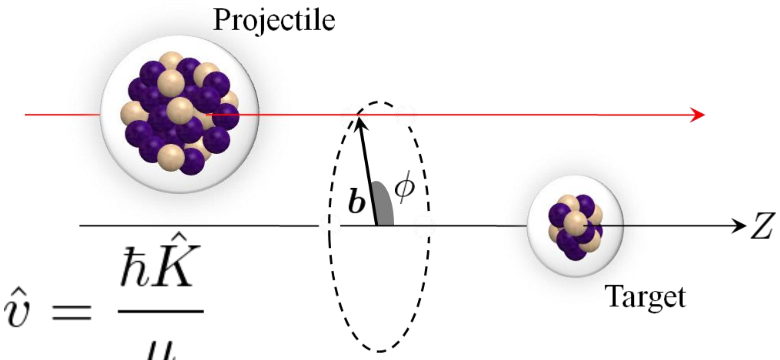
$$\left[-\frac{\hbar^2}{2\mu}\nabla_{\boldsymbol{R}}^2 + h_P + U(r_c, r_n) - E \right]\Psi = 0$$

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

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

Eikonal reaction theory (ERT)

✓ Product assumption



$$\Psi = \hat{O}\psi(\boldsymbol{R}, \boldsymbol{r})$$

$$\hat{O} = \frac{1}{\sqrt{\hbar\hat{v}}} e^{i\hat{K}\cdot Z} \qquad \hat{K} = \frac{\sqrt{2\mu(E - h_{\mathrm{P}})}}{\hbar} \qquad \hat{v} = \frac{\hbar\hat{K}}{\mu}$$

The eikonal approximation

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

$$i\frac{d\psi}{dZ} = \hat{O}^\dagger U \hat{O}\psi$$

The S-matrix as a formal solution

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

$$S = \exp\left[-i\mathcal{P} \int_{-\infty}^{\infty} dZ \hat{O}^\dagger \left(U_{\mathrm{c}}^{\mathrm{Nucl}} + U_{\mathrm{c}}^{\mathrm{Coul}} + U_{\mathrm{n}}^{\mathrm{Nucl}} \right) \hat{O} \right]$$

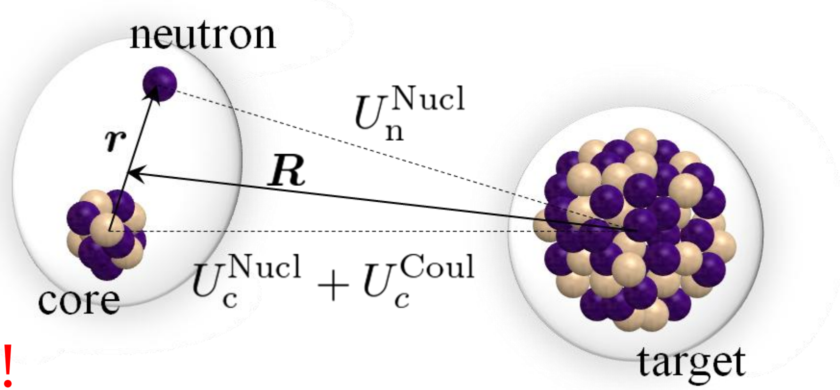
Eikonal reaction theory (ERT)

We apply the adiabatic approximation to only $\hat{O}^\dagger U_{\rm n}^{\rm Nucl} \hat{O}$.

$$\hat{O}^\dagger U_{\rm n}^{\rm Nucl} \hat{O} \rightarrow \frac{U_{\rm n}^{\rm Nucl}}{\hbar v_0}$$

The error coming
from this approximation $\sim 3\%$

Very good!



$$S = \exp\left[-i\mathcal{P} \int_{-\infty}^{\infty} dZ \hat{O}^\dagger \left(U_{\rm c}^{\rm Nucl} + U_{\rm c}^{\rm Coul} + U_{\rm n}^{\rm Nucl} \right) \hat{O} \right]$$

$$\approx \exp\left[-i\mathcal{P} \int_{-\infty}^{\infty} dZ \hat{O}^\dagger \left(U_{\rm c}^{\rm Nucl} + U_{\rm c}^{\rm Coul} \right) \hat{O} \right] \exp\left[-\frac{i}{\hbar v_0} \int_{-\infty}^{\infty} dZ \; U_{\rm n}^{\rm Nucl} \right]$$

$$= S_{\rm c} S_{\rm n}$$

Eikonal reaction theory（ERT）

How to get S_{c} and S_{n}

$$S_{\mathrm{c}} = \exp\left[- i\mathcal{P} \int_{-\infty}^{\infty} dZ \hat{O}^{\dagger} (U_{\mathrm{c}}^{\mathrm{Coul}} + U_{\mathrm{c}}^{\mathrm{Nucl}}) \hat{O} \right]$$

S_{c} is a formal solution of

$$\left[- \frac{\hbar^2}{2\mu} \nabla_{\boldsymbol{R}}^2 + h_{\mathrm{P}} + U_{\mathrm{c}}^{\mathrm{Nucl}}(r_{\mathrm{c}}) + U_{\mathrm{c}}^{\mathrm{Coul}}(r_{\mathrm{c}}) - E \right] \Psi_{\mathrm{c}} = 0$$

$$S_{\mathrm{n}} = \exp\left[- i\mathcal{P} \int_{-\infty}^{\infty} dZ \hat{O}^{\dagger} U_{\mathrm{n}}^{\mathrm{Nucl}} \hat{O} \right]$$

CDCC calculation

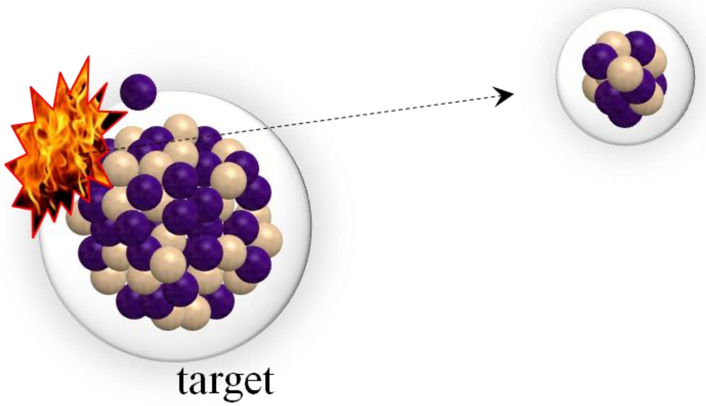
S_{n} is a formal solution of

$$\left[- \frac{\hbar^2}{2\mu} \nabla_{\boldsymbol{R}}^2 + h_{\mathrm{P}} + U_{\mathrm{n}}^{\mathrm{Nucl}}(r_{\mathrm{n}}) - E \right] \Psi_{\mathrm{n}} = 0$$

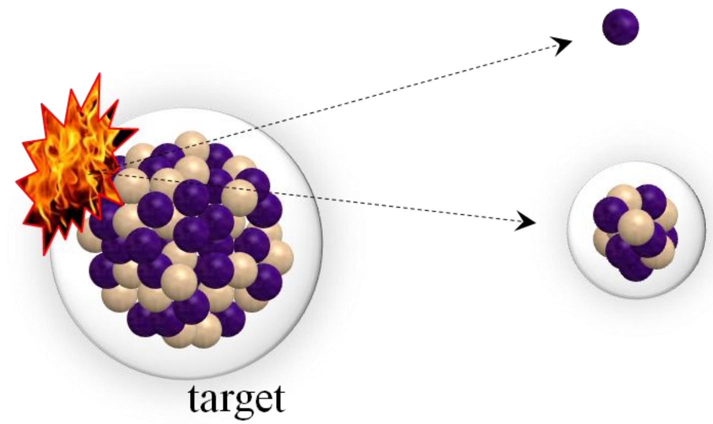
Cross sections

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

Stripping reaction



Elastic breakup



✓ Stripping cross section

$$\sigma_{\rm str} = \int d^2\boldsymbol{b} \langle \varphi_0 \big| |S_{\rm c}|^2 (1 - |S_{\rm n}|^2) \big| \varphi_0 \rangle$$

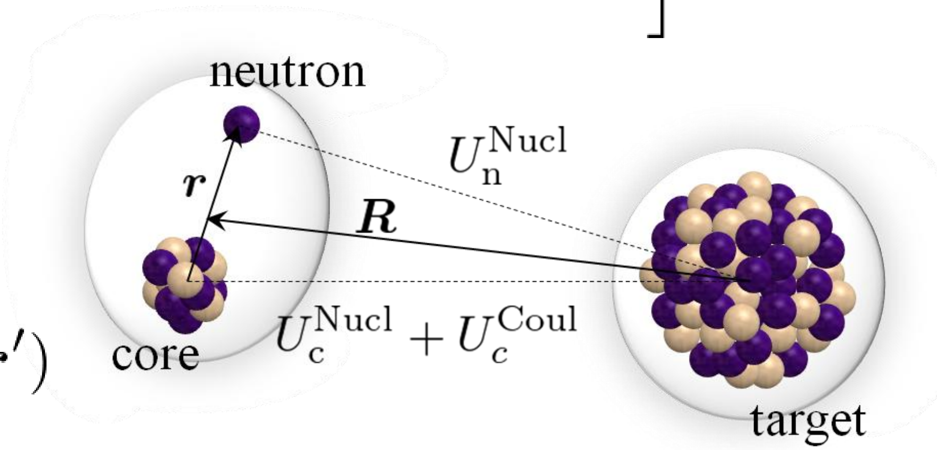
✓ Elastic breakup cross section

$$\sigma_{\rm bu} = \int d^2\boldsymbol{b} \Big(\langle \varphi_0 \big| |S_{\rm c} S_{\rm n}|^2 \big| \varphi_0 \rangle - \big| \langle \varphi_0 | S_{\rm c} S_{\rm n} | \varphi_0 \rangle \big|^2 \Big)$$

Reaction model

✓ Three-body Schrödinger equation

$$\left[-\frac{\hbar^2}{2\mu}\nabla_{\boldsymbol{R}}^2 + h_{\rm P} + U_{\rm c}^{\rm Nucl}(\boldsymbol{r}_{\rm c}) + U_{\rm c}^{\rm Coul}(\boldsymbol{r}_{\rm c}) + U_{\rm n}^{\rm Nucl}(\boldsymbol{r}_{\rm n}) - E\right]\Psi = 0$$



✓ Optical potentials

$$U_{\rm n}^{\rm Nucl}(\boldsymbol{r}_{\rm n}) = \int d\boldsymbol{r}'\rho_{\rm T}(\boldsymbol{r}')t_{\rm NN}(\boldsymbol{r}_{\rm n} - \boldsymbol{r}')$$

$$U_{\rm c}^{\rm Nucl}(\boldsymbol{r}_{\rm c}) = \int d\boldsymbol{r}'d\boldsymbol{r}''\rho_{\rm c}(\boldsymbol{r}')\rho_{\rm T}(\boldsymbol{r}'')t_{\rm NN}(\boldsymbol{r}_{\rm c} - \boldsymbol{r}' + \boldsymbol{r}'')$$

Effective interaction $t_{\rm NN}$: Niigata interaction

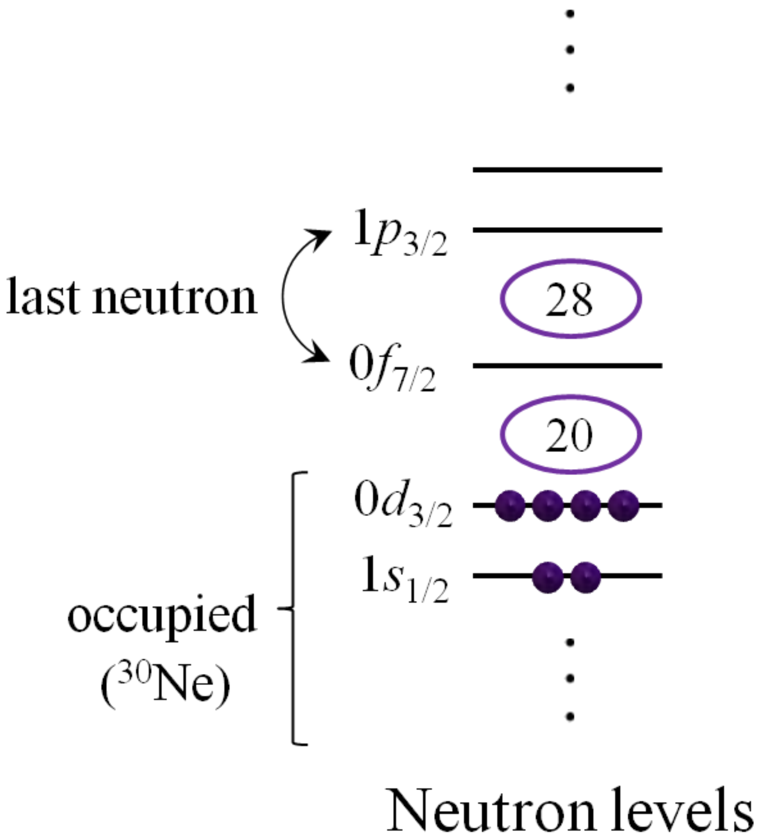
B. Abu-Ibrahim, W. Horiuchi, A. Kohama, and Y. Suzuki, Phys. Rev. C 77, 034607 (2008).

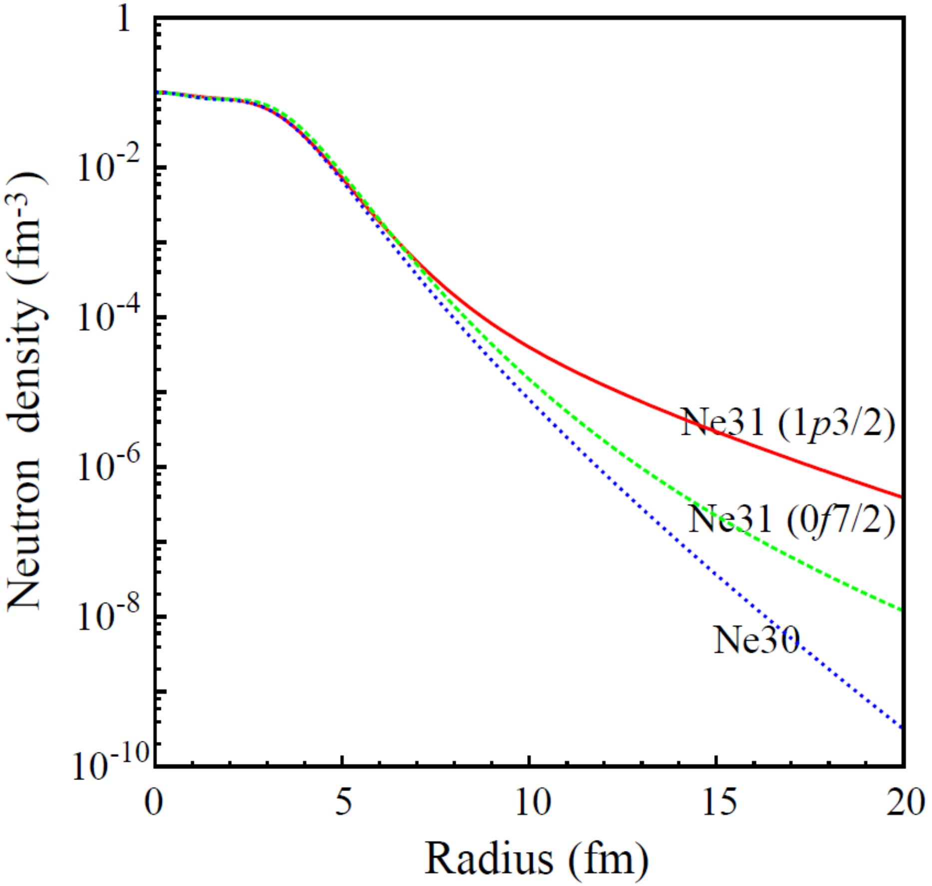
Structure of ^{31}Ne

Single particle level in Woods-Saxon potential

Neutron separation energy

^{31}Ne Core (^{30}Ne) + valence neutron ($0f_{7/2}$ or $1p_{3/2}$) $B_n = 0.33$ (MeV)





Numerical results

	^{12}C target			^{208}Pb target		
	$p_{3/2}$	$f_{7/2}$	exp	$p_{3/2}$	$f_{7/2}$	exp
$\sigma_{\rm str}$	90	29		244	53	
$\sigma_{\rm bu}$	23.3	3.3		799.5	73.0	(540)
$\sigma_{-\rm n}$	114	32	79 ± 7	1044	126	712 ± 65
$\mathcal{S}$	0.693	2.47		0.682	5.65	

cf. Horiuchi et al.

$\sigma_{-\rm n} = 96(\rm mb)\quad (\mathcal{S} = 0.823)\qquad \sigma_{-\rm n} = 1140(\rm mb)\quad (\mathcal{S} = 0.625)$

Reaction mechanism

In the ERT,

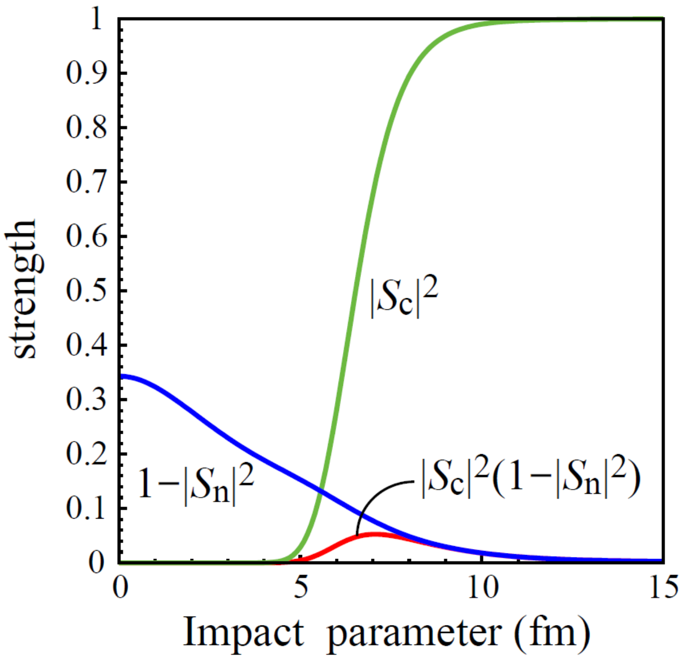
$$\sigma_{\rm str} = \int d^2\boldsymbol{b} \langle \varphi_0 | \underbrace{|S_{\rm c}|^2}_{\text{core}} \underbrace{(1 - |S_{\rm n}|^2)}_{\text{valence}} | \varphi_0 \rangle$$

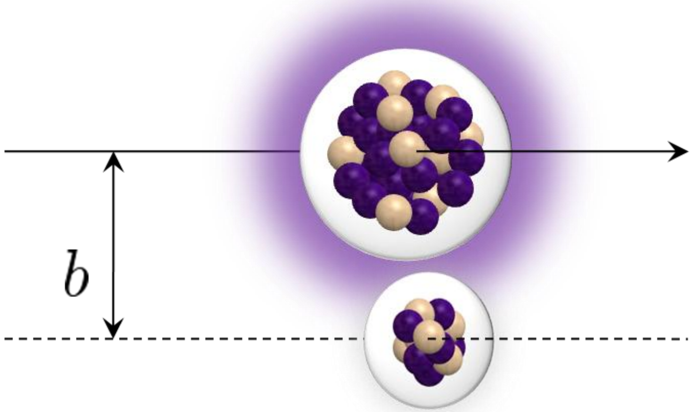
✓ The case of small *b*
Strong absorption

✓ The case of large *b*
No reaction

Peripheral reaction!

↳ Application of the ANC method

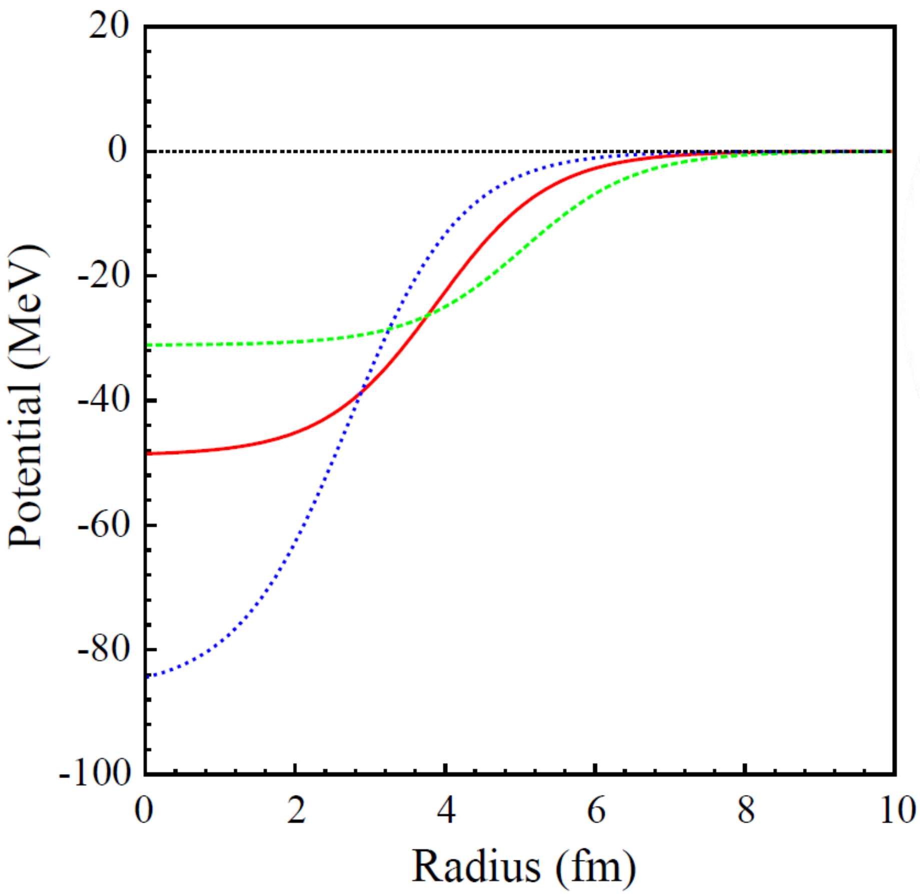


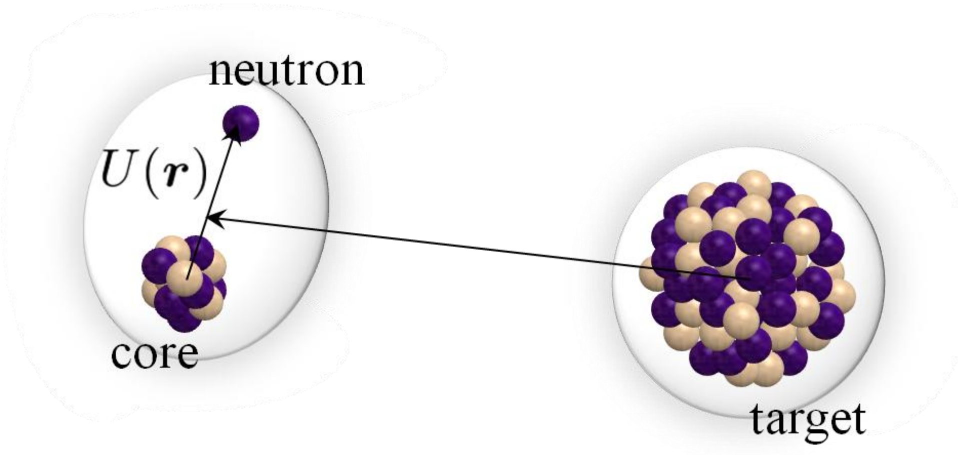


Spectroscopic factor and ANC

$$S = 0.693 \pm 0.133 \pm 0.061$$
$$C_{\mathrm{ANC}} = 0.320 \pm 0.010 \pm 0.028$$

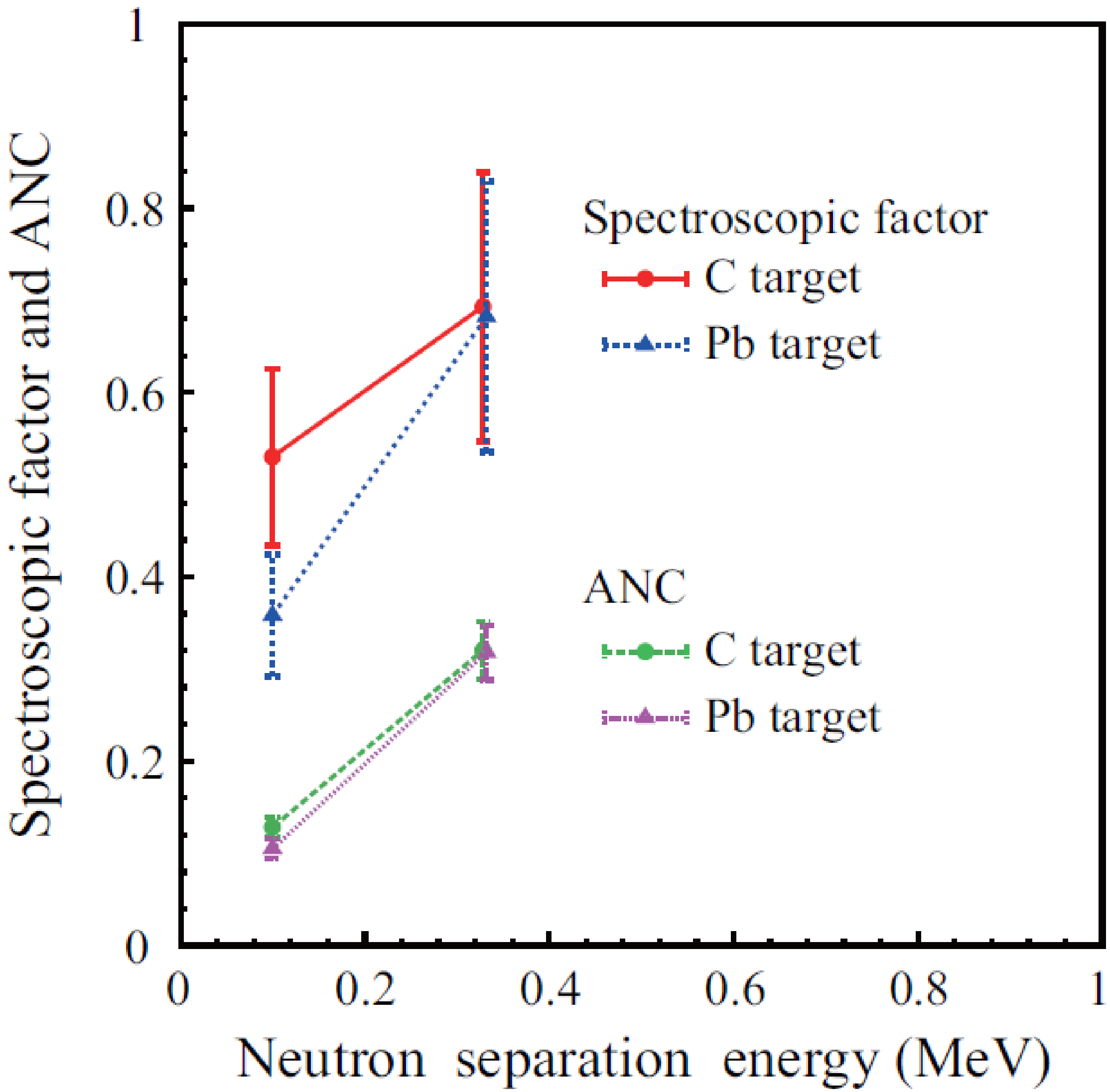
for $1p_{3/2}$ orbit and ^{12}C target





$$U(\boldsymbol{r}) = V_0 \frac{1}{1 + \exp[(r - r_0)/a_0]}$$

Spectroscopic factor and ANC



✓ S-factor

Large theoretical ambiguity (about 20%)

✓ ANC

Small theoretical ambiguity (about 3%)

Summary

✓ Theoretical framework

The eikonal reaction theory (ERT) is an accurate method to treat neutron-removal reactions.

✓ Quantitative analysis

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

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

ANC has small error bar and weak target dependence.
Meanwhile, s-factor has large error bar compared with ANC.
But, s-factor is convenient for comparison with theoretical prediction made by the shell model.
This means that s-factor should be extracted from the experimental data with the theoretical error bar.