Dynamic and static core excitation effects on deformed halo nuclei

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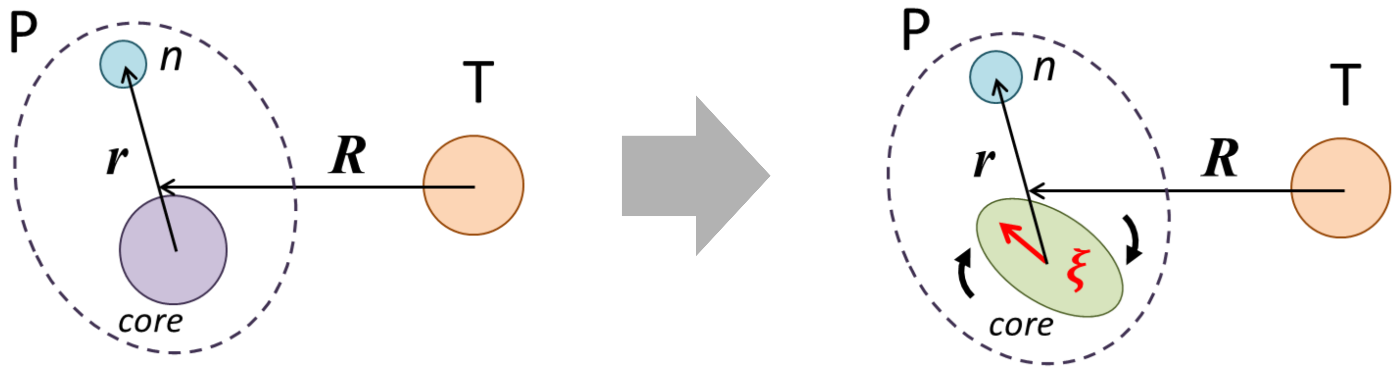

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Duy Tan University, Danang City, Vietnam

Discovery of halo

VOLUME 55, NUMBER 24 PHYSICAL REVIEW LETTERS 9 DECEMBER 1985

Measurements of Interaction Cross Sections and Nuclear Radii in the Light *p*-Shell Region

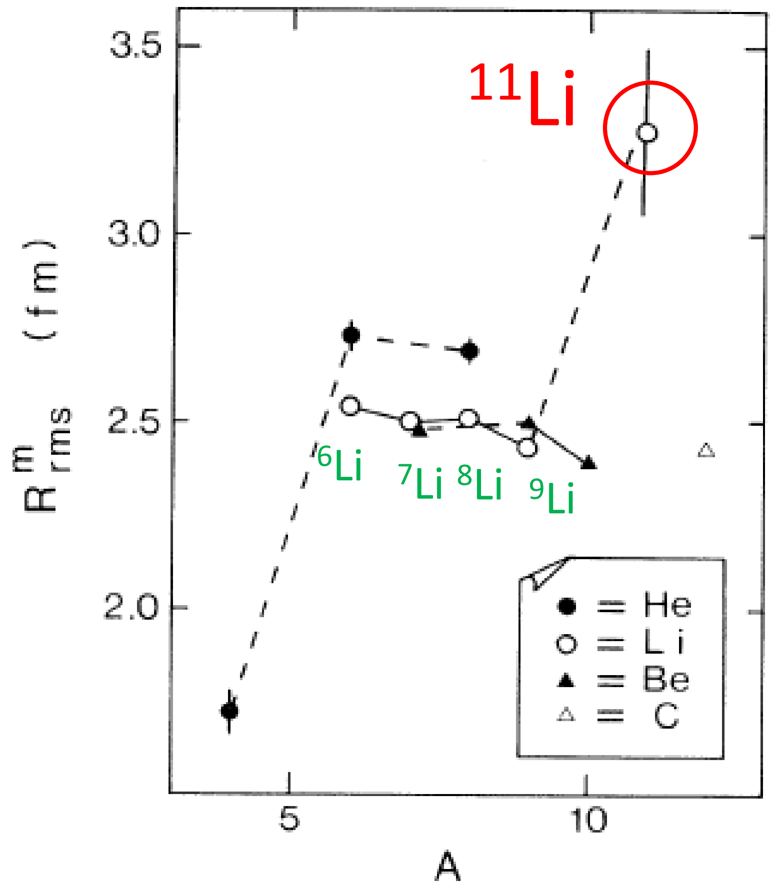
I. Tanihata,[a] H. Hamagaki, O. Hashimoto, Y. Shida, and N. Yoshikawa
Institute for Nuclear Study, University of Tokyo, Tanashi, Tokyo 188, Japan

K. Sugimoto,[b] O. Yamakawa, and T. Kobayashi
Nuclear Science Division, Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

and

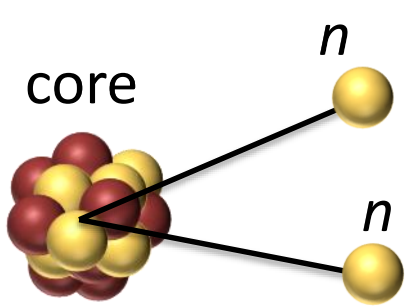
N. Takahashi

A large cross section was measured in Li isotopes.

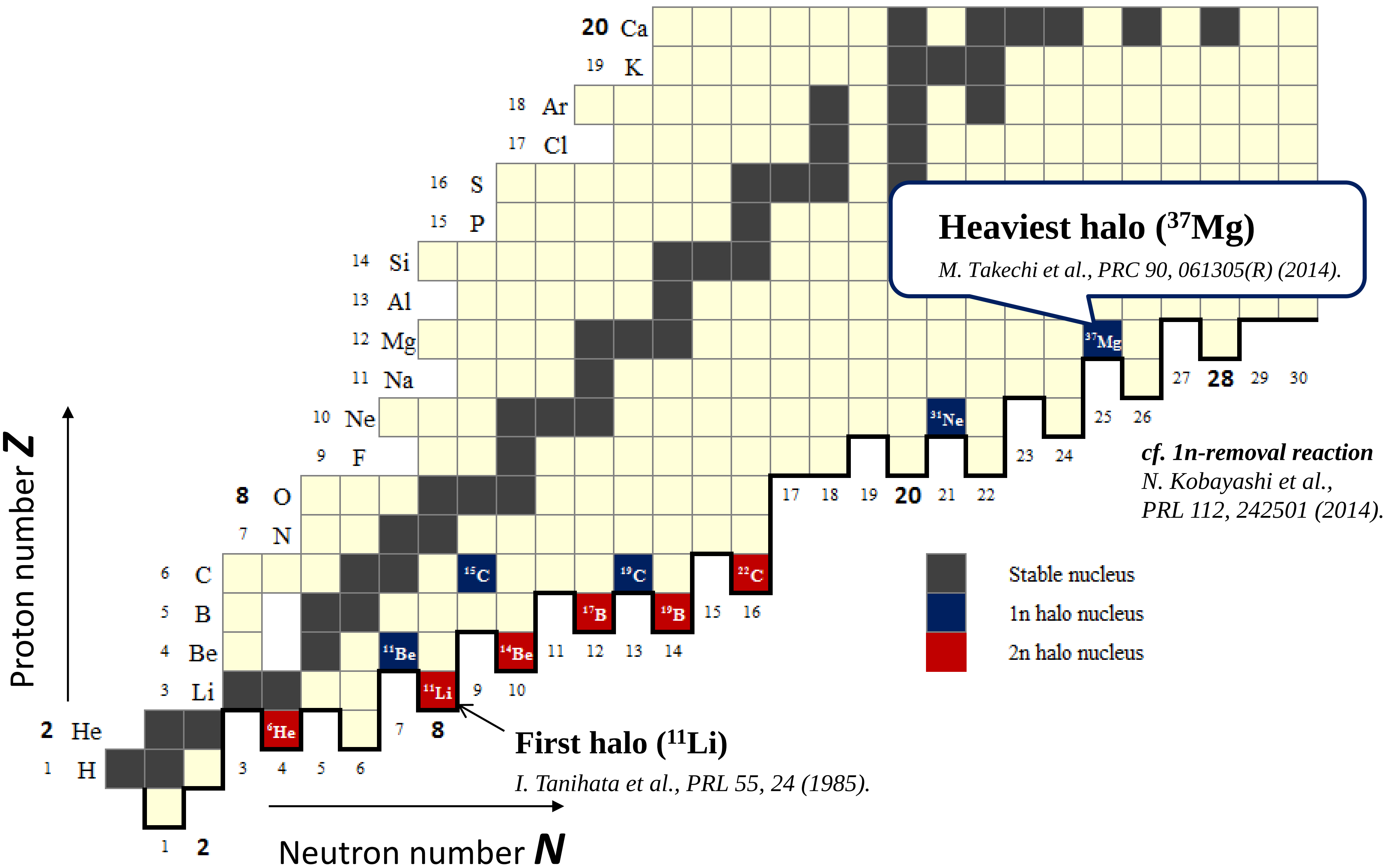


Neutron halo

One or two neutron(s) surround very far from a core nucleus.



Resent development of reaction cross sections (σ_R)



Systematic analysis of σ_R

Experiment

Total reaction cross sections (σ_R) were measured systematically.

M. Takechi et al., PRC 90, 061305(R) (2014).

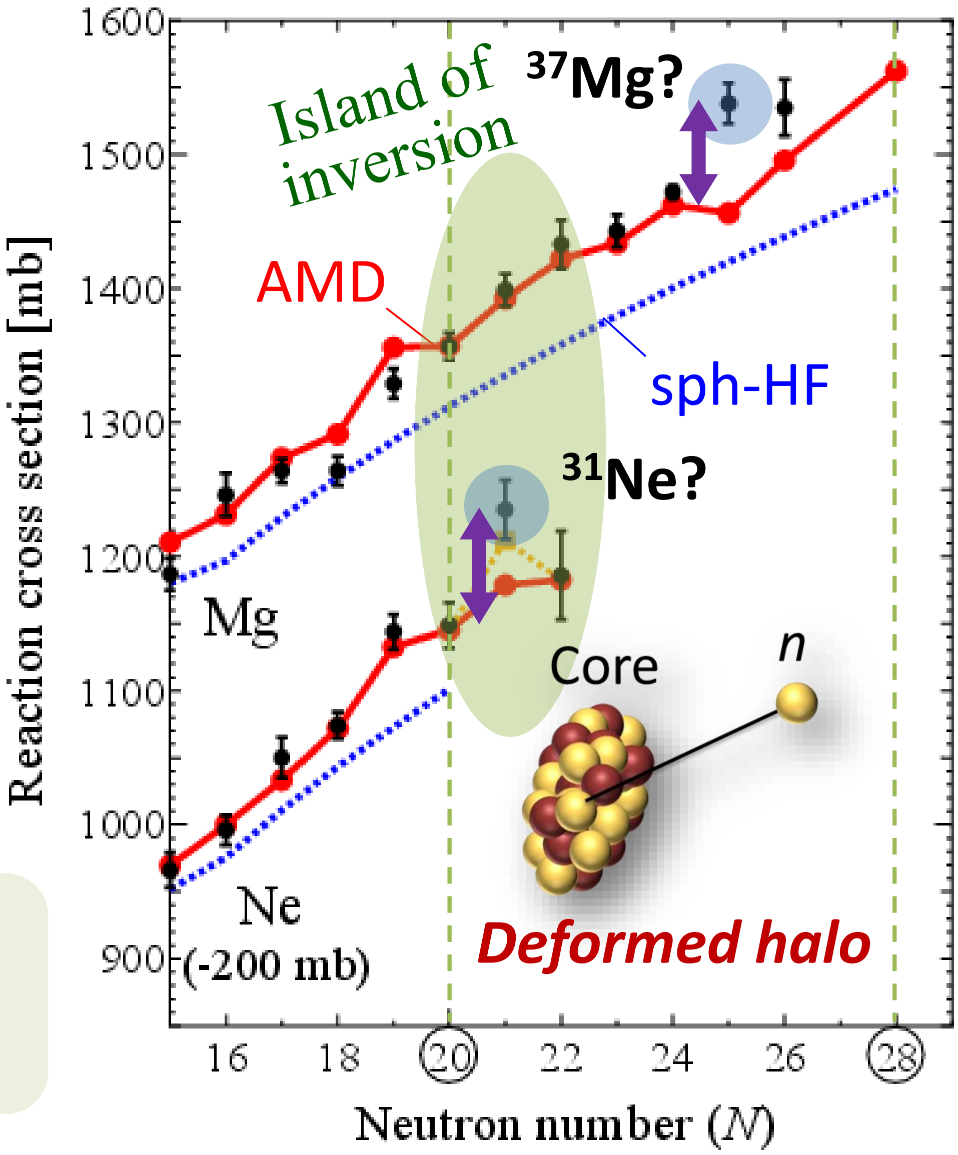
M. Takechi et al., PLB 707, 357 (2012).

Theory

The σ_R were analyzed in the microscopic framework based on AMD and the double folding model.

*S. Watanabe et al., PRC **89**, 044610 (2014).*

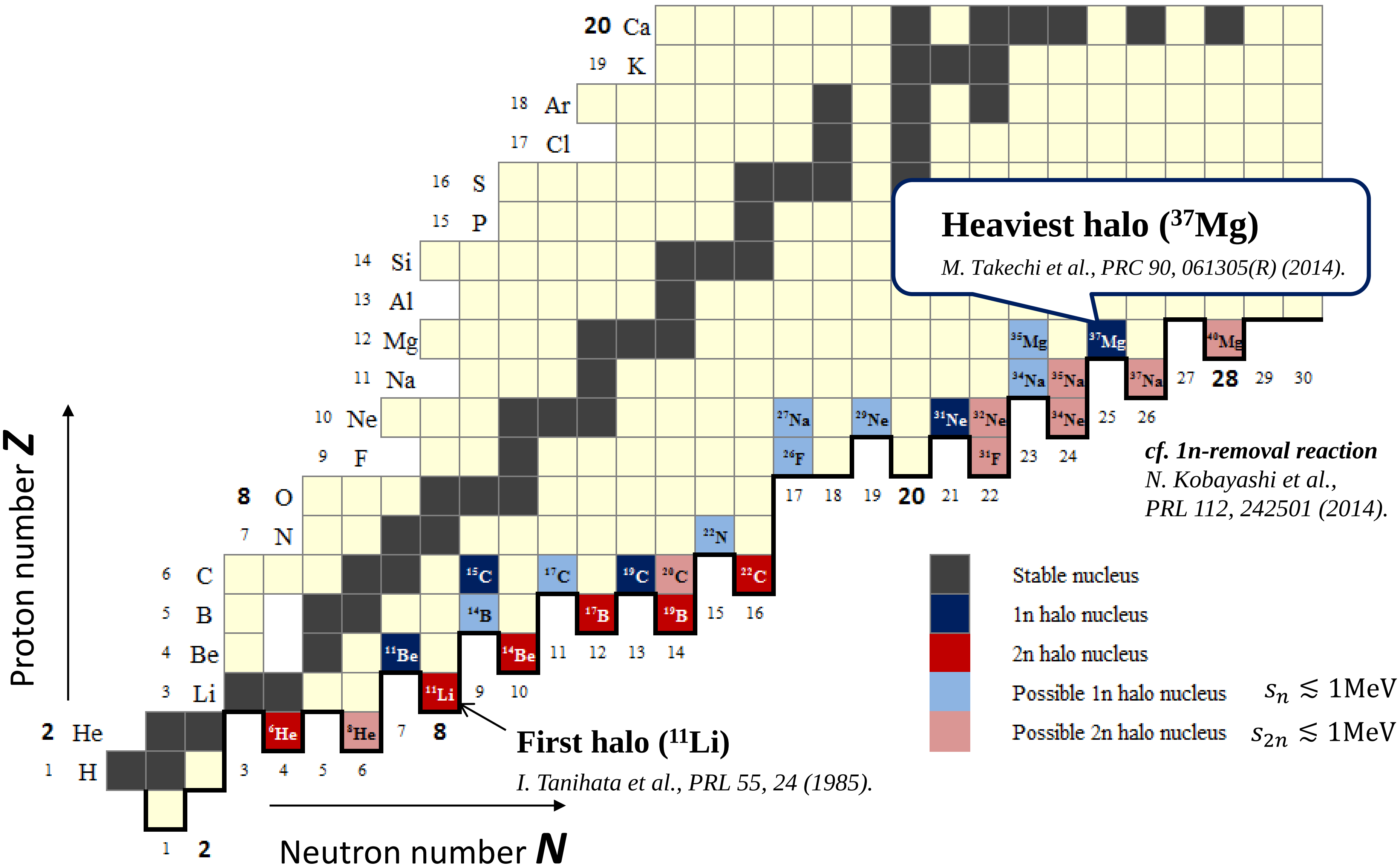
*K. Minomo et al., PRL **108**, 052503 (2012).*



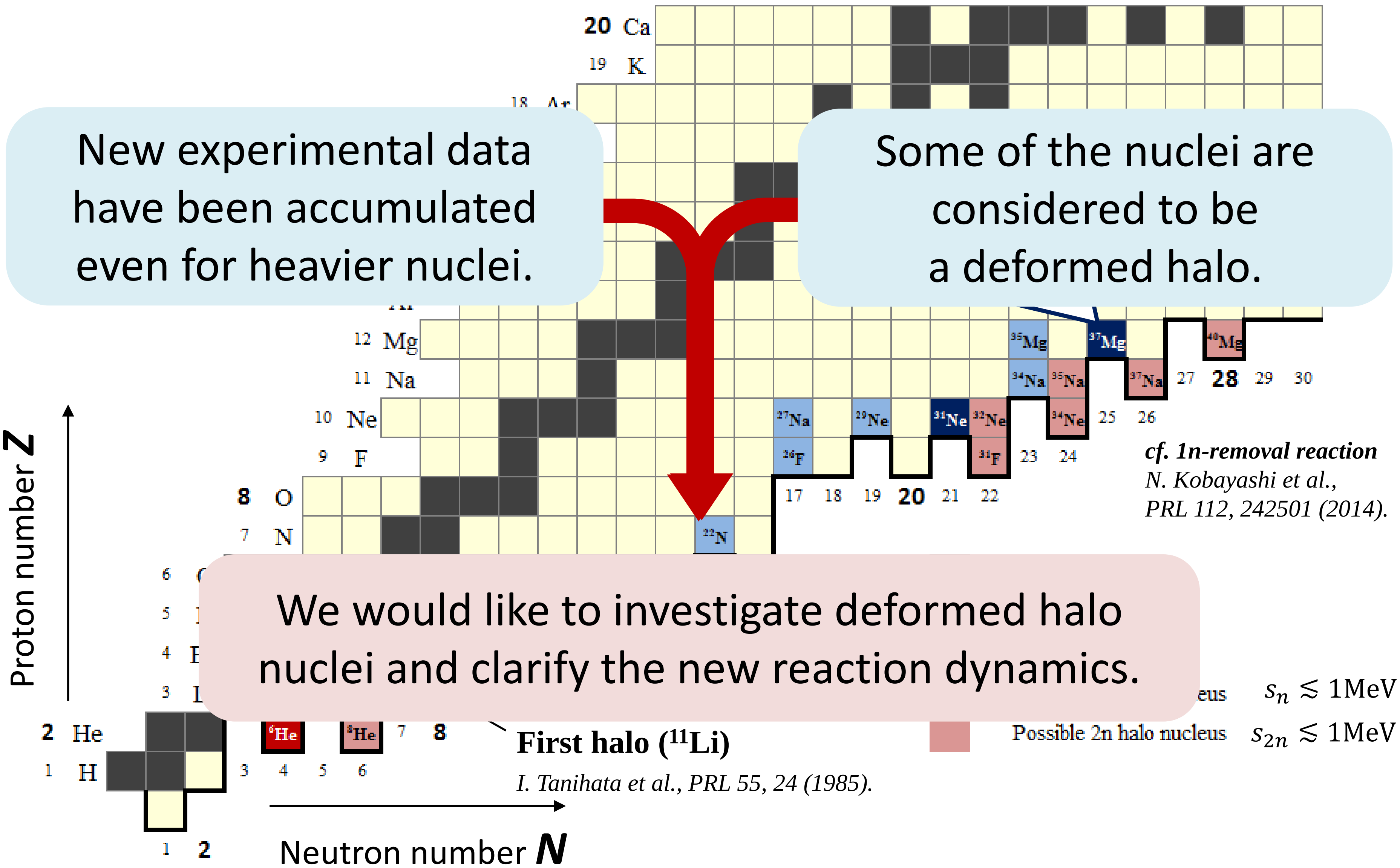
19 ≤ N : Largely deformation

^{31}Ne, ^{37}Mg: Deformed halo

Resent development of reaction cross sections (σ_R)



Resent development of reaction cross sections (σ_R)



New experimental data have been accumulated even for heavier nuclei.

Some of the nuclei are considered to be a deformed halo.

We would like to investigate deformed halo nuclei and clarify the new reaction dynamics.

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4. **Summary**

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1. **General few-body approaches**
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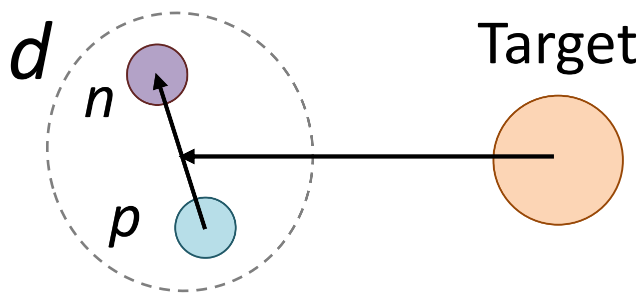
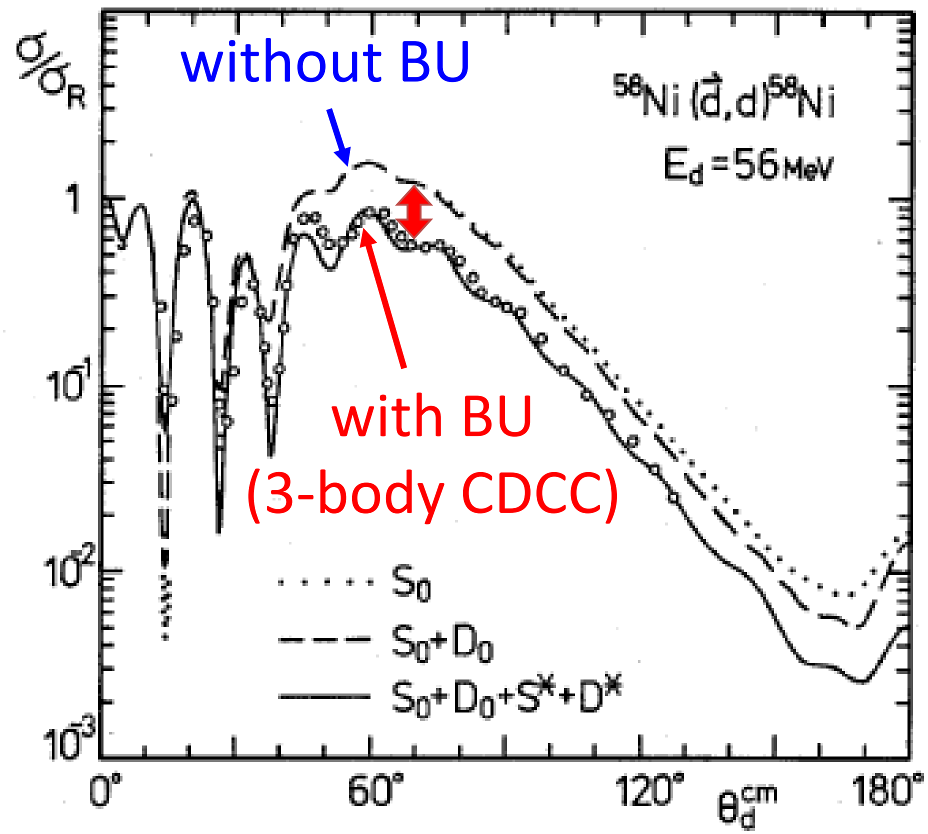
CDCC and Breakup effects

CDCC Continuum Discretized Coupled Channels

- ✓ CDCC is a fully quantum mechanical method for treating BU effects.
- ✓ CDCC was born as a theory for *d*-scattering



CDCC has been widely applied to many kinds of three-body scattering. (Ex: core + n + T)



First application of 3-body CDCC

M. Yahiro, Y. Iseri, H. Kameyama, M. Kamimura, and M. Kawai, Prog. Theor. Phys. Suppl. No. 89 (1986), 32.

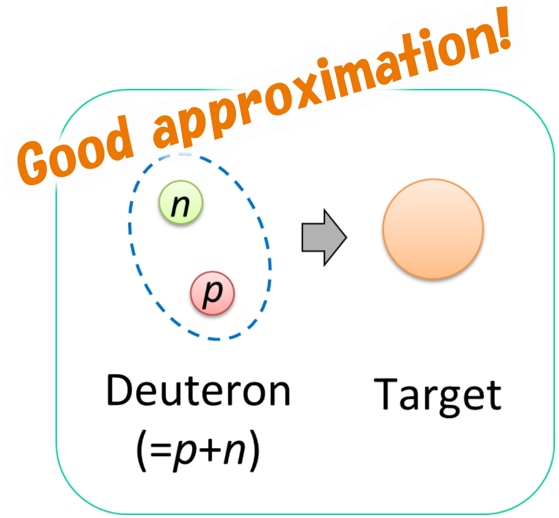
General few-body approaches（CDCC, Faddeev, DWBA, … ）

A core nucleus is assumed to be inert.

☺ **Good approximation** for *d* scattering

- Neutron and proton cannot get excited in the energy scale of our interest.

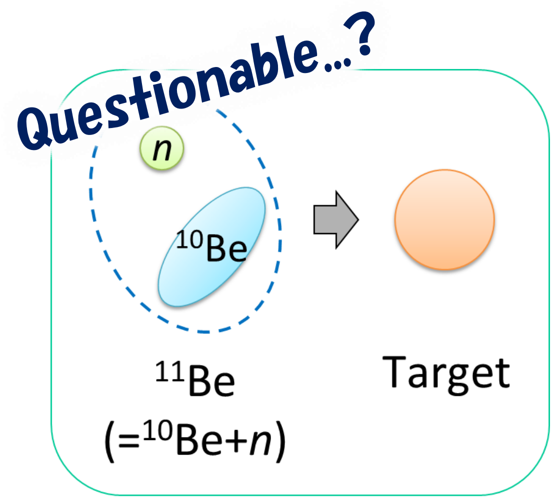
cf. ^{6}He scattering (α core is *inert*)



☹ **Questionable** for heavier systems

- Different core and valence states are coupled with each other.

ex. ^{11}Be, ^{37}Mg (Core is *deformed*)



Immediate work： To develop CDCC for treating core excitation.

Important DoF: Core excitation

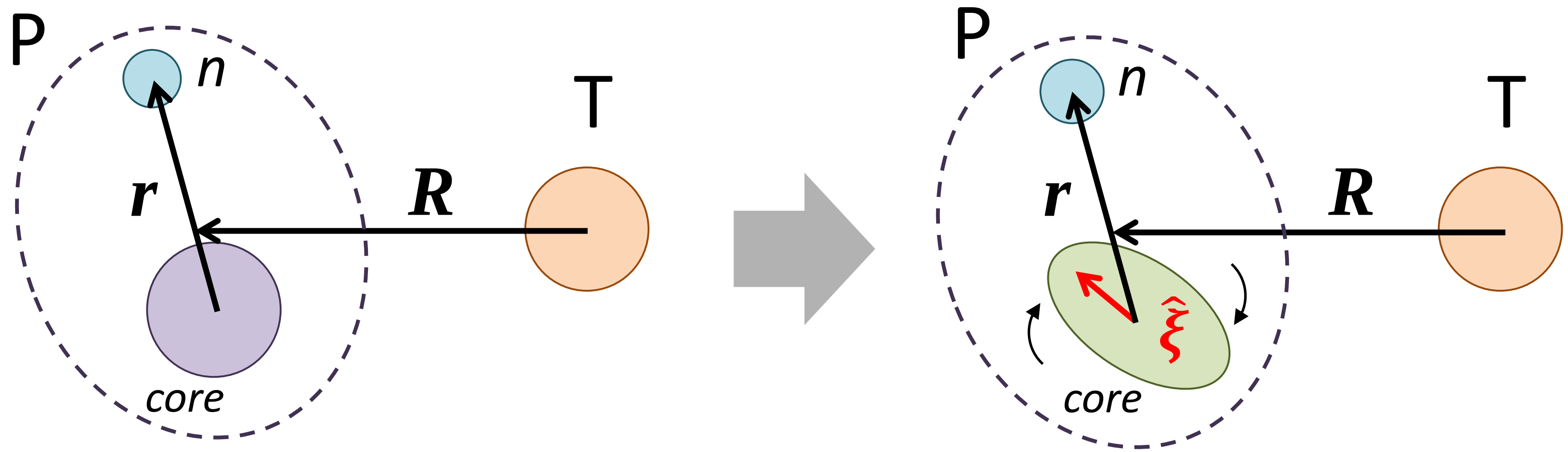
We will introduce the core coordinate $(\hat{\xi})$.

Standard 3-body CDCC

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

3-body CDCC with core Ex.

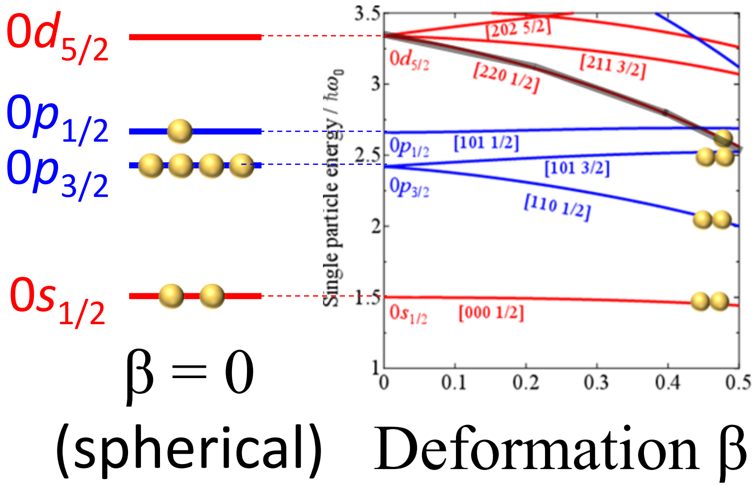
$$\Psi = \Psi(\boldsymbol{R}, \boldsymbol{r}, \hat{\xi})$$



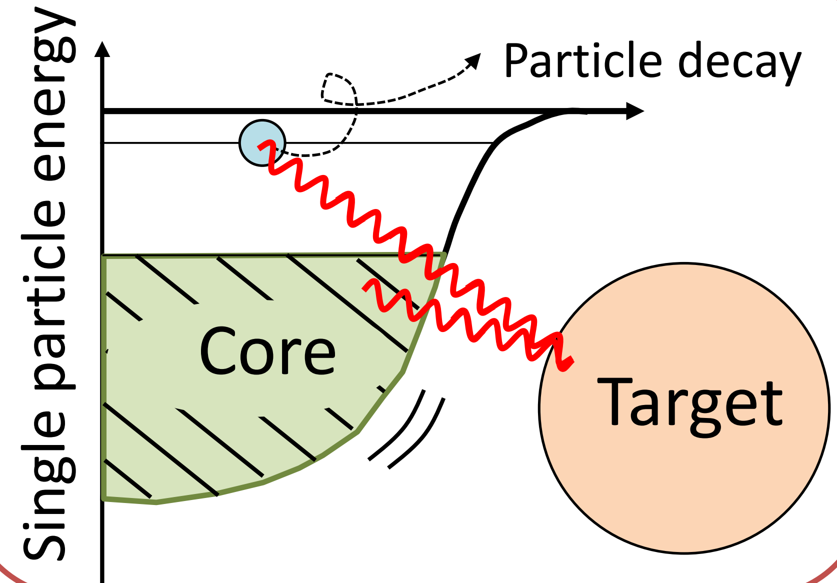
What kind of physics appears
by taking into account the core excitation?

Static and Dynamic Core Excitation Effects

Static core excitation



Dynamic core excitation



- Single particle energy changes
- Coupled to several core states

- BU due to neutron excitation
- BU due to core excitation

Competition

I would like to understand "Static" and "Dynamic" core excitation effects simultaneously.

Purpose

Final goal

To develop the CDCC method for treating core-excitation effects explicitly.

- Investigation of scattering of deformed halos
- Application for cluster physics

DWBA: First order approximation of CDCC

Present goal

To develop DWBA (Distorted Wave Born Approximation) for treating core excitation.

- Good prototype (DWBA = CDCC for $\hat{V} \sim 0$)
- Simple estimation of core-excitation effects in the BU reaction

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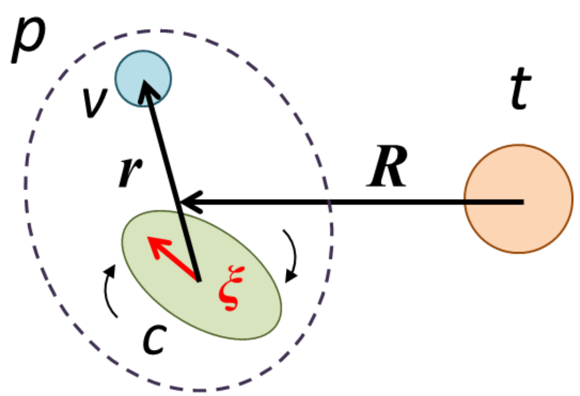
Total Hamiltonian

We explicitly introduce the core DoF $(\hat{\xi})$.

$$H_{\text{tot}} = K_{\boldsymbol{R}} + V_{vt}(R_{vt}) + V_{ct}(\boldsymbol{R}_{ct}, \hat{\xi}) + h_p$$

$$h_p = K_{\boldsymbol{r}} + V(\boldsymbol{r}, \hat{\xi}) + h_c(\hat{\xi})$$

→ I will show you the actual interactions later.

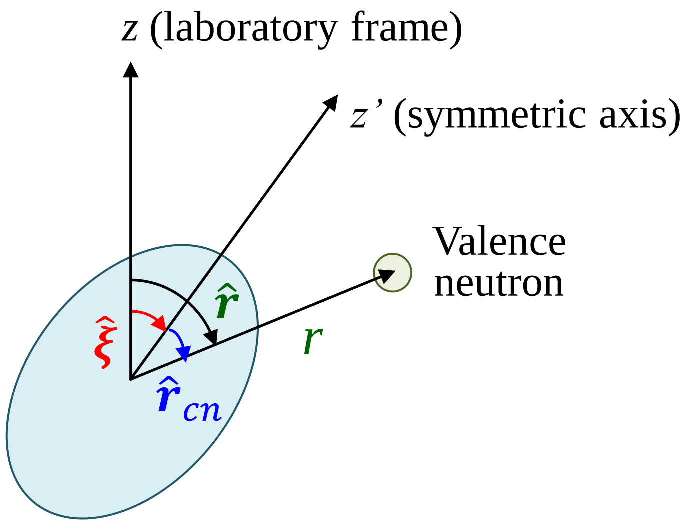


First, we should understand projectile part (h_p).

→ Let’s take ^{11}Be as an example.

Particle Rotor Model (PRM)

✓ ^{11}Be is described as
n (Particle) + active core (Rotor)



■ Hamiltonian

$$H = -\frac{\hbar^2}{2\mu}\nabla_{\boldsymbol{r}}^2 + V(\boldsymbol{r}, \hat{\boldsymbol{\xi}}) + \frac{\hbar^2 I_c^2}{2\mathcal{J}}$$

$$\approx -\frac{\hbar^2}{2\mu}\nabla_{\boldsymbol{r}}^2 + V_0(r) - R_0\beta_2\frac{dV_0(r)}{dr}Y_{20}(\hat{\boldsymbol{r}}_{cn}) + \frac{\hbar^2 I_c^2}{2\mathcal{J}}$$

Spherical Hamiltonian $\equiv H_{\mathrm{sph}}$

Deformation term $\equiv V_{\mathrm{def}}$

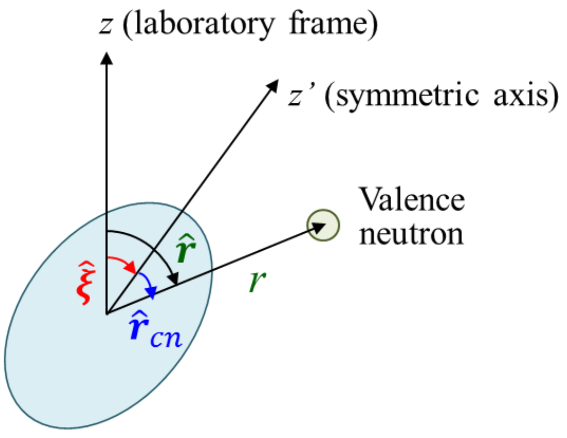
Internal Hamiltonian of core $\equiv H_{\mathrm{rot}}$

$$H \equiv H_{\mathrm{sph}}(\boldsymbol{r}) + V_{\mathrm{def}}(\hat{\boldsymbol{r}}_{cn}) + H_{\mathrm{rot}}(\hat{\boldsymbol{\xi}})$$

How to solve this problem?

$$[H - E]\Psi_{JM}(\boldsymbol{r}, \hat{\xi}) = 0$$

$$H = H_{\rm sph}(\boldsymbol{r}) + V_{\rm def}(\boldsymbol{r}, \hat{\xi}) + H_{\rm rot}(\hat{\xi})$$



$$\Psi_{JM}(\boldsymbol{r}, \hat{\xi}) = \sum_{n\ell j} \sum_{I} \alpha_{n\ell jI} \left[\phi_{n\ell j}^{(\rm sph)}(\boldsymbol{r}) \otimes \Phi_{I}^{(\rm rot)}(\hat{\xi}) \right]_{JM}$$

$$\phi_{n\ell j}^{(\rm sph)}(\boldsymbol{r}) = \sum_{k=1}^{N} \beta_k \boxed{\varphi_k(r)} \mathcal{Y}_{(\ell s)j}(\hat{\boldsymbol{r}})$$

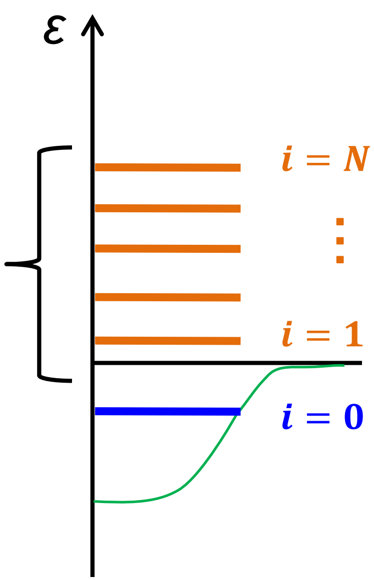
Gaussian basis

E. Hiyama, Y. kino, M. Kamimura, Prog. Part. Nucl. Phys. ***51****, 223 (2003).*

Diagonalization

Discretized continuum states (Pseudostates)

Bound state

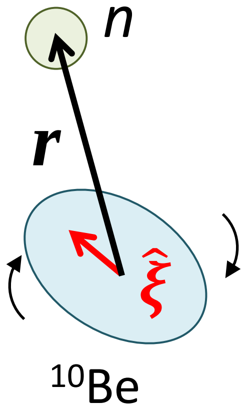


Model Setting

Hamiltonian

$$H = -\frac{\hbar^2}{2\mu}\nabla_{\boldsymbol{r}}^2 + V_0(r) + V_{\mathrm{def}}(\hat{\boldsymbol{r}}_{cn}) + \frac{\hbar^2 I_c^2}{2\mathcal{J}}$$

Parameter set of WS potential



$$V_{\mathrm{WS}} = -54.239\ \mathrm{MeV}, V_{\mathrm{SO}} = -8.50\ \mathrm{MeV}$$

$$R = 2.483\ \mathrm{fm}, a = 0.65\ \mathrm{fm}$$

F.M. Nunes et al., NPA609 43 (1996).

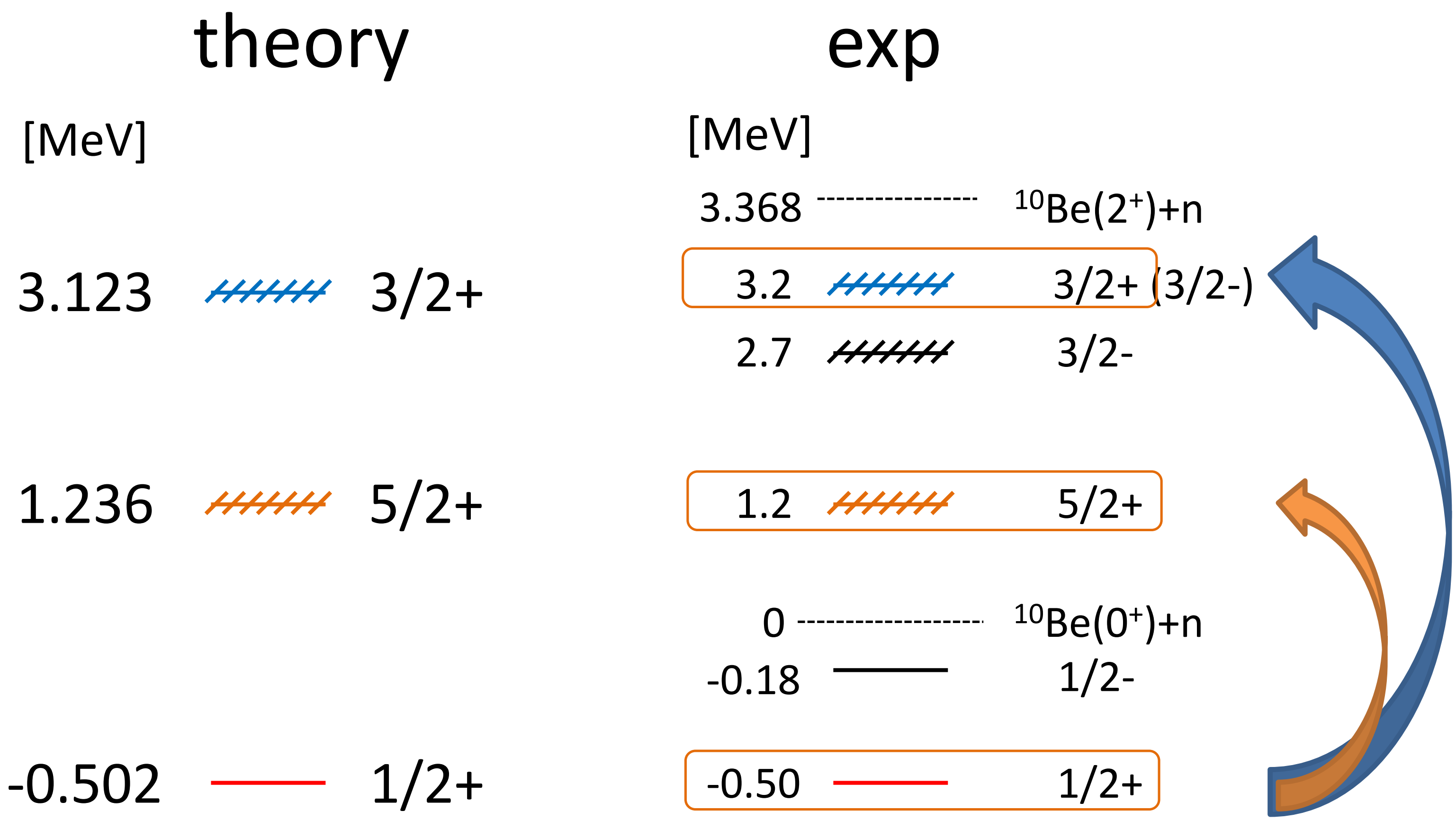
^{10}Be core

$$\beta_2 = 0.67, E(2+) = 3.368\ \mathrm{MeV}$$

Model space

$$\ell = 0, 2 \quad I = 0, 2$$

Result of the positive-state energies



We will consider the 5/2+ and 3/2+ BU reactions.

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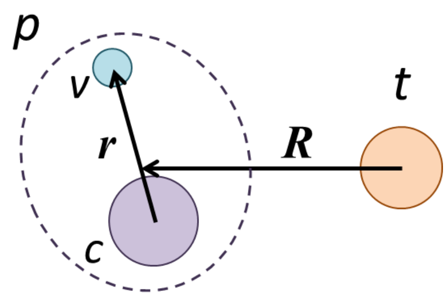
DWBA (Distorted Wave Born Approximation)

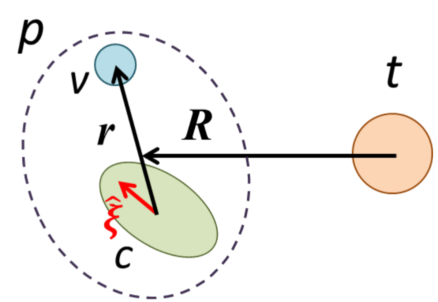
Standard DWBA (since 1950s)



$$T_{pt}^{J'M',JM}(\boldsymbol{K}',\boldsymbol{K}) = \left\langle \chi_{\boldsymbol{K}'}^{(-)}(\boldsymbol{R})\Psi_{J'M'}^{f}(\boldsymbol{r}) \middle| V_{vt}(R_{vt}) + V_{ct}(R_{ct}) \middle| \chi_{\boldsymbol{K}}^{(+)}(\boldsymbol{R})\Psi_{JM}^{i}(\boldsymbol{r}) \right\rangle$$

Extended DWBA

A. Moro and R. Crespo., PRC ***85****, 054613 (2012)*



static core excitation

$$T_{pt}^{J'M',JM}(\boldsymbol{K}',\boldsymbol{K}) = \left\langle \chi_{\boldsymbol{K}'}^{(-)}(\boldsymbol{R})\boxed{\Psi_{J'M'}^{f}(\boldsymbol{r},\hat{\xi})} \middle| V_{vt}(R_{vt}) + \boxed{V_{ct}(\boldsymbol{R}_{ct},\hat{\xi})} \middle| \chi_{\boldsymbol{K}}^{(+)}(\boldsymbol{R})\boxed{\Psi_{JM}^{i}(\boldsymbol{r},\hat{\xi})} \right\rangle$$

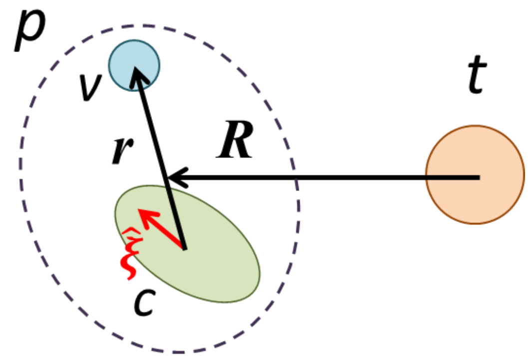
dynamic core excitation

DWBA description of BU reaction

Extended DWBA

$$T_{pt}^{J'M',JM} = \left\langle \chi_{\boldsymbol{K}'}^{(-)}(\boldsymbol{R})\Psi_{J'M'}^{f}(\boldsymbol{r},\hat{\xi}) \middle| V_{vt}(R_{vt}) + V_{ct}(\boldsymbol{R}_{ct},\hat{\xi}) \middle| \chi_{\boldsymbol{K}}^{(+)}(\boldsymbol{R})\Psi_{JM}^{i}(\boldsymbol{r},\hat{\xi}) \right\rangle$$

Multipole expansion of V_{ct}



$$V_{vt}(R_{vt}) + V_{ct}(\boldsymbol{R}_{ct},\hat{\xi})$$

$$= V_{vt}(R_{vt}) + \sum_{\mathcal{LM}} V_{ct}^{(\mathcal{L})}(R_{ct}) Y_{\mathcal{LM}}^{*}(\hat{\boldsymbol{R}}_{ct}) Y_{\mathcal{LM}}(\hat{\xi})$$

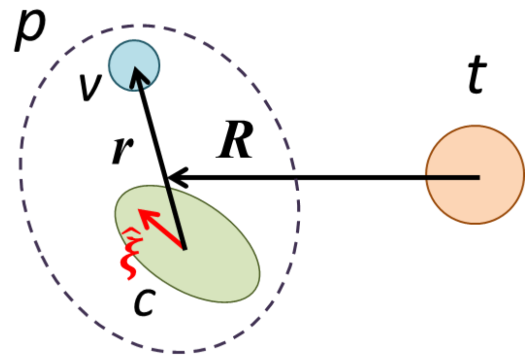
$$= V_{vt}(R_{vt}) + V_{ct}^{(0)}(R_{ct}) + \sum_{\mathcal{L}>0,\mathcal{M}} V_{ct}^{(\mathcal{L})}(R_{ct}) Y_{\mathcal{LM}}^{*}(\hat{\boldsymbol{R}}_{ct}) Y_{\mathcal{LM}}(\hat{\xi})$$

DWBA description of BU reaction

Extended DWBA

$$T_{pt}^{J'M',JM} = \left\langle \chi_{\boldsymbol{K}'}^{(-)}(\boldsymbol{R})\Psi_{J'M'}^{f}(\boldsymbol{r},\hat{\xi})\middle| V_{vt}(R_{vt}) + V_{ct}(\boldsymbol{R}_{ct},\hat{\xi}) \middle| \chi_{\boldsymbol{K}}^{(+)}(\boldsymbol{R})\Psi_{JM}^{i}(\boldsymbol{r},\hat{\xi})\right\rangle$$

$$T_{pt}^{J'M',JM} = T_{\mathrm{val}}^{J'M',JM} + T_{\mathrm{corex}}^{J'M',JM}$$



Valence excitation

$$T_{\mathrm{val}}^{J'M',JM} = \left\langle \chi_{\boldsymbol{K}'}^{(-)}(\boldsymbol{R})\Psi_{J'M'}^{f}(\boldsymbol{r},\hat{\xi})\middle| V_{vt}(R_{vt}) + V_{ct}^{(0)}(R_{ct}) \middle| \chi_{\boldsymbol{K}}^{(+)}(\boldsymbol{R})\Psi_{JM}^{i}(\boldsymbol{r},\hat{\xi})\right\rangle$$

→ Excite valence coordinate $(\boldsymbol{r})$

Core excitation

$$T_{\mathrm{corex}}^{J'M',JM} = \left\langle \chi_{\boldsymbol{K}'}^{(-)}(\boldsymbol{R})\Psi_{J'M'}^{f}(\boldsymbol{r},\hat{\xi})\middle| \sum V_{ct}^{(\mathcal{L})}(R_{ct})Y_{\mathcal{L}\mathcal{M}}^{*}(\hat{\boldsymbol{R}}_{ct})Y_{\mathcal{L}\mathcal{M}}(\hat{\xi}) \middle| \chi_{\boldsymbol{K}}^{(+)}(\boldsymbol{R})\Psi_{JM}^{i}(\boldsymbol{r},\hat{\xi})\right\rangle$$

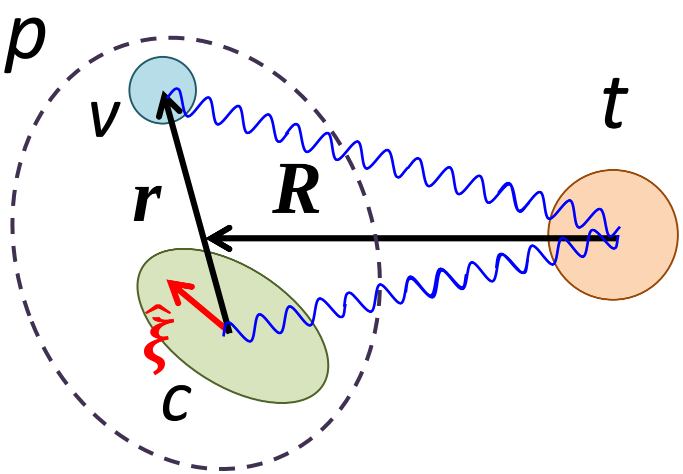
→ Excite core coordinate $(\hat{\xi})$

Brief summary：Two types of BU mechanisms

$$T_{pt}^{J'M',JM}(\boldsymbol{K}',\boldsymbol{K}) = T_{\mathrm{val}}^{J'M',JM}(\boldsymbol{K}',\boldsymbol{K}) + T_{\mathrm{corex}}^{J'M',JM}(\boldsymbol{K}',\boldsymbol{K})$$

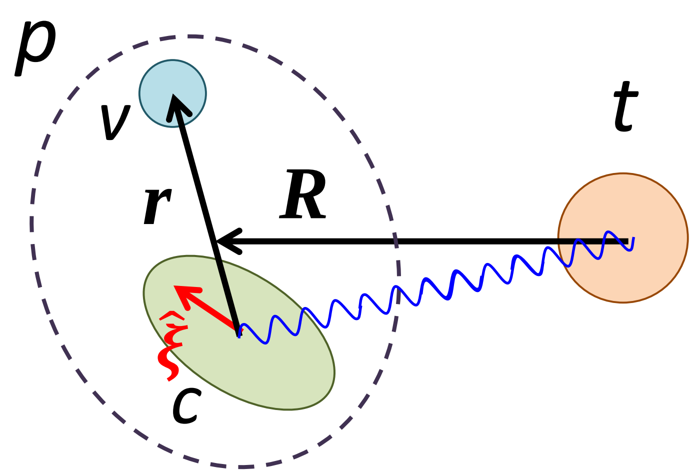
Valence excitation

interaction： $V_{vt}(R_{vt}) + V_{ct}^{(0)}(R_{ct})$



Core excitation

interaction： $\sum V_{ct}^{(\mathcal{L})}(R_{ct}) Y_{\mathcal{LM}}^{*}(\hat{\boldsymbol{R}}_{ct}) Y_{\mathcal{LM}}(\hat{\xi})$



These two mechanisms compete with each other.

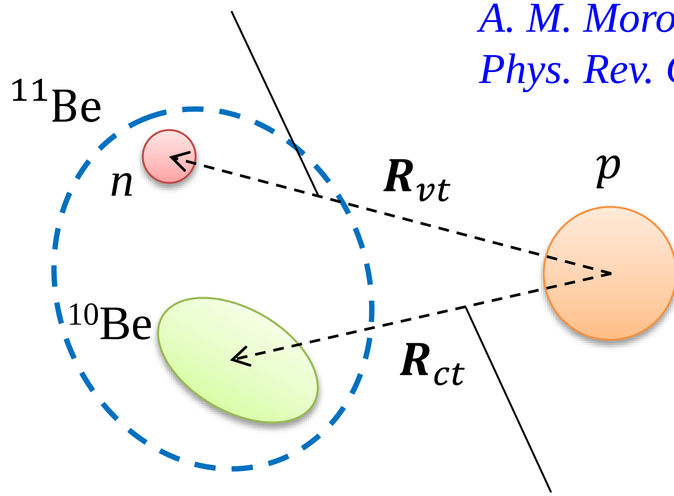
Model setting of reaction part

^{11}Be+p at 63.7 MeV/nucl.

$$V_{nt}: \quad V(r) = -45e^{-(r/1.484)^2}$$

Determined to reproduce the realistic Faddeev calculation. (with CD Bonn)

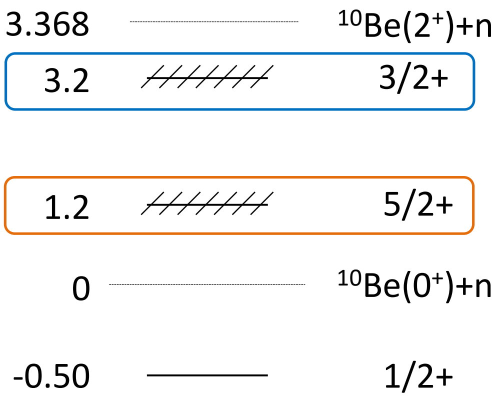
A. M. Moro and R. Crespo, Phys. Rev. C ***85****, 054613 (2012).*



V_{ct}: Phenomenological optical potential

B. A. Watson et al., Phys. Rev. ***182****, 977 (1969).*

Resonant breakup cross section



$$\frac{d\sigma}{d\Omega} \propto \sum_{MM'} \left| T_{pt}^{J'M',JM} \right|^2$$

$$T_{pt}^{J'M',JM} = T_{\mathrm{val}}^{J'M',JM} + T_{\mathrm{corex}}^{J'M',JM}$$

Sorry.

Summary

We are developing our reaction model (CDCC) for the explicit treatment of core excitation.

First, we developed DWBA for treating core excitation.

Until now : Core is assumed to be inert.

From now: Core excitation will be a key mechanism in nuclear reaction.

- This effect appears in ^{11}Be+p scattering.

Future plan: Develop DWBA into CDCC.

Analyze ^{31}Ne, ^{37}Mg etc. (deformed halo)

^{15}C (spherical halo)

⇒ General properties of core-induced BU reaction?