Investigation of transfer to the bound states and resonance of ^{11}Be via the ^{10}Be(d,p) reaction using the ADWA method

A Spectroscopic Study of Halo Nucleus ^{11}Be

J. Yang[1,2], P. Capel[1,3], R. Raabe[2]

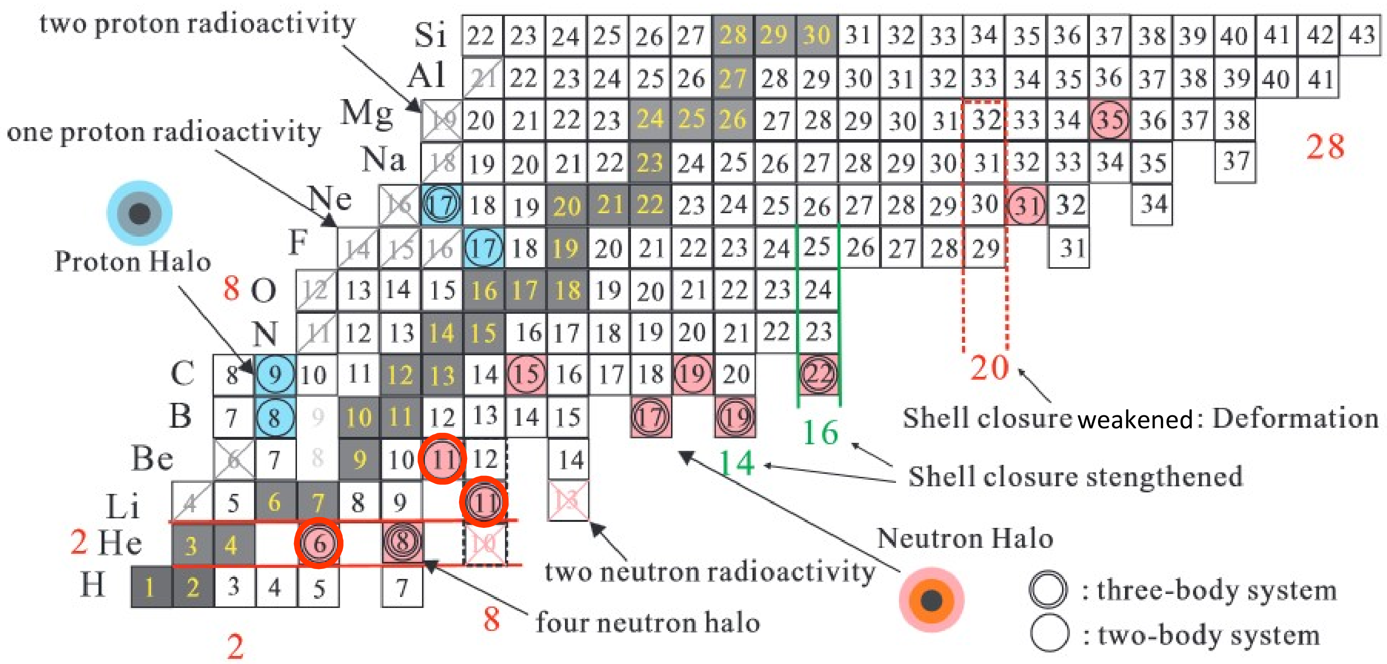
[1] Physique Nucléaire et Physique Quantique, Université Libre de Bruxelles, B-1050 Bruxelles
[2] Afdeling Kern- en Stralingsfysica, Celestijnenlaan 200d - bus 2418, 3001 Leuven
[3] Institut für Kernphysik, Technische Universität Darmstadt, 64289 Darmstadt, Germany

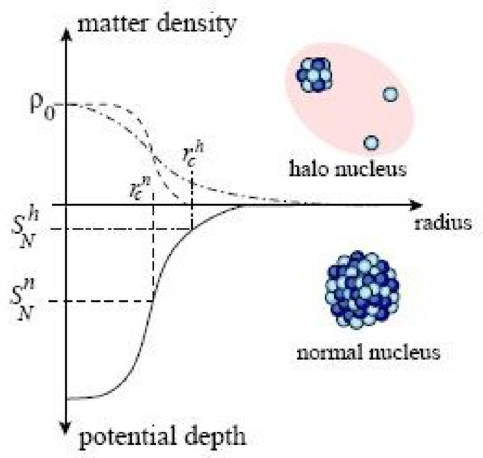
March 2018

Physics Motivation

- Halo nuclei

(Pictures are taken from WIKIMEDIA and other websites)





^{6}He — first halo produced

^{11}Be — one neutron halo

^{11}Li — famous Borromean nucleus

Features:
i) weakly bound
ii) large size
iii) short lifetime
…

How to study halo nuclei ? → **Transfer reaction, elastic scattering, break up, …**

What is the property of this "halo" ? → **Spectroscopic factor, ANC, …**

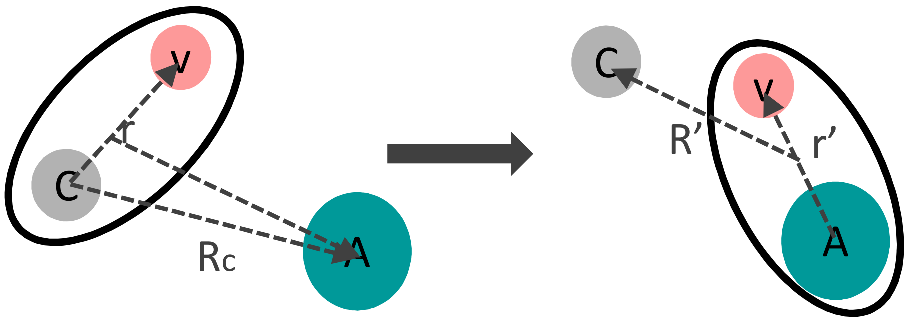
Outline

- **Theoretical framework of transfer reaction**
  - What is transfer reaction
  - Theoretical approximation
- **ADWA calculation of ^{10}Be(d,p)^{11}Be**
  - Influence of the description of n-^{10}Be bound state
  - ANC extraction from the peripheral part
- **Conclusion and prospects**

Theoretical Framework

Transfer reaction

- Transfer up to several nucleons between the projectile and target
- A powerful tool to selectively populate states with a strong single-particle character
- (d,p) reaction



Some history of deuteron stripping reaction

Ref: Pang's seminar,ect Trento,2016

Ernest O. Lawrence Phys. Rev. 45, 66(1933) — Possibly first (d,p) measurement

J.Horowitz & A.M.L. Messiah Phys. Rev. 92, 1326(1953) — Plane wave approximation

B.Buck & P.E. Hodgson Phil. Mag. 6, 1371(1961) — DWBA used

G.R. Satchler Nucl. Phys. 55, 1(1964) — Including spin-orbit effects

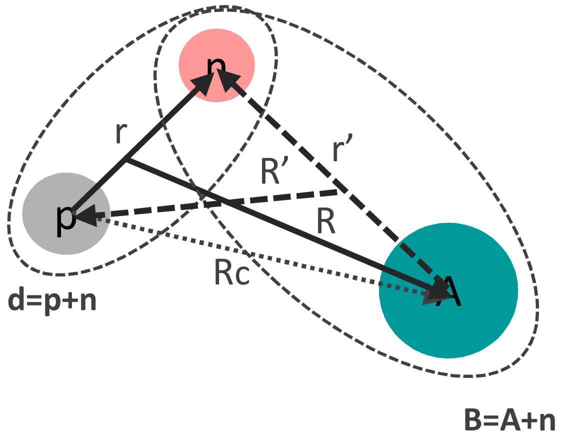
Johnson & Soper Phy. Rev. C 1.3 (1970): 976 — ZR-ADWA

Johnson & Tandy, Nucl. Phys. A235 (1974) 56 — FR-ADWA

Theoretical Framework

(d,p) reaction

- Mathematical description



Transition amplitude (post form) $\boldsymbol{T(pB,dA) = \langle \Phi^{(-)}(R',r') | V_{post} | \Psi^{(+)}(R,r) \rangle}$

Interaction term $V_{post} = V_d(r) + U_{pA}(R_c) - U_{pB}(R')$

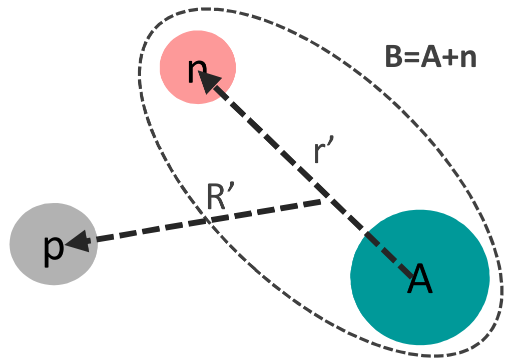
Differential cross section $\frac{d\sigma}{d\Omega} = \frac{\mu_{dA}\mu_{pB}}{(2\pi\hbar^2)^2}\frac{k_p}{k_d}|T(pB,dA)|^2$

Theoretical Framework

Final state $\boldsymbol{\Phi}^{(-)}$

$$\boldsymbol{\Phi}^{(-)} = \phi_B \chi_{pB}(R') \quad \text{with } \phi_B = [S_{nA}^B]^{1/2}\phi_A \varphi_{nA}(r') + \phi_B^C$$

$$\xrightarrow{two-body\ approx} [S_{nA}^B]^{1/2}\varphi_{nA}(r')\chi_{pB}(R')$$



- Bound-state wave function

$$\varphi_{nA}(r') \xrightarrow{r'\to\infty} b_{nlj} W_{-\eta,l+\frac{1}{2}}(2kr')/r' \xrightarrow{l=0} b_{nlj} exp(-kr')/r'$$, in which b_{nlj} is the single-particle ANC (SPANC)

- Overlap function

$$[S_{nA}^B]^{1/2}\varphi_{nA} = I_{nA}^B(r') \xrightarrow{r'\to\infty} C_{lj} W_{-\eta,l+\frac{1}{2}}(2kr')/r$$, in which C_{lj} is the ANC

In the single-particle approach, the spectroscopic factor $S \approx S_{nA}^B$, which is always obtained by $S(\frac{d\sigma}{d\Omega})^{th} = (\frac{d\sigma}{d\Omega})^{exp}$

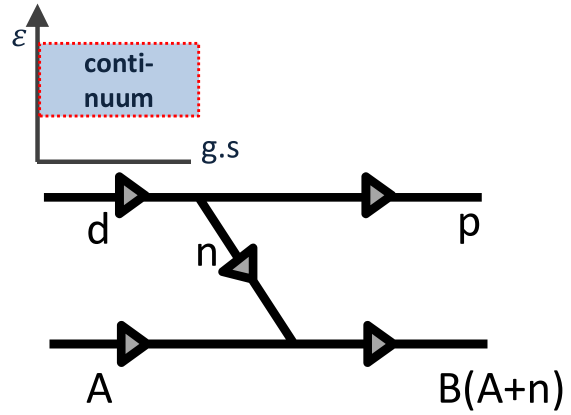
- Relationship between

$$C_{lj}^2 = S_{nA}^B b_{nlj}^2$$

Theoretical Framework

3-body solution $\boldsymbol{\Psi}^{(+)}$

$$\Psi^{(+)}(r,R) = \phi_{pn}(r)\chi_{dA}^{(+)}(R) + \int dk\,\phi_k(\varepsilon_k, r)\chi_k^{(+)}(\varepsilon_k, R)$$



DWBA	ADWA	CDCC
$\Psi^{(+)}(r,R) \approx \phi_{pn}(r)\chi_{dA}^{(+)}(R)$	Adiabatic approximation: Replacing all the continuum states by one state	discretize continuum into bin states $\Psi^{(+)}(r,R) = \sum_{i=0} \phi_{pn,i}(r)\chi_{dA,i}^{(+)}(R)$
U_{dA}: Omit all except elastic part in the 3-body wave function	Effective d-A interaction (zero-range) $U_{dA} = U_{nA} + U_{pA}$ Phys. Rev. C 1, 976 (1970).	Three-body equation turned into Coupled-Channel equations

- Connection with the Faddeev formalism

Theoretical Framework

- Comparison --- ADWA versus Other methods

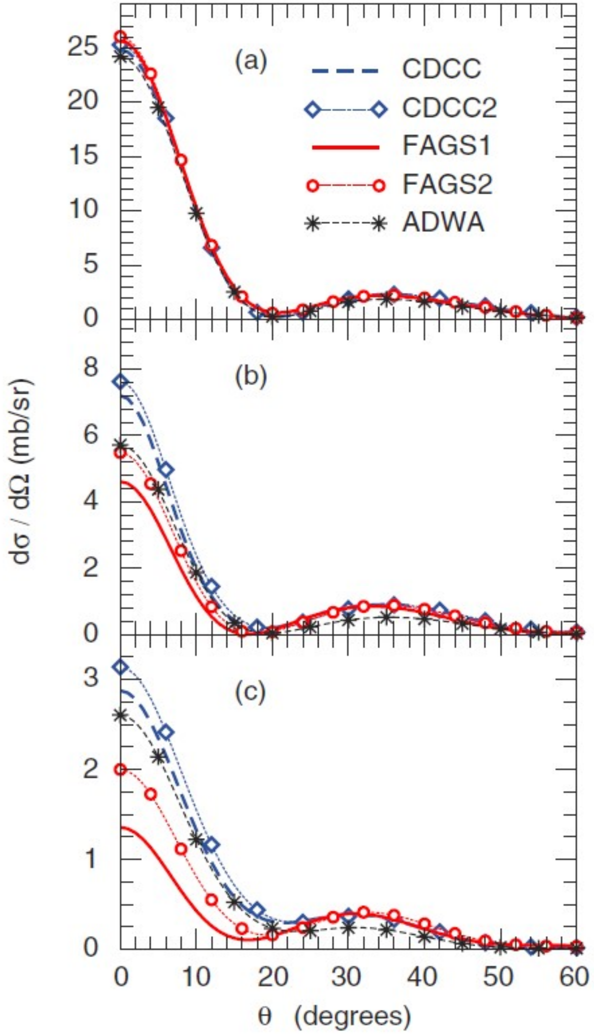


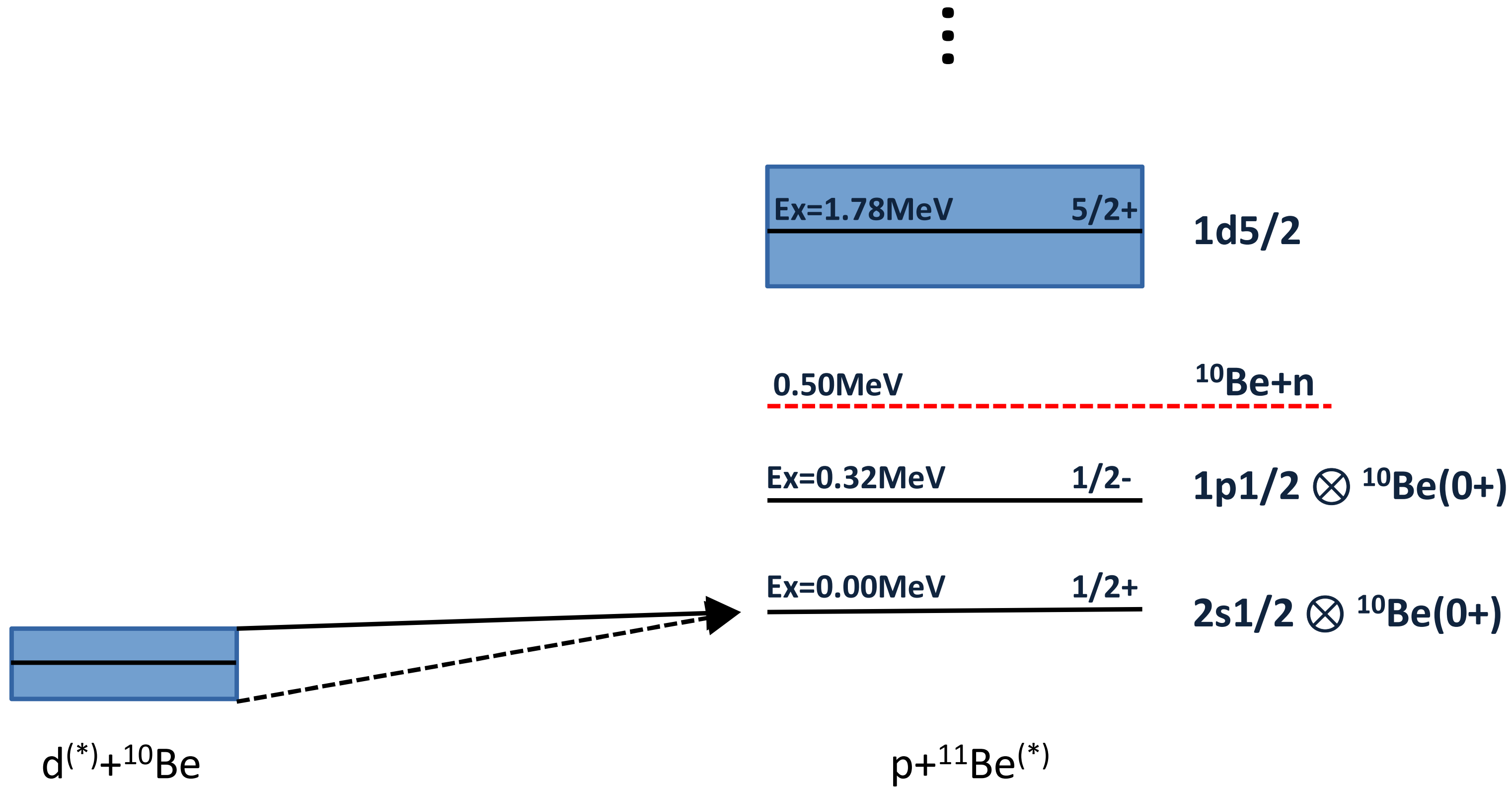
Fig. $^{10}Be(d,p)^{11}Be$ computed with Faddeev, CDCC and ADWA: (a) Ed = 21.4 MeV, (b) 40.9 MeV, and (c) 71 MeV

Ref: Upadhyay PRC 85, 054621 (2012)

a. For this reaction at low energy, ADWA is in good agreement with the CDCC and the Faddeev-type results.
b. For the reactions on ^{10}Be, ADWA performs just as well or even better than CDCC.

ADWA Calculation

- **^{10}Be(d,p)^{11}Be**



ADWA model

- ***Fresco***: program developed by Ian Thompson to perform reaction calculations

Calculation of ^{10}Be(d,p)^{11}Be

- **^{10}Be(d,p)^{11}Be (g.s) at different energies**

Potential choice

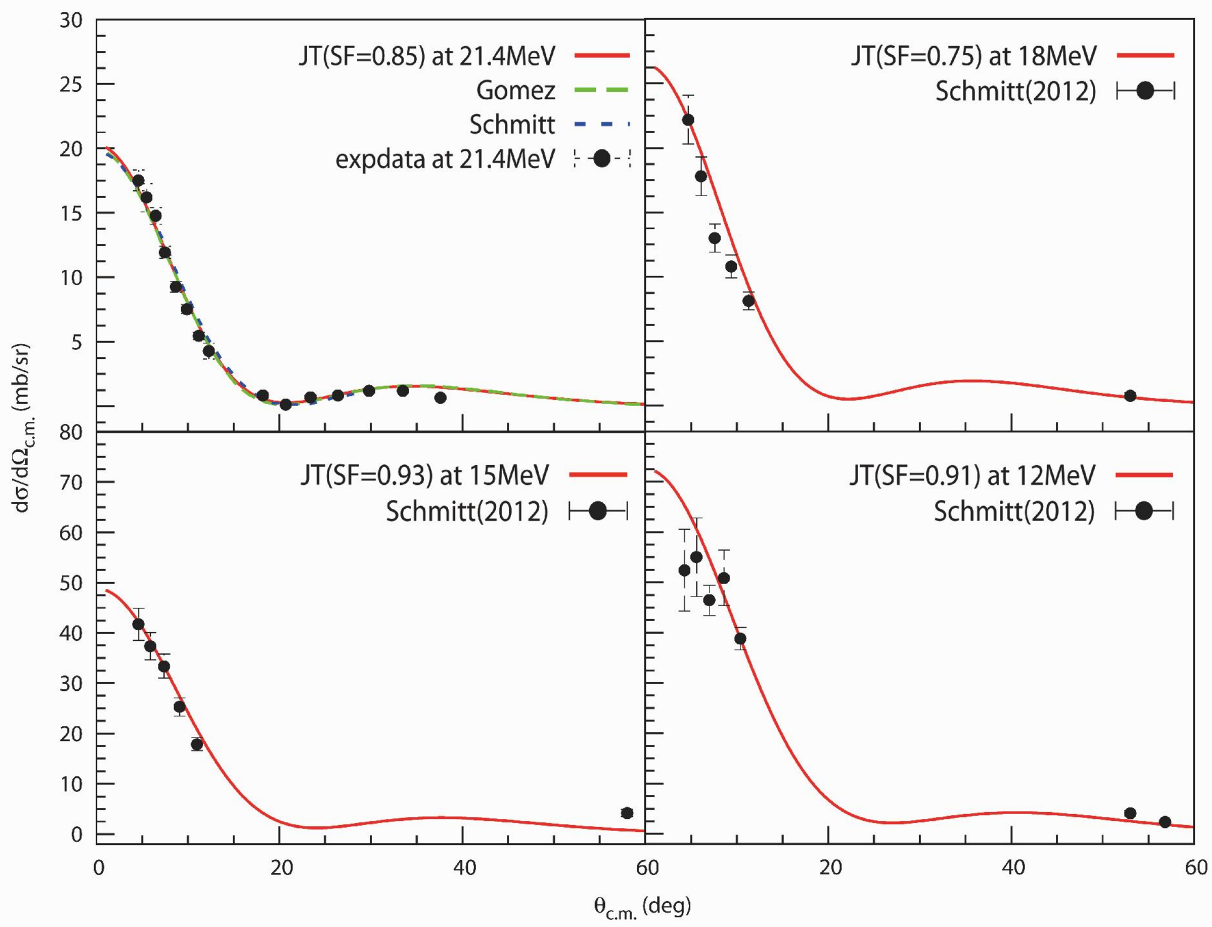
n-^{10}Be : *Woods-Saxon form*

d-^{10}Be : *Johnson & Tandy (CH89)*

n-p : *Reid soft core*

Rest : *CH89*

Ref: Schmitt et al, PRL 108,192701 (2012)
Gomez et al, PRC 92,014613 (2015)



◊ Successfully reproduce the calculation results and good agreement with experimental data obtained

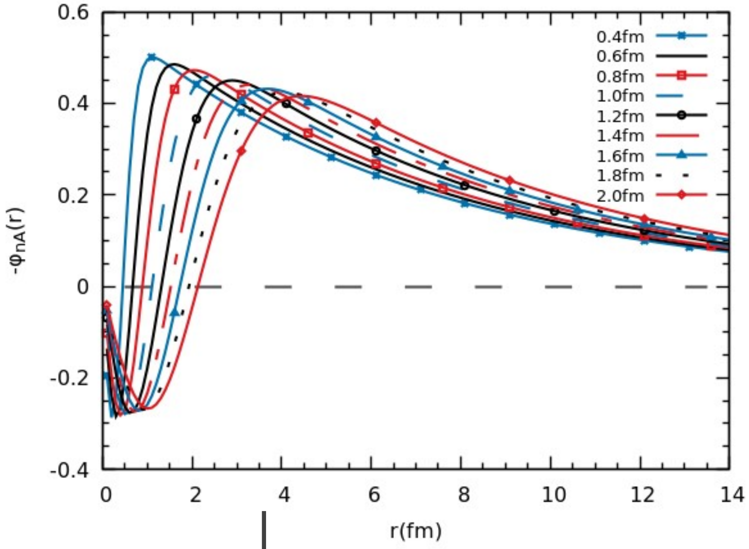
◊ What the reaction is sensitive to with respect to the description of the halo nucleus ^{11}Be?

Calculation of $^{10}Be(d,p)^{11}Be$ (g.s)

- **Description of n-^{10}Be: 2s1/2 ⊗ ^{10}Be(0+)**
  - Nine sets of Gaussian potentials developed to help study the peripheral characteristics of the reaction

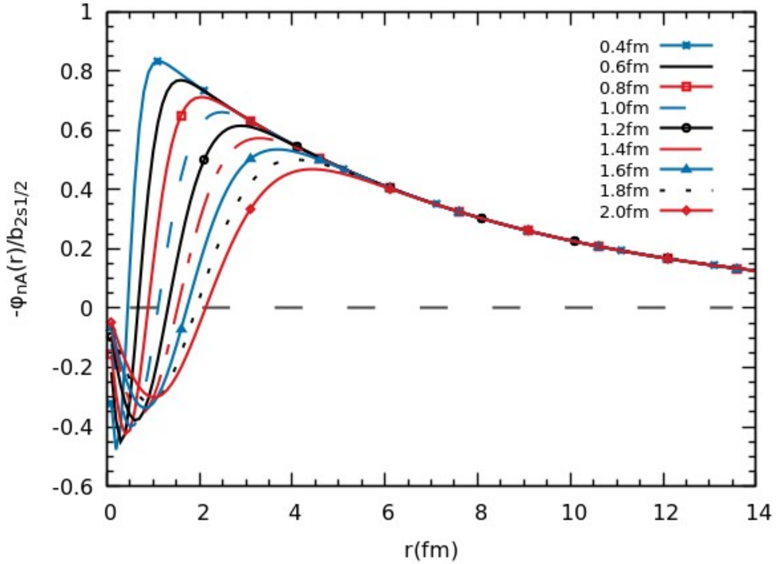
$$V(r) = -V_0 \cdot \exp\frac{-r^2}{2r_0^2}$$

	r_0 (fm)	V_0 (MeV)	$b_{2s1/2}$
V1	0.4	1314.6	**0.601**
V2	0.6	592.3	**0.632**
V3	0.8	337.8	**0.664**
V4	1.0	219.2	**0.697**
V5	1.2	154.4	**0.732**
V6	1.4	115.1	**0.769**
V7	1.6	89.3	**0.807**
V8	1.8	71.6	**0.846**
V9	2.0	58.8	**0.888**



Scaling by b_{nlj}

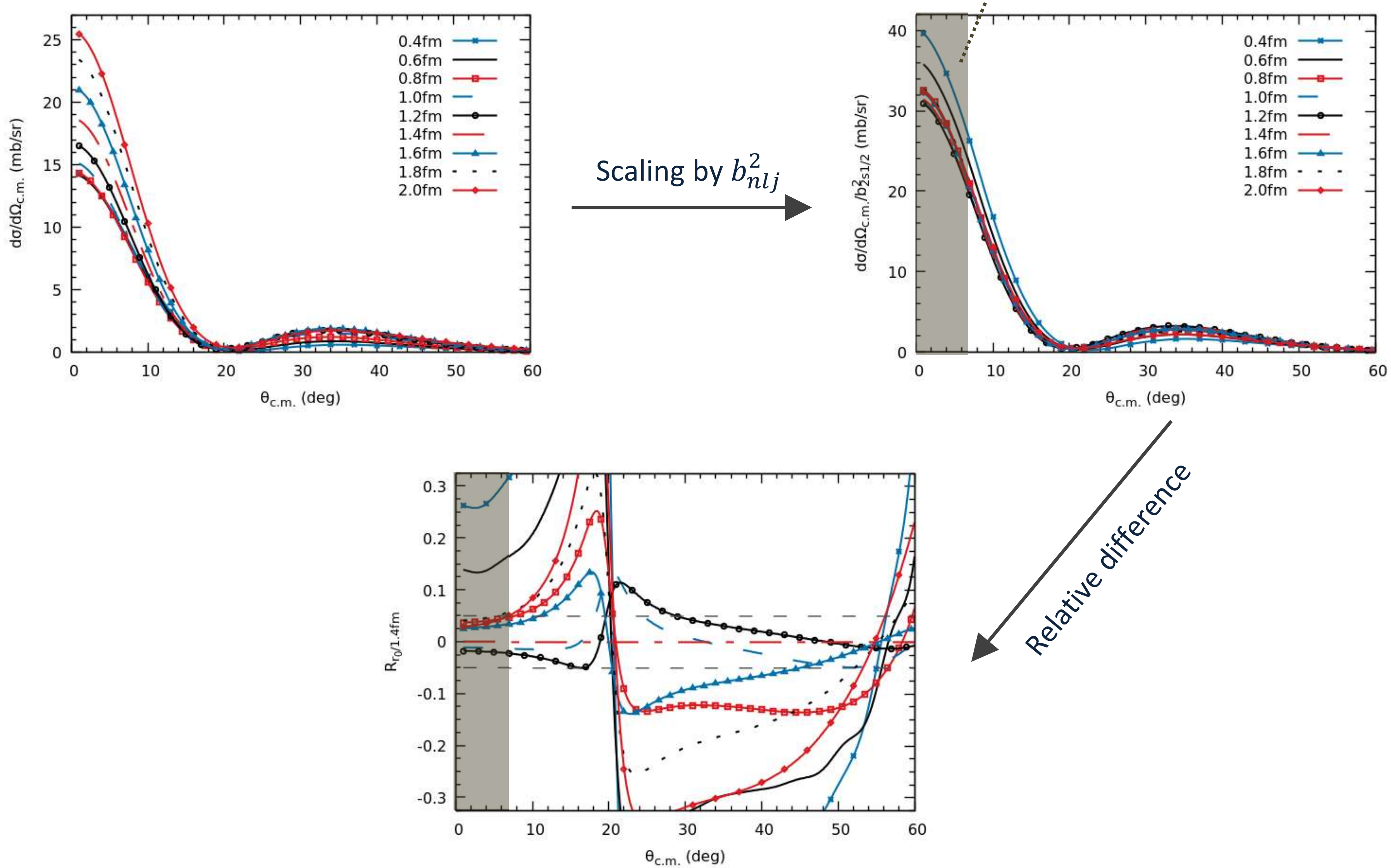
$-\varphi(r)$



Calculation of $^{10}Be(d,p)^{11}Be$ (g.s)

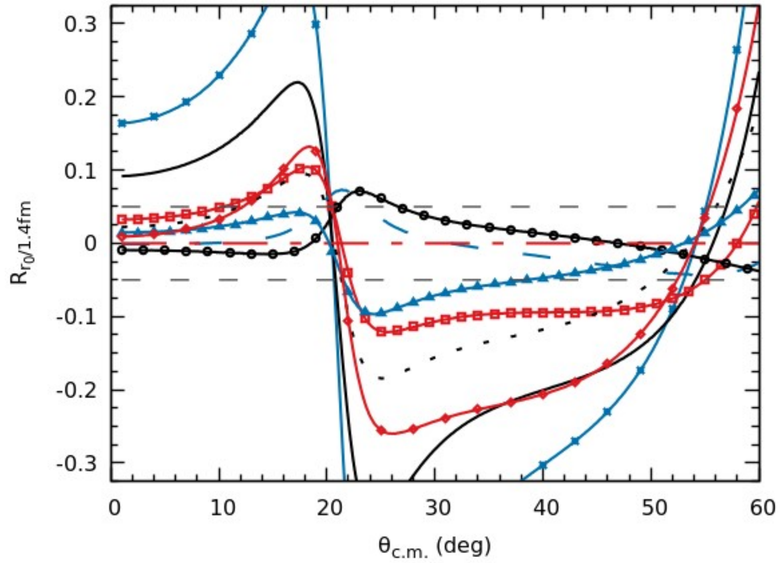
- E_d = 21.4MeV

Peripheral part: 0-7deg except 0.4, 0.6fm



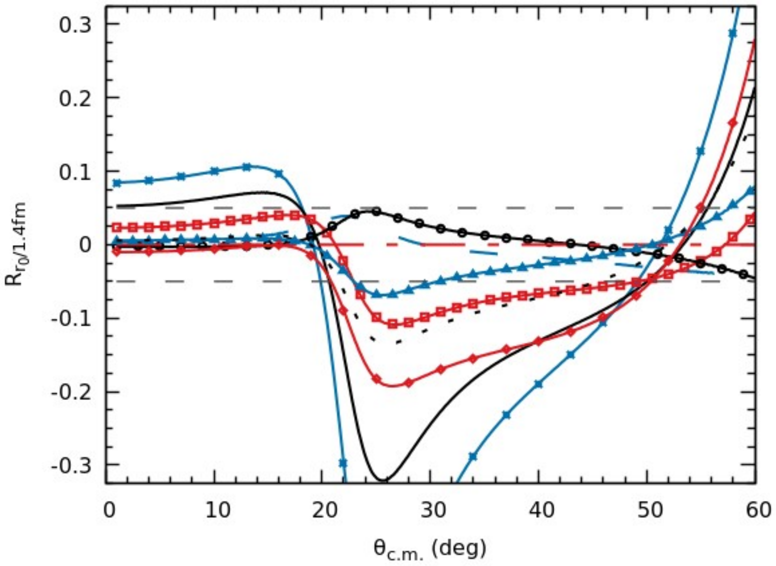
Calculation of $^{10}Be(d,p)^{11}Be$ (g.s)

- **E_d = 18MeV**



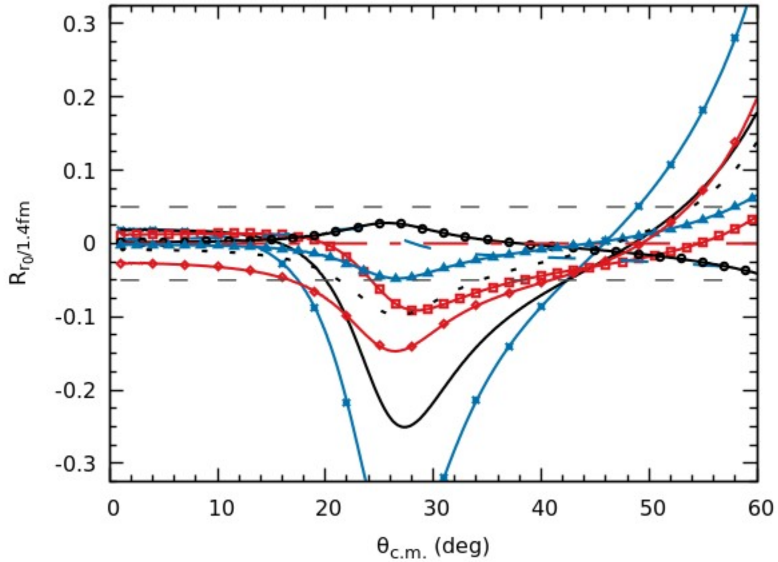
Calculation of $^{10}Be(d,p)^{11}Be$ (g.s)

- **E_d = 15MeV**



Calculation of $^{10}Be(d,p)^{11}Be$ (g.s)

- **E_d = 12MeV**



Lowering the energy, the reaction becomes more and more peripheral, mostly at forward angles.

ANC extraction from peripheral part

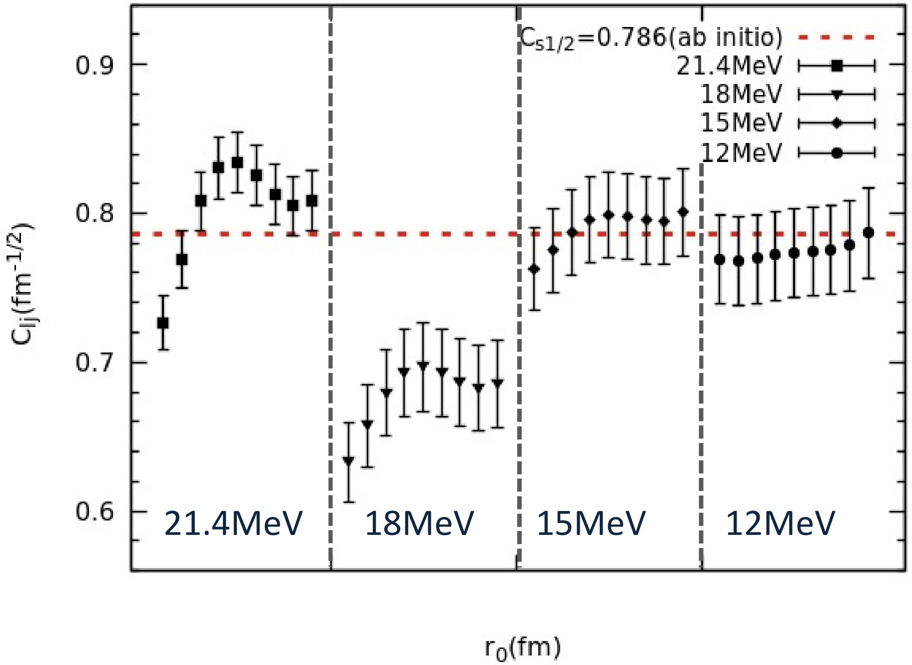
- **Extract the ANCs with the experimental data at peripheral part**

χ^2 analysis

$$\chi^2 = \sum_i \frac{\left(C_{lj}^2 \cdot (\frac{d\sigma}{d\Omega})_i^{th} / b_{nlj}^2 - (\frac{d\sigma}{d\Omega})_i^{exp}\right)^2}{\delta_i^2}$$

i represent all the data points in the peripheral region

C_{lj} is the ANC obtained by minimizing the χ^2



Conclusion

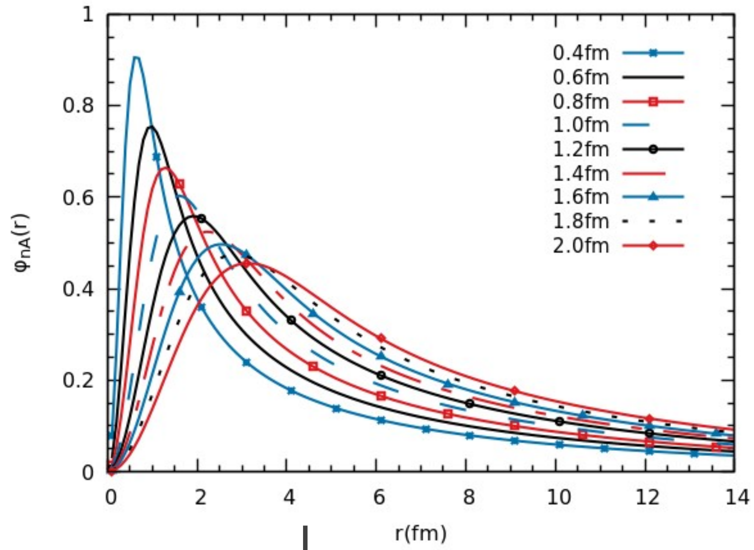
- The peripheral area of this transfer reaction is always found at forward angles;
- When the incident energy decreases, the scaling by b_{nlj}^2 works better which means the reaction exhibits a more pronounced peripheral property;
- The ANC obtained for the g.s of ^{11}Be (C_{lj}=$0.785^{+0.029}_{-0.030}$fm$^{-1/2}$) shows perfect agreement with the one given by ab initio calculations (0.786 fm$^{-1/2}$).

Ref: PRL 117, 242501 (2016)

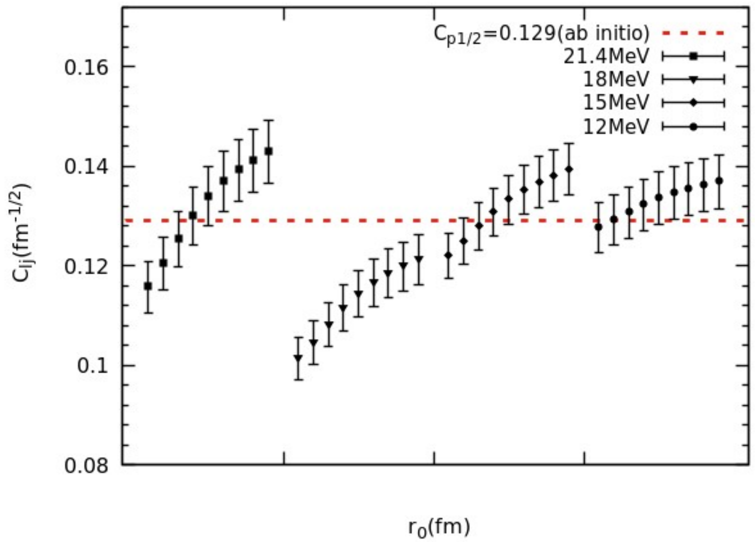
Calculation of $^{10}Be(d,p)^{11}Be$ (ex.s)

- **Description of n-^{10}Be: 1p1/2 $\otimes$ ^{10}Be(0+)**
  - Similar method used to study the excited state of ^{11}Be

	r_0 (fm)	V_0 (MeV)	$b_{1p1/2}$
V1	0.4	869.4	**0.068**
V2	0.6	387.3	**0.085**
V3	0.8	218.4	**0.100**
V4	1.0	140.2	**0.114**
V5	1.2	97.7	**0.127**
V6	1.4	72.1	**0.140**
V7	1.6	55.4	**0.152**
V8	1.8	44.0	**0.165**
V9	2.0	35.8	**0.177**



ANC extracted

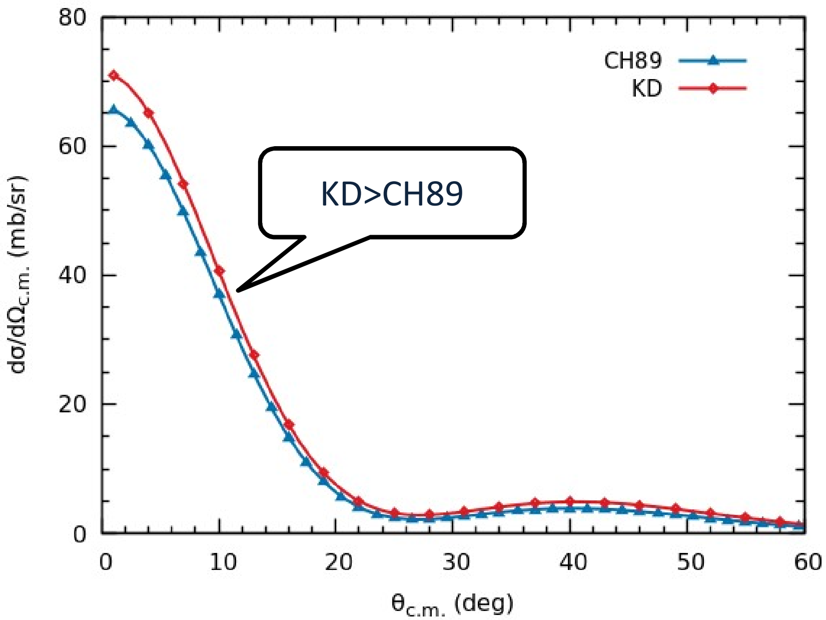


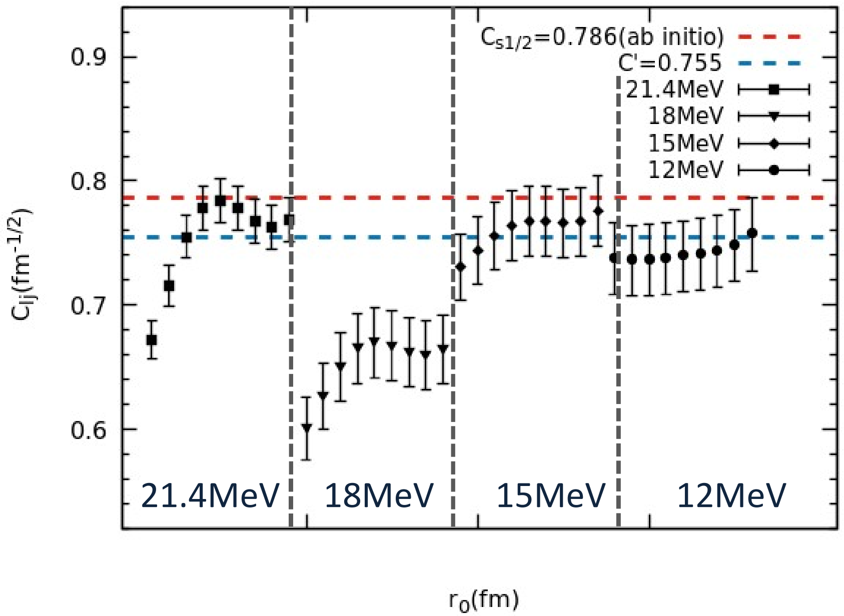
  - The ANC obtained for the ex.s of ^{11}Be is $0.136^{+0.005}_{-0.005}\mathrm{fm}^{-1/2}$ while the ab initio method gives $0.129\mathrm{fm}^{-1/2}$.

ANC extraction from peripheral part

- **Optical potentials for the entrance channel d-^{10}Be**
  a. Johnson & Tandy (CH89) pot
  b. Johnson & Tandy (KD) pot

A example at 12MeV





Conclusion

- ANC extraction is sensitive to the optical potential choice.

Transfer to the first resonance of ^{11}Be

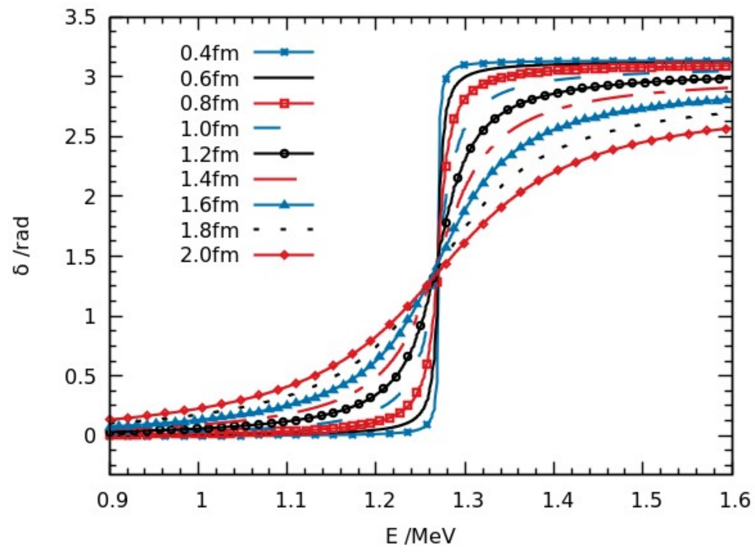
- **Description of n-^{10}Be: 1d5/2 ⊗ ^{10}Be(0+)**
  - Bin description for the overlap function

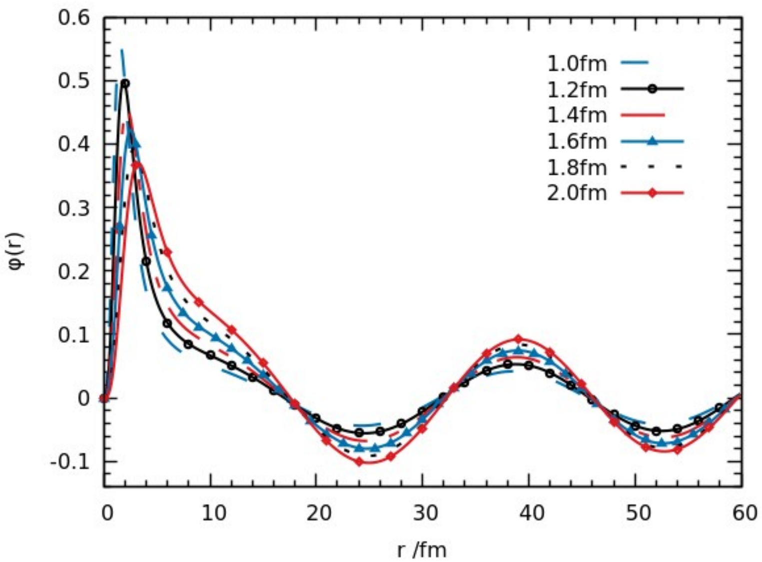
$$\phi(r)=\sqrt{\frac{2}{\pi N_p}}\int_{k_{p-1}}^{k_p} g_p(k)u_k(r)dk$$

  - Relation with ANC **(PRC 59.6 (1999): 3418)**

$$C_{lj}^2 \propto \Gamma$$

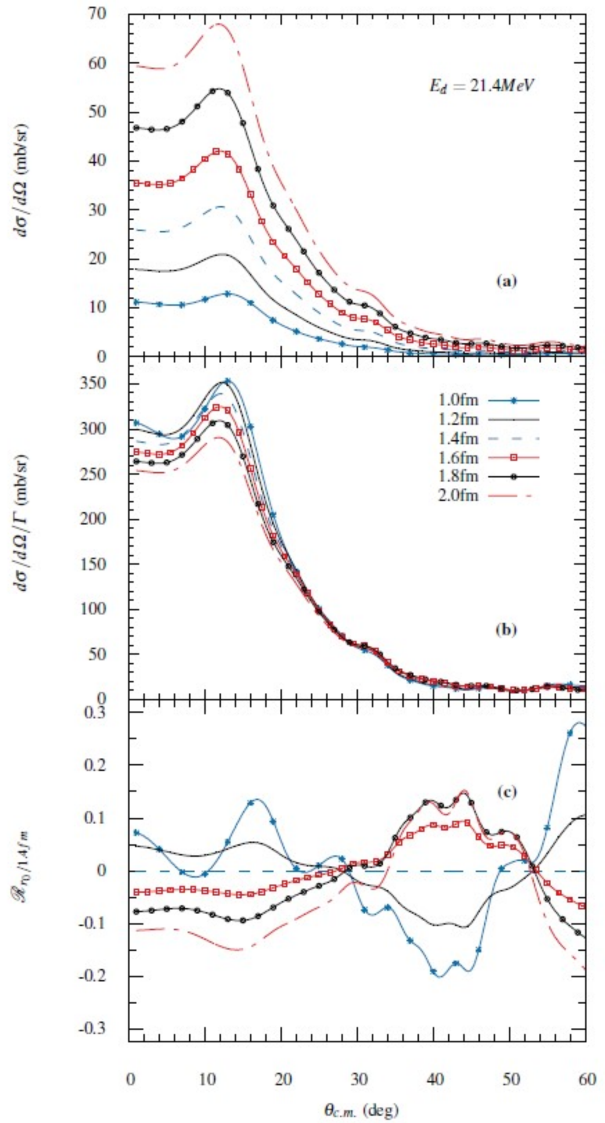
	r_0 (fm)	V_0 (MeV)	Γ(MeV)
V1	1.0	303.86	**0.0364**
V2	1.2	209.29	**0.0595**
V3	1.4	152.22	**0.0904**
V4	1.6	115.14	**0.1294**
V5	1.8	89.67	**0.1771**
V6	2.0	71.42	**0.2340**

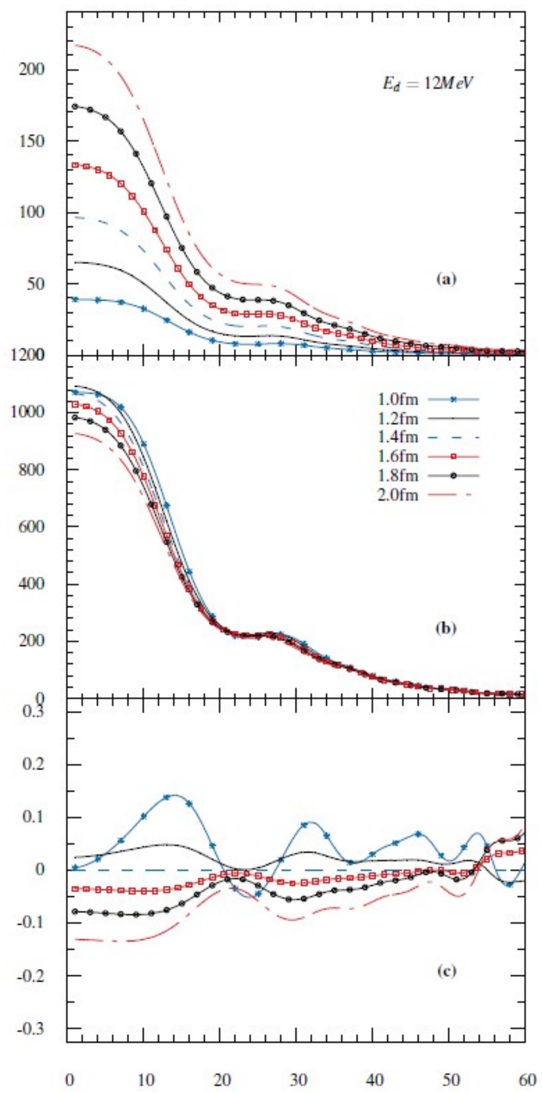




Variation with different energies

- **Transfer to the first resonance of ^{11}Be**





Conclusion and prospects

Conclusion

- Brief review of the theoretical framework of transfer reaction
- ADWA calculation performed for ^{10}Be(d,p)^{11}Be
- Spectroscopic study of this reaction
  - Influence of the description of n-^{10}Be bound state
  - ANC extraction from the peripheral part
- Investigation at lower energies and forward angles for transfer reaction can ensure us the peripherality of the reaction and is the best way to obtain a reliable ANC from experimental data
  - When the incident energy decreases, the scaling by b_{nlj}^2 works better
  - The peripheral area of this transfer reaction is always found at forward angles
- The role of the γ width in the resonance can be analogous to the effect of the square of the ANC on bound states.

Thanks for your attention!