Coupling Halo EFT to reaction models: a testcase study on ^{15}C for transfer, breakup and radiative-capture

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Outline

Introduction

Halo-EFT and transfer
- Effective interaction
- Conditions for ANC determination
- Halo-EFT ^{14}C+n interactions at NLO

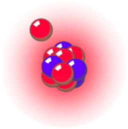
Coulomb breakup of ^{15}C on Pb
- Reaction model
- Results

Radiative capture

Conclusions

Halo nuclei

Exotic nuclear structure far from stability



One-neutron halo

$^{11}\mathrm{Be} = {}^{10}\mathrm{Be} + \mathrm{n}$

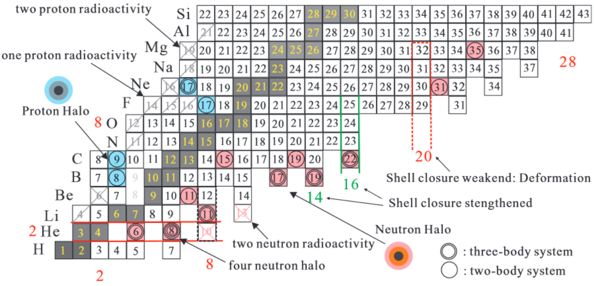
$^{15}\mathrm{C} = {}^{14}\mathrm{C} + \mathrm{n}$

Two-neutron halo

$^{6}\mathrm{He} = {}^{4}\mathrm{He} + \mathrm{n} + \mathrm{n}$

$^{11}\mathrm{Li} = {}^{9}\mathrm{He} + \mathrm{n} + \mathrm{n}$

- Light, n-rich nuclei
- Low S_n or S_{2n}
- Cluster structure: core + halo ⇒ exibit **large matter radius**
- $\tau_{1/2}(^{15}\mathrm{C}) = 2.4$ s ⇒ indirect techniques: **reactions**



Our goal

To provide good predictions for many reactions

- transfer
- breakup at intermediate and high energies
- radiative capture

using **one Halo-EFT model** of ^{15}C

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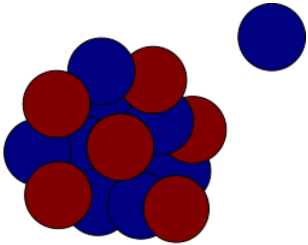
Description of ^{15}C structure



- ^{14}C core
  - structureless
  - in its ground state ($E_{e.s.}$ 6 MeV above $E_{g.s.}$)
- loosely bound neutron

$1/2^+$ $E_{g.s.} = -1.218$ MeV
$5/2^+$ $E_{e.s.} = -0.478$ MeV

$$H_0 = -\frac{\hbar^2}{2\mu_{^{14}Cn}}\Delta + V_{^{14}Cn}(\mathbf{r})$$

$\mu_{^{14}Cn} = m_{^{14}C} m_n / m_{^{15}C}$ reduced mass
$V_{^{14}Cn}$ effective potential simulating their interaction

Description of ^{15}C structure

$H_0\ \varphi_{n'lj}(E,\mathbf{r}) = E\ \varphi_{n'lj}(E,\mathbf{r})$ eigenvalues and eigenfunctions

$E_{n'lj} < 0 \rightarrow$ bound states, normed to unity,
asymptotical reduced radial wave function behaviour

$$u_{n'lj}(r) \underset{r\to\infty}{\longrightarrow} \mathcal{C}_{n'lj}\ e^{-k_{n'lj}r}$$

- $\hbar k_{n'lj} = \sqrt{2\mu_{^{14}Cn}|E_{n'lj}|}$
- $\mathcal{C}_{n'lj}$ single-particle asymptotic normalization constant ANC

◦ strength of the exponential bound-state wave function tail
◦ it depends on the geometry of the $V_{^{14}Cn}$ potential

Description of ^{15}C structure

$H_0 \; \varphi_{n' lj}(E,\mathbf{r}) = E \; \varphi_{n' lj}(E,\mathbf{r})$ **eigenvalues and eigenfunctions**

$E > 0 \rightarrow {}^{14}$C-$n$ continuum

reduced radial parts are normalized according to

$$u_{klj} \underset{r\rightarrow\infty}{\longrightarrow} sin(kr - l\frac{\pi}{2} + \delta_{lj})$$

- δ_{lj} phaseshift at energy E
- $\hbar k = \sqrt{2\mu_{^{14}Cn} E}$

Description of ^{15}C structure

The interaction to calculate $\varphi_{^{14}C\,n}$ is described by a phenomenological potential $V_{^{14}C\,n}$ within Halo-EFT model

Halo nucleus ⇒ clear separation of scales:

◦ small scale ↔ core radius ∼ 8 fm

◦ large scale ↔ halo range ∼ 16 fm

⇒ provides an expansion parameter *small scale/large scale* upon which the Hamiltonian is expanded

Hammer, Ji, Phillips JPG 44, 103002 (2017)

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We use narrow Gaussian potentials:

@LO $V_{^{14}Cn}(r) = V_0 e^{-\frac{r^2}{2r_0^2}}$

V_0 adjusted to fit binding energy (BE) in s wave ($V_{^{14}Cn} = 0\ \forall l > 0$)

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r_0 to evaluate the sensitivity to short-range physics

Extraction of ANC from transfer reactions

No direct measurement of ANC ⇒ we analyze a (d,p) reaction following work done for ^{11}Be by Yang and Capel PRC98,054602(2018)

They study the optimal experimental conditions that enable a safe ANC extraction

- low deuteron energy
- forward angles

⇒ **peripheral** process

Extraction of ANC from transfer reactions

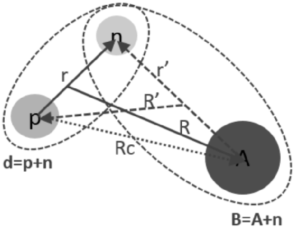
Two experiments satisfying the low energy condition

- $E_d = 14$ MeV University of Notre Dame
  Goss *et al.*, PRC12, 1730 (1975)
- $E_d = 17.06$ MeV Nuclear Physics Institute of the Czech Academy of Sciences
  Mukhamedzhanov *et al.*, PRC84, 024616 (2011)

The first one does not provide enough points at forward angles to constrain the ANC within a properly peripheral condition
$\Rightarrow$ we analyze the latter experiment

^{14}C$(d,p)^{15}$C transfer reaction

- Halo-EFT description of ^{15}C
- FR-ADWA: finite-range adiabatic distorted wave approximation model
  → one-step transition matrix between initial and final states, includes the breakup description
  Johnson and Tandy, NPA235, 56 (1974)
- transfer calculations performed using FRESCO



- Chappel-Hill global nucleons-nucleus potential
- Reid soft core potential for the deuteron bound state
- deuteron adiabatic potentials obtained with TWOFNR

How we proceed:

1. determination of different potentials $V_{^{14}Cn}$ @LO with different r_0
   $\Rightarrow$ adjusted on the ^{15}C bound state energy
   $\Rightarrow$ related to as many ANCs
2. calculation of different wave functions $\varphi_{^{14}Cn}$ describing the ^{15}C final state
3. with this input, computation of corresponding $\frac{d\sigma_{th}}{d\Omega}$
4. comparison with the experimental cross section
5. ^{15}C ANC extraction

1) Gaussian potentials @LO

with different widths r_0

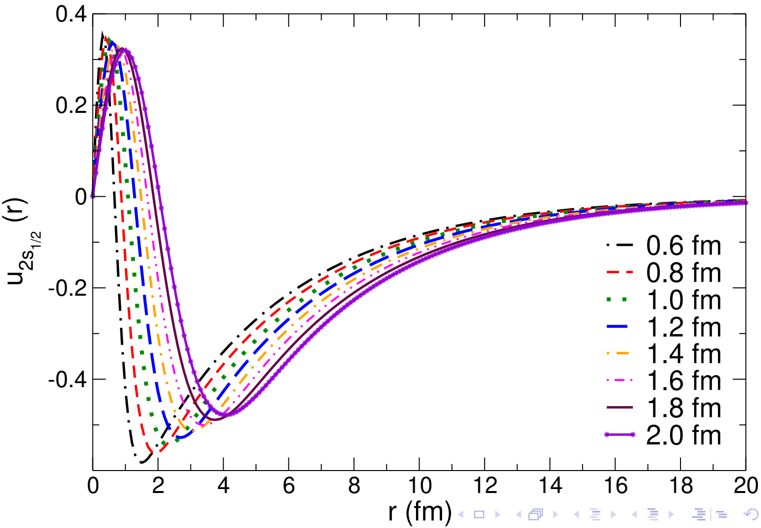
$$V_{^{14}C n}(r) = V_0 e^{-\frac{r^2}{2{r_0}^2}}$$

For each width r_0 the depth V_0 is adjusted to reproduce the **neutron binding energy**

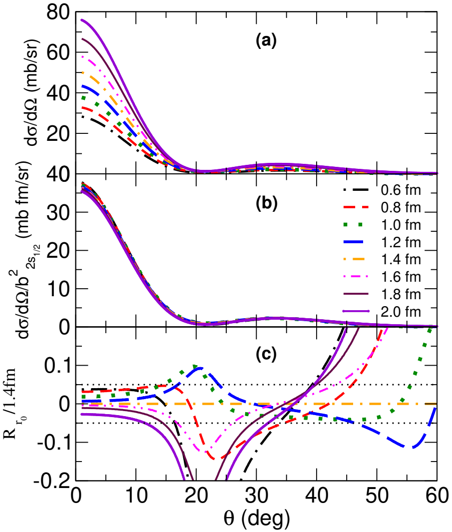
$\Rightarrow$ each one generates a WF with a corresponding **ANC**

2) The bound-state wave functions

obtained with the different potentials



3) Theoretical cross section

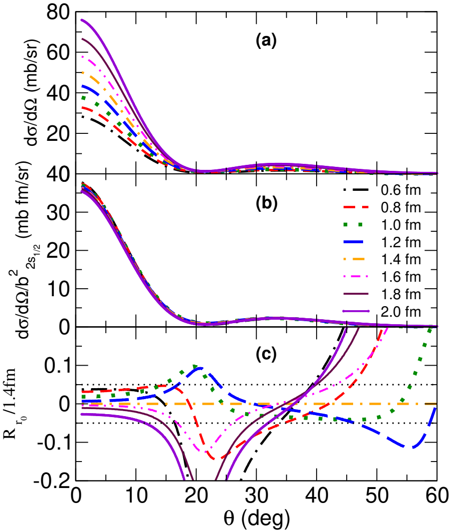


(a)

$d\sigma_{th}/d\Omega$

theoretical differential cross section for the transfer to the ^{15}C g.s.

3) Theoretical cross section

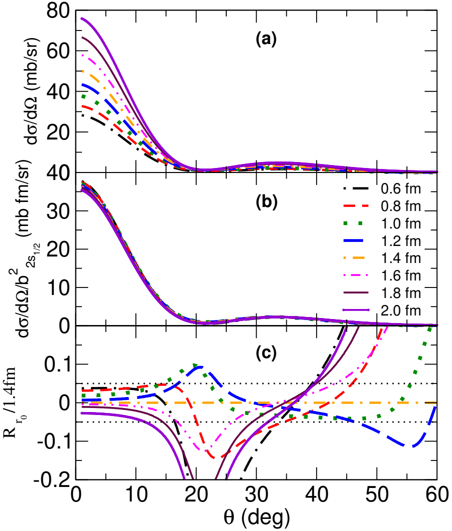


(b)

transfer cross section scaled by ANC^2

$\Rightarrow$ the spread in the results is significantly reduced at forward angle

3) Theoretical cross section



(c)

To determine the angular range of purely peripheral process

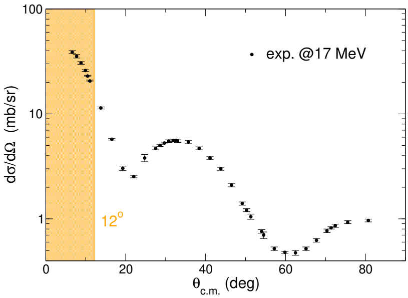
$$\mathcal{R}_{r_0/1.4fm}(\theta) = \left(\frac{ANC^{(1.4fm)}}{ANC^{(r_0)}}\right)^2 \frac{d\sigma_{th}^{(r_0)}/d\Omega}{d\sigma_{th}^{(1.4fm)}/d\Omega} - 1$$

5% difference

$\Rightarrow$ peripherality condition
$\theta < 12^\circ$

4) Comparison with data

We infer an ANC $\mathcal{C}^{(r_0)}_{1/2^+}$ for each potential width r_0 from a χ^2 analysis



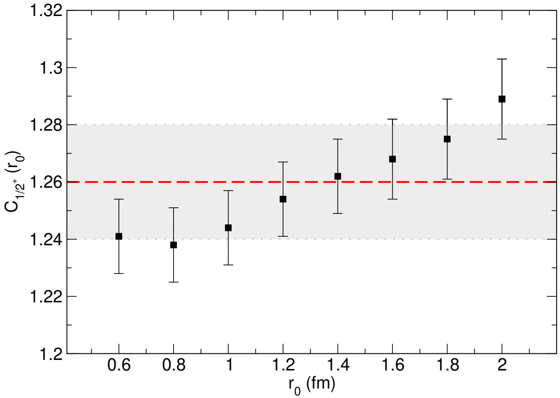
$$\chi^2_{r_0} = \sum_{i'} \frac{\left[\left(\frac{\mathcal{C}^{(r_0)}_{n'lj}}{b^{(r_0)}_{n'lj}}\right)^2 \frac{d\sigma^{(r_0)}_{th}}{d\Omega}\Big|_{i'} - \frac{d\sigma_{exp}}{d\Omega}\Big|_{i'}\right]^2}{(\delta_{exp}|_{i'})^2}$$

- $\delta_{exp}|_{i'}$ exp. uncertainty at $\theta_{i'}$
- sum limited to data i' $\theta < 12°$

5) ^{15}C ANC extraction

We obtain $\mathcal{C}_{1/2^+} = 1.26 \pm 0.02$ fm$^{-1/2}$ for g.s.

in analogous way for the e.s. $\mathcal{C}_{5/2^+} = 0.056 \pm 0.001$ fm$^{-1/2}$



error bars $\leftrightarrow$ uncertainty in χ^2 minimization

Halo-EFT ^{14}C+n interactions at NLO

Now we can adjust a NLO Halo-EFT Gaussian potential

$$V_{^{14}Cn}(r) = V_0 e^{-\frac{r^2}{2r_0^2}} + V_2 r^2 e^{-\frac{r^2}{2r_0^2}}$$

to our ANC final result and binding energy

Note that we do not have info for p wave → we assume it is small
as for ^{11}Be: Calci *et al.*, PRL117, 242501 (2016)

We provide

- two ^{14}C+n potentials for the ground state
  with $r_0 = 1.2$ and 1.5 fm
  to check sensibility on short-range physics

Halo-EFT ^{14}C+n interactions at NLO

...and beyond

Now we can adjust a NLO Halo-EFT Gaussian potential

$$V_{^{14}Cn}(r) = V_0 e^{-\frac{r^2}{2r_0^2}} + V_2 r^2 e^{-\frac{r^2}{2r_0^2}}$$

to our ANC final result and binding energy

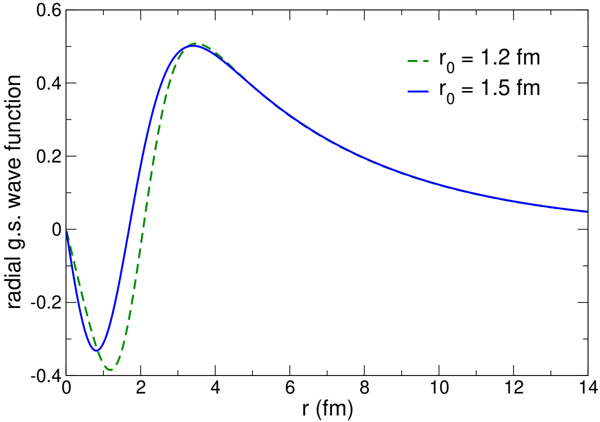
Note that we do not have info for p wave → we assume it is small as for ^{11}Be: Calci *et al.*, PRL117, 242501 (2016)

We provide

- two ^{14}C+n potentials for the ground state with $r_0 = 1.2$ and 1.5 fm to check sensibility on short-range physics
- one for the excited state (beyond NLO) with $r_0 = 1.5$ fm to understand if we should go to higher order than NLO

The wavefunctions

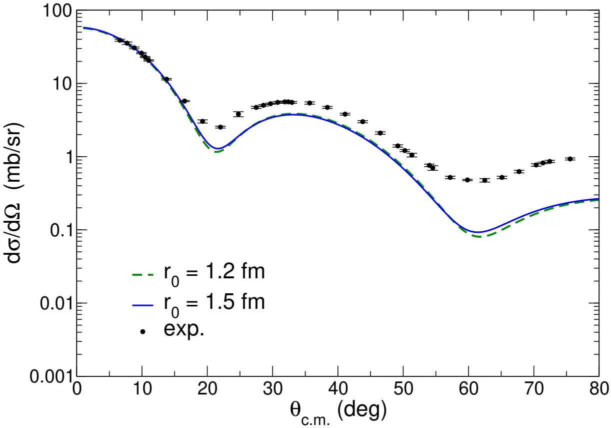
adjusted on our Halo-EFT potential



As expected: both WFs have the same tail

Transfer cross section

using the Halo-EFT potential



As expected: both WFs reproduce cross section for $\theta < 12^\circ$

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Coulomb breakup of ^{15}C on Pb

Experiments

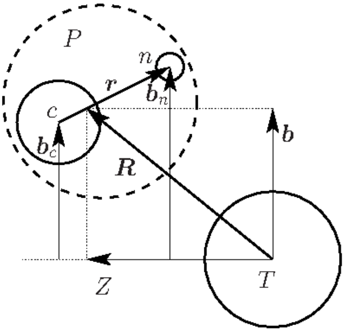
605 AMeV GSI experiment:
Datta Pramanik *et al.*, PLB551 (2003) 63

68 AMeV RIKEN measurment:
Nakamura *et al.*, PRC79 (2009) 035805

Coulomb breakup of ^{15}C on Pb

The initial conditions in the laboratory frame of reference (LAB)

The three-body reaction model applied to ^{11}Be in
Capel, Baye, Suzuki, PRC78 (2008) 054602
Moschini and Capel arXiv:1807.07537



- ^{208}Pb target T at rest
- projectile P described within the Halo-EFT model
- bombarding energies $E_{LAB} = 605$ and 68 AMeV
  - → P has constant velocity
  - → P follows a straight line

⇒ ideal conditions to apply the Eikonal model!

The Eikonal model

in the frame of reference of the P-T center of momentum (CM)

In the T-P CM system Klein-Gordon equation is

$$\left[(\hbar c)^2\nabla^2 + (\hbar c k)^2 - 2EV_{PT}\right]\Psi = 0$$

- $\hbar k$ is the relativistic momentum of P in CM
- $E = (M_P M_T c^2)/(M_P + M_T)$ reduced energy
- $M_P c^2$ and $M_T c^2$ are P and T total energies in the CM
- $M_P = \gamma_P m_P$ and $M_T = \gamma_T m_T$ are the relativistic masses

Satchler, *Nucl. Phys. A* **540** (1992) 533

The Eikonal model

in the frame of reference of the P-T center of momentum (CM)

Klein-Gordon equation reduces to a Schroedinger equation

$$\left[-\frac{\hbar^2}{2\mu}\nabla^2 + V(\mathbf{R},\mathbf{r})\right]\Psi(\mathbf{R},\mathbf{r}) = E_{CM}\Psi(\mathbf{R},\mathbf{r})$$

for the scattering of two nuclei of masses M_P and M_T
and a CM kinetic energy $E_{CM} = (\hbar k)^2/2\mu$
where $\mu = E/c^2 = M_P M_T/(M_P + M_T)$
plays the role of reduced mass

$\Rightarrow$ one can solve the usual nonrelativistic model
provided one uses these kinematics prescriptions

P is initially bound in its ground state $\Phi_{l_0 j_0 m_0}$ of energy E_0

Satchler, *Nucl. Phys. A* **540** (1992) 533

The Eikonal approximations

Adiabatic approximation: the collision occurs in a very brief time and the internal P coordinates are frozen during reaction

○ no core excitation

Eikonal approximation: the wavefunction is factorized as

$$\Psi(\mathbf{b}, z, \mathbf{r}) = e^{ikz}\hat{\Psi}(\mathbf{b}, z, \mathbf{r})$$

since $\hat{\Psi}$ is expected to vary weakly in **R**
→ we assume ∇^2 negligible with respect to $\frac{\partial}{\partial z}$

$$i\hbar v \frac{\partial}{\partial_z}\hat{\Psi}(\mathbf{b}, z, \mathbf{r}) = V_{PT}(\mathbf{R}, \mathbf{r})\hat{\Psi}(\mathbf{b}, z, \mathbf{r})$$

$v = \hbar k/\mu$ relative P-T velocity

The solution for a one-neutron halo nucleus

So we obtain the Eikonal expression

$$\hat{\Psi}(\mathbf{b}, z, \mathbf{r}) = e^{i\chi(\mathbf{b},\mathbf{s})}\Phi_{l_0 j_0 m_0}(E_0, \mathbf{r})$$

where the Eikonal phase could be divided
into its nuclear and Coulomb contributions:

$$\chi(\mathbf{b}, \mathbf{s}) = \chi^N(\mathbf{b}, \mathbf{s}) + \chi^C(\mathbf{b}, \mathbf{s}) + \chi^C_{PT}(b)$$

The nuclear phase

The nuclear interaction is usually calculated using optical potentials

$$\chi^N = -\frac{1}{\hbar v}\int_{-\infty}^{z} V_{CT}(\mathbf{b}, z', \mathbf{r}) + V_{fT}(\mathbf{b}, z', \mathbf{r}) dz'$$

At higher energies
it is difficult to find data to fit optical potentials
expecially for radioactive nuclei!

The nuclear phase

We apply the optical limit approximation of Glauber theory

$$\chi^N_{OLA}(\mathbf{b}) = i \int\int \rho_T(\mathbf{r'})\rho_X(\mathbf{r''})\Gamma_{NN}(\mathbf{b}-\mathbf{s'}+\mathbf{s''})d\mathbf{r''}\,d\mathbf{r'}$$

- $\rho(\mathbf{r})$ is neutron or proton Fermi density
- $\Gamma_{NN}(\mathbf{b}) = \frac{1-i\alpha_{NN}}{4\pi\beta_{NN}}\sigma^{tot}_{NN}e^{-\frac{b^2}{2\beta_{NN}}}$ is a profile function that correspond to effective nucleon-nucleon interaction
  - σ^{tot}_{NN} total cross section for the NN collision
  - α_{NN} ratio of real to imag. part of the NN-scattering amplitude
  - β_{NN} slope of NN elastic differential cross section

Horiuchi, Suzuki, Capel and Baye, PRC **81** (2010)

The Coulomb phases

- Rutherford scattering between the P center-of-mass and the T

$$\chi_{PT}^{C} = 2\eta \ln(kb)$$

- Coulomb tidal force

$$\chi^{C} = -\eta \int_{-\infty}^{\infty} \left(\frac{1}{|\mathbf{R} - \frac{m_f}{m_P}\mathbf{r}|} - \frac{1}{R} \right) dz$$

The Coulomb phases

- Rutherford scattering between the P center-of-mass and the T

$$\chi^C_{PT} = 2\eta \ln(kb)$$

- Coulomb tidal force

$$\chi^C = \eta \ln\left(1 - 2\frac{m_f}{m_P}\frac{\mathbf{b}\cdot\mathbf{s}}{b} + \frac{m_f^2}{m_P^2}\frac{s^2}{b^2}\right)$$

$\rightarrow$ Divergence due to the slow decrease of χ^C in b
$e^{i\chi^C} = 1 + i\chi^C - \frac{1}{2}(\chi^C)^2 + ...$

The Coulomb phases

- Rutherford scattering between the P center-of-mass and the T

$$\chi^C_{PT} \sim 2\eta \ln\left(\frac{b}{2z_{max}}\right)$$

- Coulomb tidal force: $\Rightarrow$ we make the replacement

$$e^{i\chi} = e^{i\chi^N}(e^{i\chi^C} - i\chi^C + i\chi^{FO})e^{i\chi^C_{PT}}$$

first order term of the perturbation theory

$$\chi^{FO} = -\eta \int_{-\infty}^{\infty} e^{i\omega z/v} \left(\frac{1}{|\mathbf{R} - \frac{m_f}{m_P}\mathbf{r}|} - \frac{1}{R}\right) dz$$

where $\omega = (E - E_0)/\hbar$, and E C-f relative energy after dissociation

Margueron, Bonaccorso and Brink, *Nucl. Phys. A* **720** (2003)

Changing frame of reference

from the P-T CM frame to P rest frame

Dynamics is Lorentz invariant $\Leftrightarrow$ $V_{PT(\mathbf{b},z,\mathbf{r})}$ is Lorentz invariant

$\Rightarrow$ it should transform as the time-like component of a Lorentz four-vector

$$V_{PT(\mathbf{b},z,\mathbf{r})} \rightarrow \gamma V_{PT(\mathbf{b},\gamma z,\mathbf{r})}$$

where $\gamma = \left(1 - w^2/c^2\right)^{-1/2}$
and w the P velocity in P-T CM frame

This transformation is

- well established for electromagnetic field
- a conjecture for the nuclear interaction

Winther and Alder, *Nucl. Phys. A* **319** (1979)
Bertulani, *Phys. Rev. Lett.* **94** (2005)
Ogata and Bertulani, *Progr. Theor. Phys.* **123** (2010)

Changing frame of reference

from the P-T CM frame to P rest frame

Let's apply the Lorentz boost:

- Nuclear phase χ^N and Coulomb phases χ^C_{PT} and χ^C are already Lorentz invariant in our model:
  no changes under the transformation $V(z) = \gamma V(\gamma z)$
- The phase χ^{FO} is not Lorentz invariant:
  $\chi^{FO} = -\eta \int_{-\infty}^{\infty} e^{i\omega z/\gamma v} \left(\frac{1}{|\mathbf{R} - \frac{m_f}{m_P}\mathbf{r}|} - \frac{1}{R} \right) dz$

  consistent with Winther and Alder's
  relativistic Coulomb excitation result

The breakup cross section

So the breakup amplitude is

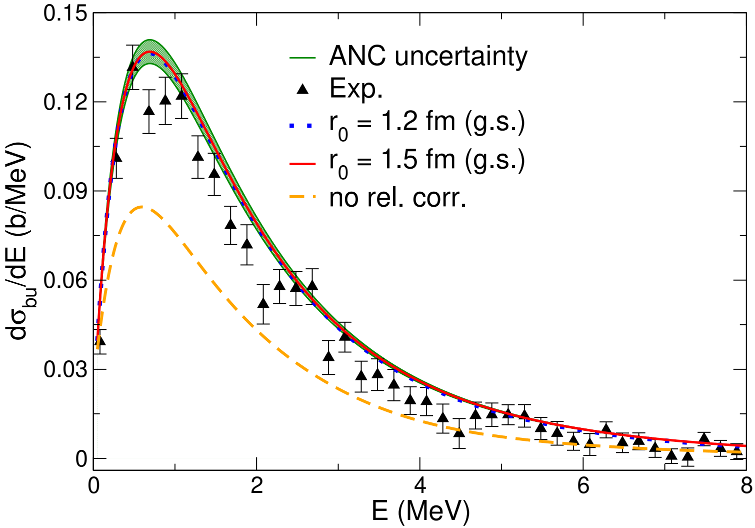
$$S^{m_0}_{kljm}(b) \sim \langle \varphi_{ljm}(E) | e^{i\chi^N} (e^{i\chi^C} - i\chi^C + i\chi^{FO}) e^{i\chi^C_{PT}} | \varphi_{l_0 j_0 m_0}(E_0) \rangle$$

Breakup cross section
as a function of C-f relative energy E after dissociation

$$\frac{d\sigma_{bu}}{dE} = \frac{4\mu_{cf}}{\hbar^2 K} \frac{1}{2j_0+1} \sum_{m_0} \sum_{ljm} \int_0^\infty bdb |S^{m_0}_{kljm}(b)|^2$$

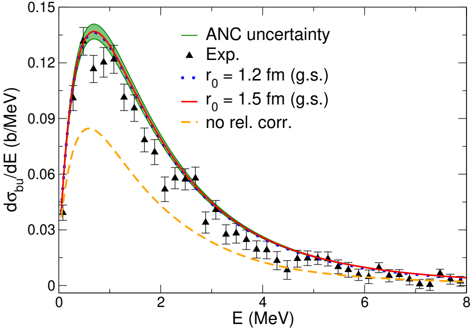
where μ_{cf} and K
are C-f reduced mass and momentum in P rest frame
no relativistic effects considered here
^{15}C wavefunctions obtained with Halo-EFT @NLO

Coulomb breakup of ^{15}C on Pb at 605 AMeV



Coulomb breakup of ^{15}C on Pb at 605 AMeV

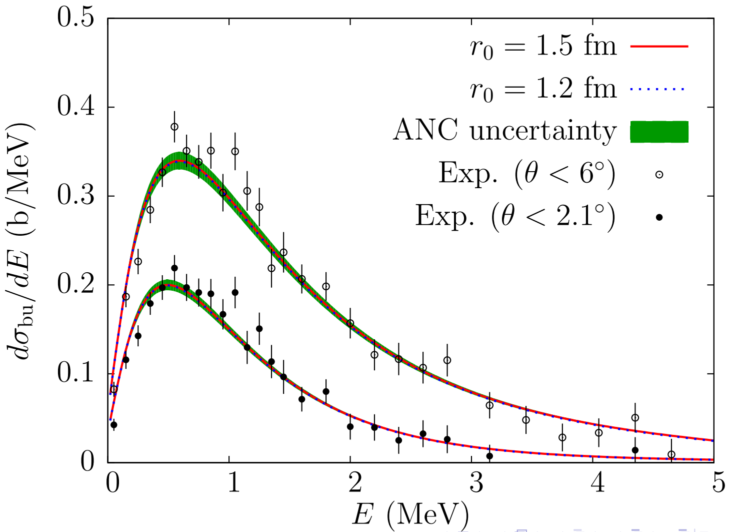
- relativistic corrections are important
- full calc. in good agreement with data



- band related to ANC uncertainty
- the reaction does not depend on WF inner part $r_0 = 1.2\text{fm} \sim r_0 = 1.5\text{fm}$
- no effect for the e.s. inclusion

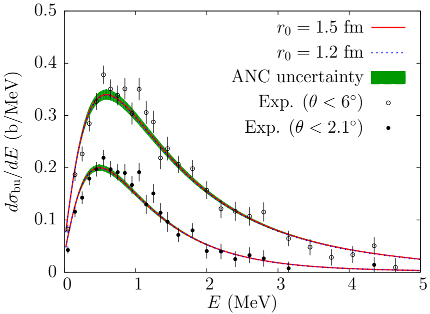
$\Rightarrow$ for this reaction model of Coulomb breakup the Halo-EFT expansion works fine at NLO

Coulomb breakup of ^{15}C on Pb at 68 AMeV



Coulomb breakup of ^{15}C on Pb at 68 AMeV

- excellent agreement with the data at all angles



- band related to ANC uncertainty
- the reaction does not depend on WF inner part $r_0 = 1.2\text{fm} \sim r_0 = 1.5\text{fm}$
- the result obtained taking into account the ^{15}C e.s. is barely different from the others

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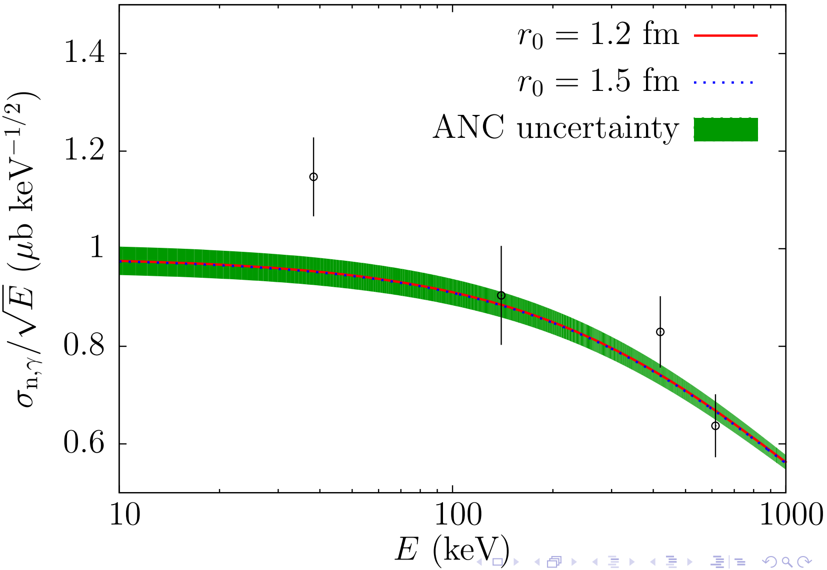
Radiative capture model ^{14}C$(n,\gamma)^{15}$C

^{14}C and n merge to form ^{15}C by emitting a photon
$\Rightarrow$ electromagnetic transition
from ^{15}C continuum (E) to one of its bound states $(E_{n_0 l_0})$

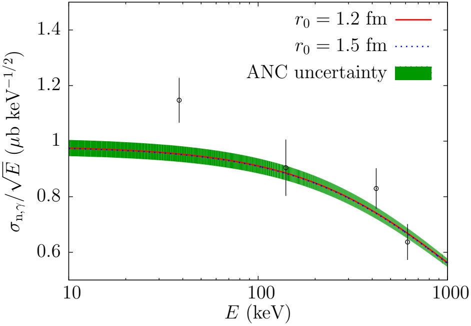
$$\sigma_{n_0 l_0}(E) \sim \sum_{\lambda\sigma} \mathcal{A}_\lambda \sum_l \frac{2l_0+1}{2l+1} |\langle \varphi_{n_0 l_0}(E_{n_0 l_0}) || \mathcal{M}^{\sigma\lambda} || \varphi_l(E)\rangle|^2$$

$\hbar k_\gamma c = E - E_{n_0 l_0}$ photon energy
dominant term is $\sigma\lambda = \text{E1} \Rightarrow \mathcal{M}^{E1}_\mu = e\frac{Z_{^{14}C}}{A_{^{14}C}+1} r Y^{(1)}_\mu(\Omega)$
Capel and Nollet, PRC96, 015801 (2017)

Experiment: Reifarth *et al.*, PRC77 (2008) 015804


$r_0 = 1.2$ fm
$r_0 = 1.5$ fm
ANC uncertainty
1.4
1.2
1
0.8
0.6
$\sigma_{n,\gamma}/\sqrt{E}$ (μb keV$^{-1/2}$)
10
100
1000
E (keV)

Experimentally they cannot distinguish between the capture to g.s. and e.s. so we include our potential beyond NLO for e.s.



- fine agreement with data
- band related to ANC uncertainty
- cross section does not depend on wave function inner part
- Problem at low energy:
  - experimental problem?
  - new physics?

⇒ more research on this point is needed!

Outline

Introduction

Halo-EFT and transfer
- Effective interaction
- Conditions for ANC determination
- Halo-EFT ^{14}C+n interactions at NLO

Coulomb breakup of ^{15}C on Pb
- Reaction model
- Results

Radiative capture

Conclusions

Conclusions

We have developed **one Halo-EFT** description of ^{15}C adjusted on

- binding energy $\rightarrow$ known from experiment
- ANC $\rightarrow$ "measured" analysing transfer reaction

and we have **reproduced data** for **different reactions**
transfer, radiative capture,
and breakup (at intermediate and high energy)

In particular:
◦ Halo-EFT description works well @NLO
◦ using the r_0 parameter we can test short-range physics
which results to be important in transfer processes at high angles

In the future...

Navrátil and collaborators are working on
ab initio calculations on ^{15}C
this could help us to
◦ have some info to constrain the interaction in p wave
◦ check our ANC result: $\mathcal{C}_{1/2^+} = 1.26 \pm 0.02$ fm$^{-1/2}$

We would also like to study other reactions involving ^{8}B:

- ^{8}B breakup
- ^{7}Be(p,γ)^{8}B radiative capture

Thank you for your attention!

Appendix

Satchler kinematical presctiptions

In the T-P CM system Klein-Gordon equation is

$$\left[(\hbar c)^2\nabla^2 + (\hbar c k)^2 - 2EV_{PT}\right]\Psi = 0$$

- $\hbar k$ is the relativistically correct CM momentum of P
- $E = (M_P M_T c^2)/(M_P + M_T) \rightarrow$ reduced energy function of P and T total energies in the CM frame: $M_P c^2$ and $M_T c^2$
- $M_P = \gamma_P m_P$ is the corrected projectile mass
  - $\gamma_P = \frac{x+\gamma_L}{\sqrt{1+x^2+2x\gamma_L}}, \quad x = m_P/m_T, \quad \gamma_L = 1 + (E_{LAB}/m_P c^2)$
  - E_{LAB} is the projectile bombarding energy in the LAB system
- same for M_T
- $\mu = E/c^2 = M_P M_T/(M_P + M_T) \rightarrow$ reduced "mass"
- $\Rightarrow k = \frac{m_P c}{\hbar}\sqrt{\gamma_P^2 - 1}$

Why ^{15}C is an interesting nucleus?

^{15}C has astrophysical interest

- the radiative capture ^{14}C$(n,\gamma)^{15}$C
  is part of the neutron-induced CNO cycle
  in the helium-burning shell of light AGB stars
- ^{15}C plays a role in the primordial nucleosynthesis
  of intermediate-mass elements

Wiescher, Görres, Schatz, *J. Phys. G* **25**, R133 (1999)
Kajino, Mathews, Fuller, *Astrophys. J.* **364**, 7 (1990)

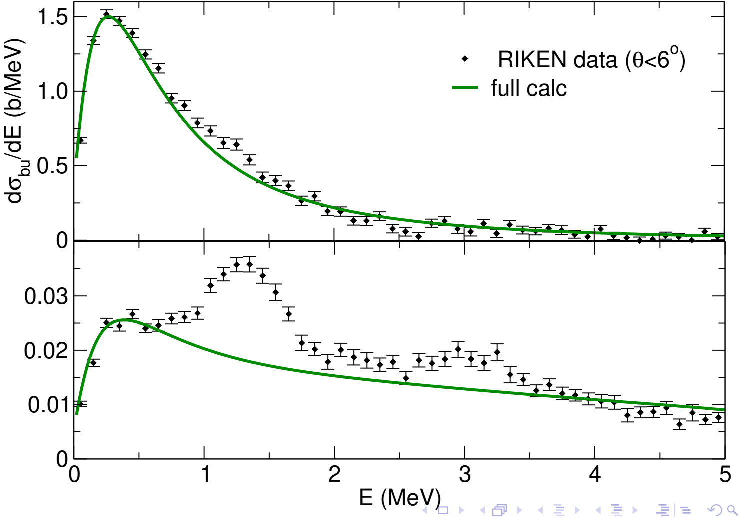
Comparison with ^{15}C ANC in literature

We obtain $\mathcal{C}_{1/2^+} = 1.26 \pm 0.02$ fm$^{-1/2}$
in analogous way for the e.s. $\mathcal{C}_{5/2^+} = 0.056 \pm 0.001$ fm$^{-1/2}$

ANC^2 (fm^{-1})	reference
1.48 $\pm$ 0.18	Trache *et al.* Tex. A&M Cycl. Prog. Rep. 1 (2002) 16
1.89 $\pm$ 0.11	Timofeyuk *et al.* PRL96 (2006) 162501
2.14	Pang *et al.* PRC75 (2007) 024601
1.74 $\pm$ 0.11	Summers and Nunes PRC78 (2008) 069908
1.64 $\pm$ 0.26	Mukhamedzhanov *et al.* PRC84 (2011) 024616
1.88 $\pm$ 0.18	McCleskey *et al.* PRC89 (2014) 044605
1.59 $\pm$ 0.03	this work

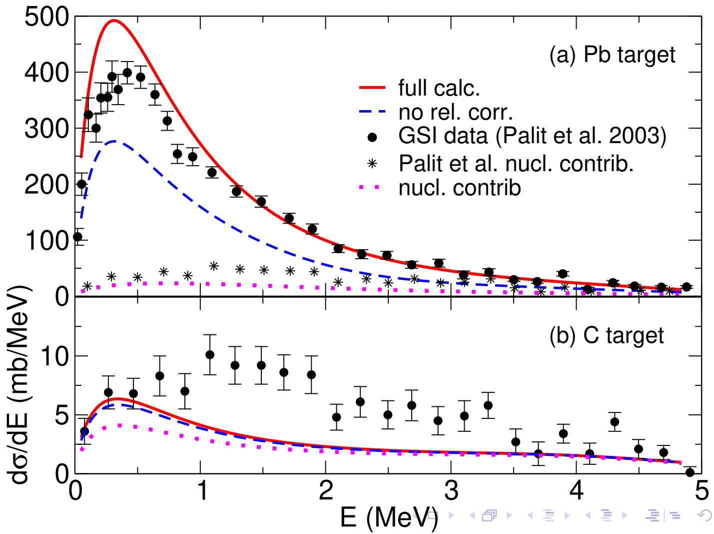
^{11}Be model tested at RIKEN

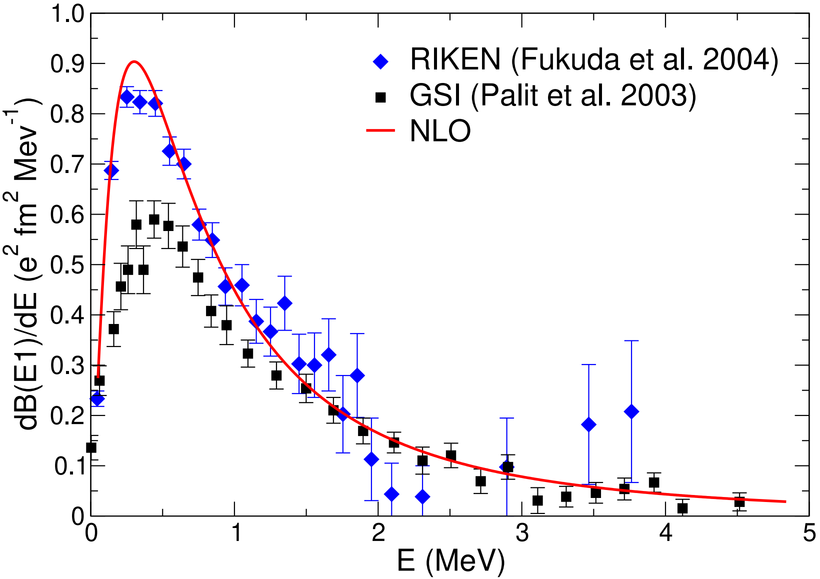
^{11}Be+^{208}Pb @ 69 AMeV and ^{11}Be+^{12}C @ 67 AMeV



^{11}Be model tested at GSI energy

^{11}Be+^{208}Pb and ^{11}Be+^{12}C @ 520 AMeV




RIKEN (Fukuda et al. 2004)
GSI (Palit et al. 2003)
NLO
dB(E1)/dE (e² fm² Mev⁻¹)
E (MeV)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
1
2
3
4
5

What's the reason for the discrepancy?

Both cross sections can be reproduced using one structure model
(and hence one E1 strength)
$\Rightarrow$ the discrepancy between RIKEN and GSI estimates
is most likely due to differences in the data analysis

- **GSI analysis**
  - proper treatment of relativity
  - Coulomb contribution evaluated by subtracting
  a nuclear contribution estimate
  extrapolated from the breakup on C
  from the total breakup cross section on Pb
  $\Rightarrow$ Coulomb and nuclear contributions interferences neglected!
  Typel and Shyam, PRC**64** (2001) 024605
- **RIKEN analysis** is less sensitive to this issue
  because it focuses on a measurement at forward angles
  where the nuclear contribution is negligibly small