From the Coulomb breakup of halo nuclei to neutron radiative capture

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Radiative capture

Radiative capture : reaction in which two nuclei fuse by emitting a γ :

$$b + c \rightarrow a + \gamma \quad \text{also noted} \quad c(b,\gamma)a$$

Most of the nuclear reactions in stars are radiative captures :

- d(p,γ)^{3}He or ^{3}He(α,γ)^{7}Be in the pp chain — V. Mossa
- (n,γ) reactions in the s and r processes,... — D. Atanasov

To constrain stellar models, cross sections must be measured at astrophysical (i.e. low) energy

Such measurements are very difficult

⇒ go deep underground to reduce background (cf. LUNA project)

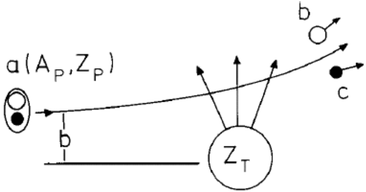
Or use indirect methods... — H. Merkel

Link with Coulomb breakup

Coulomb breakup : projectile breaks up colliding with a heavy target

$$a + T \rightarrow b + c + T$$

Coulomb dominated ⇒ due to exchange of virtual photons



Baur and Rebel Ann. Rev. Nucl. Part. Sc. 46, 321 (1996)

⇒ seen as the time-reversed reaction of the radiative capture
⇒ use Coulomb breakup to infer radiative-capture cross section

[Baur, Bertulani and Rebel NPA458, 188 (1986)]

Coulomb breakup of ^{15}C

^{15}C is a good test case to study the Coulomb breakup method :

Both the Coulomb breakup ^{15}C + Pb $\rightarrow$ ^{14}C + n + Pb at $68A$MeV

[Nakamura *et al.* PRC 79, 035805 (2009)]

and the radiative capture ^{14}C(n,γ)^{15}C

[Reifarth *et al.* PRC 77, 015804 (2008)]

have been measured accurately

$\Rightarrow$ one can confront the direct radiative-capture measurement with the cross section extracted from Coulomb breakup

Analysis by Summers & Nunes [PRC 78, 011601 (2009)]

Summers and Nunes use different $V_{^{14}\mathrm{C-n}}$ to calculate

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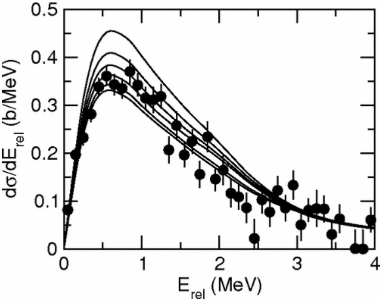

Exp. : Nakamura *et al.*
Th. : Summers, Nunes

Significant dynamical effects ⇒ requires an accurate reaction model

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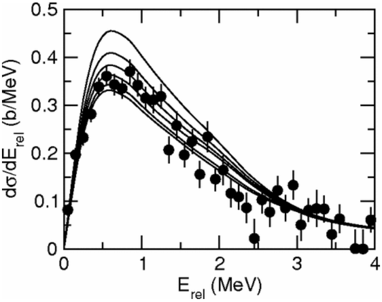

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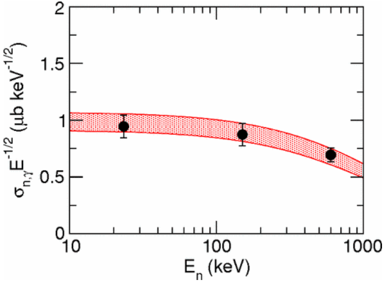

Exp. : Reifarth *et al.*
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Significant dynamical effects ⇒ requires an accurate reaction model

From a χ^2 fit to the data, they extract an ANC they use to get $\sigma_{\mathrm{n},\gamma}$

^{15}C model

$3/2^+$	3.25	$d(3/2)$
	^{14}C+n	
$5/2^+$	-0.478	$0d(5/2)$
$1/2^+$	-1.218	$1s(1/2)$

^{15}C spectrum

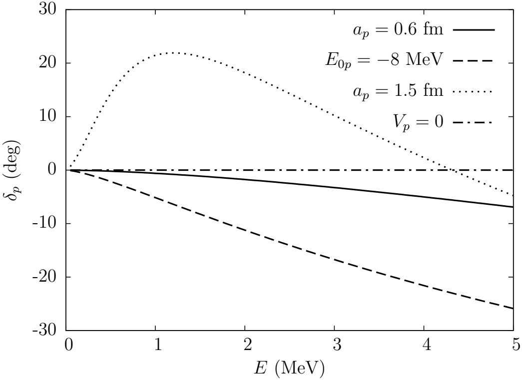
$^{15}\mathrm{C} \equiv {}^{14}\mathrm{C}(0^+)$+n
Woods-Saxon $V_{^{14}\mathrm{C-n}}$ fitted
to reproduce ^{15}C bound spectrum
$\Rightarrow$ s and d waves constrained

No direct constraint on p waves
which are populated in Coulomb breakup
by E1 transitions from the $1s$ ground state

We analyse the role of the continuum…

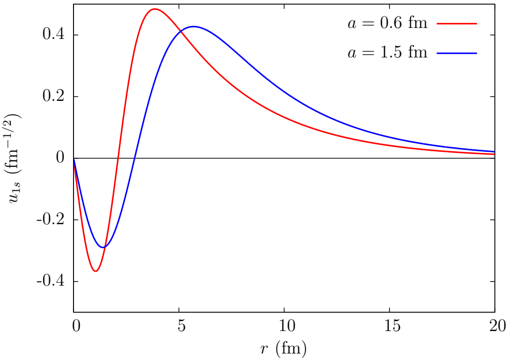
^{14}C-n continuum

Different $V_{^{14}\mathrm{C-n}}$ chosen to produce (very) different δ_p



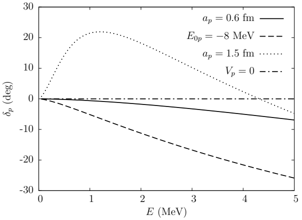
- a_p = 0.6 fm
- V_p set to E_{0p} = −8 MeV
  = $S_{\mathrm{n}}(^{14}\mathrm{C})$
- a_p = 1.5 fm
- V_p = 0

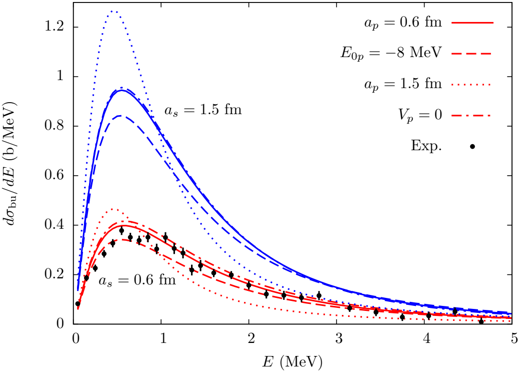
^{15}C ground state



Diffuse potential wave function extends further away
⇒ larger ANC visible in breakup calculation

^{15}C+Pb @ 68AMeV





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- Large influence of ANC : diffuse potential higher than $a = 0.6$ fm confirms Summers and Nunes PRC 78, 011601 (2008)

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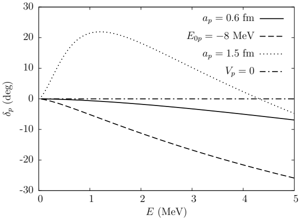

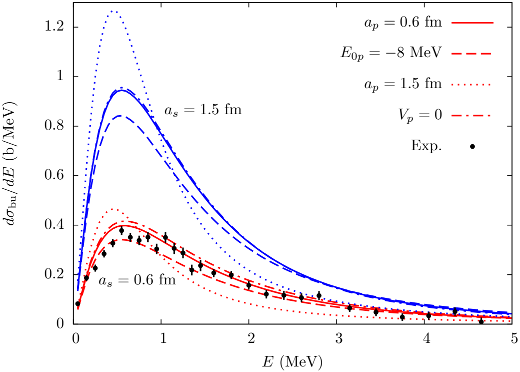

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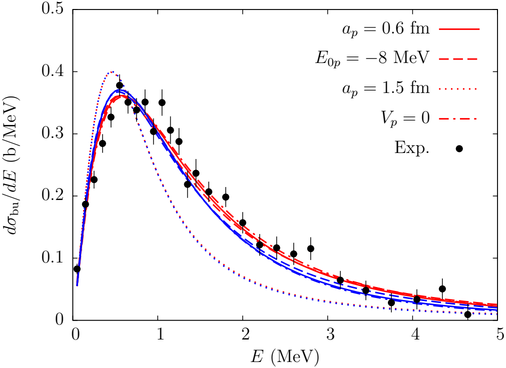
- Large influence of ANC : diffuse potential higher than $a = 0.6$ fm confirms Summers and Nunes PRC 78, 011601 (2008)
- Significant effect of continuum :
  - $E_{0p} = -8$ MeV 15% below $a_p = 0.6$ fm
  - $d\sigma_{\rm bu}/dE$ distorted due to E dependence of δ_p, especially $a_p = 1.5$ fm

χ^2 fit

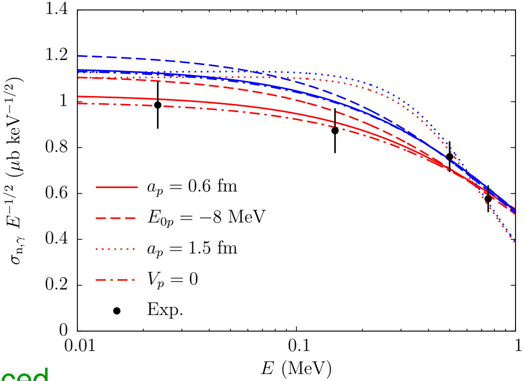
Fit C to get $C\, d\sigma_{\text{bu}}^{\text{th}}/dE \sim d\sigma_{\text{bu}}^{\text{exp}}/dE$



- Once fitted most calculations agree with data
  $a_p = 1.5$ fm has a wrong shape (unphysical choice)
- Since δ_p plays a significant role
  the fitting factor is not due only to ANC

Scaling $\sigma_{\mathrm{n},\gamma}$ using the χ^2 fit on breakup

As suggested by Summers and Nunes, $\sigma_{\mathrm{n},\gamma}$ are scaled using the factor C found from the fit of $d\sigma_{\mathrm{bu}}/dE$



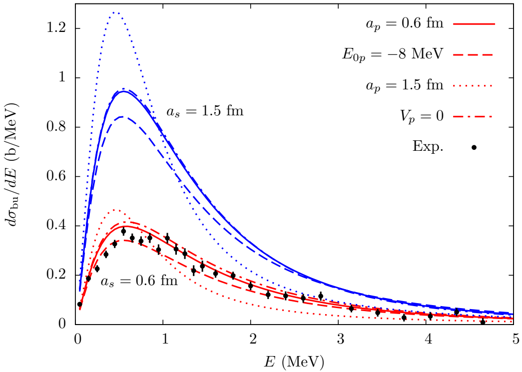
Spread is reduced

but direct measurements overestimated (even with realistic V_p)

Low-E fit

At low E, all $d\sigma_{\mathrm{bu}}/dE$ exhibit the same behaviour

[Typel and Baur PRL 93, 142502 (2004)]



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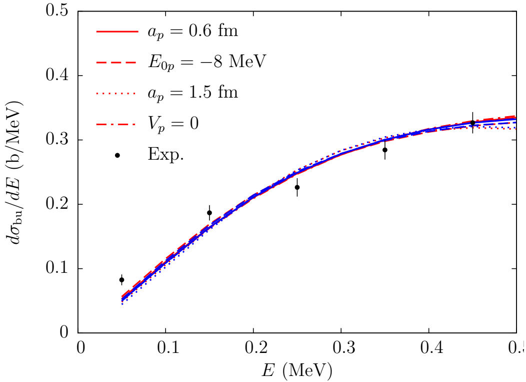
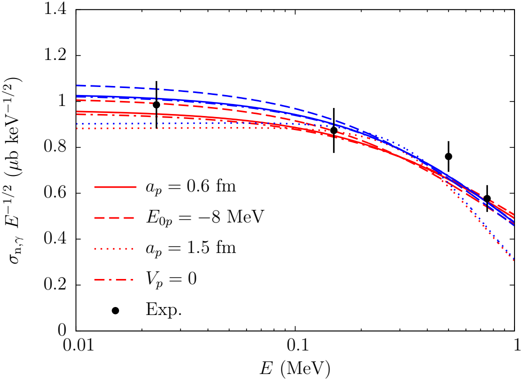


If fitted only at $E < 0.5$ MeV
all calculations are nearly superimposed (no distortion)
and in excellent agreement with breakup data

Scaling using the χ^2 fit on breakup at $E < 0.5$ MeV



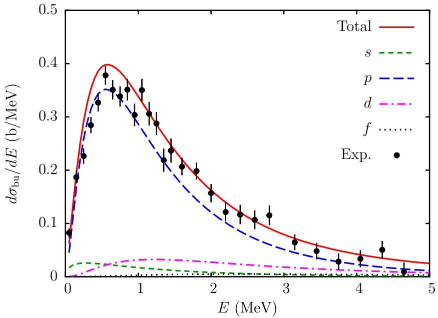
Better agreement with direct measurements
(even with unrealistic $V_{^{14}\mathrm{C-n}}$)

Conclusions and prospects

- The indirect Coulomb-breakup method to infer radiative-capture cross sections is analysed for ^{14}C(n,γ)^{15}C with emphasis on the ^{14}C-n continuum
- Breakup calculations are shown to be sensitive to both the projectile ground state (ANC) and its continuum (δ)
- That sensitivity is better removed if the fit suggested by Summers and Nunes is performed at low E
- Would this idea be improved if one looks at forward-angle data, where nuclear interaction is less significant ?
- Can this be applied to charged cases ? ^{3}He(α,γ)^{7}Be, ^{16}O(p,γ)^{17}F…

Our analysis

Using DEA, we compute $^{15}\mathrm{C} + \mathrm{Pb} \rightarrow\ ^{14}\mathrm{C} + \mathrm{n} + \mathrm{Pb}$ at $68A$MeV



Data : Nakamura *et al.* PRC 79, 035805 (2009)

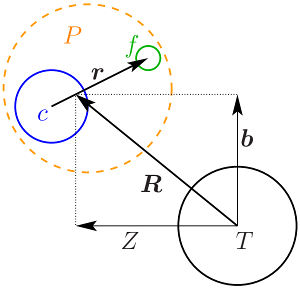
- Good agreement with experiment and CDCC calculations
- s and d contributions confirm dynamical effects

In this study we analyse the sensitivity of this method to the description of the ^{14}C-n continuum

Framework

Projectile (P) modelled as a two-body system :
core (c)+loosely bound nucleon (f) described by

$$H_0 = T_r + V_{cf}(\boldsymbol{r})$$



V_{cf} adjusted to reproduce bound state Φ_0 and resonances

Target T seen as structureless particle

P-T interaction simulated by optical potentials
$\Rightarrow$ breakup reduces to three-body scattering problem :

$$\left[T_R + H_0 + V_{cT} + V_{fT}\right]\Psi(\boldsymbol{r},\boldsymbol{R}) = E_T\Psi(\boldsymbol{r},\boldsymbol{R})$$

with initial condition $\Psi(\boldsymbol{r},\boldsymbol{R}) \underset{Z\to-\infty}{\longrightarrow} e^{iKZ+\cdots}\Phi_0(\boldsymbol{r})$

Dynamical eikonal approximation

Three-body scattering problem :

$$\left[T_R + H_0 + V_{cT} + V_{fT}\right]\Psi(\boldsymbol{r}, \boldsymbol{R}) = E_T\Psi(\boldsymbol{r}, \boldsymbol{R})$$

with condition $\Psi \underset{Z\to-\infty}{\longrightarrow} e^{iKZ}\Phi_0$

Eikonal approximation : factorise $\Psi = e^{iKZ}\widehat{\Psi}$

$$T_R\Psi = e^{iKZ}[T_R + vP_Z + \frac{\mu_{PT}}{2}v^2]\widehat{\Psi}$$

Neglecting T_R vs P_Z and using $E_T = \frac{1}{2}\mu_{PT}v^2 + \epsilon_0$

$$i\hbar v\frac{\partial}{\partial Z}\widehat{\Psi}(\boldsymbol{r}, \boldsymbol{b}, Z) = [H_0 - \epsilon_0 + V_{cT} + V_{fT}]\widehat{\Psi}(\boldsymbol{r}, \boldsymbol{b}, Z)$$

solved for each $\boldsymbol{b}$ with condition $\widehat{\Psi} \underset{Z\to-\infty}{\longrightarrow} \Phi_0(\boldsymbol{r})$

This is the dynamical eikonal approximation (DEA)

[Baye, P. C., Goldstein, PRL 95, 082502 (2005)]

Comparison of reaction models

Comparison between CDCC, TD and DEA

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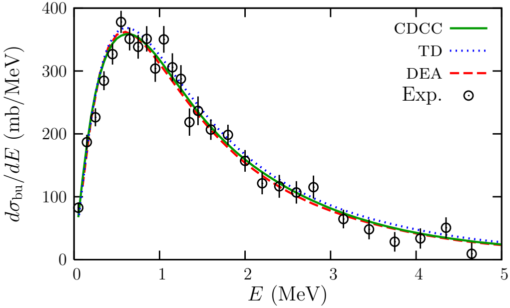
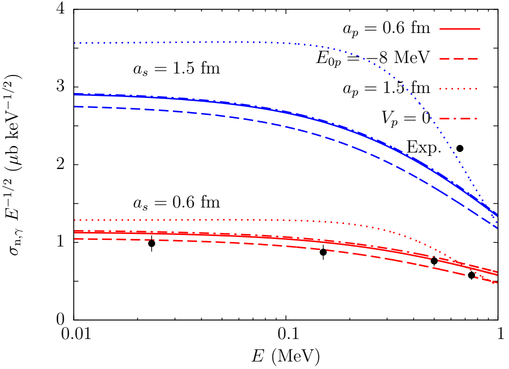


Data : Nakamura *et al.* PRC 79, 035805 (2009)

Excellent agreement between all three models

^{14}C(n,γ)^{15}C

$\sigma_{n,\gamma}$ computed using all the $V_{^{14}C-n}$
(E1 transition from ^{14}C-n continuum to bound state)



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Large spread of the calculations, like in breakup