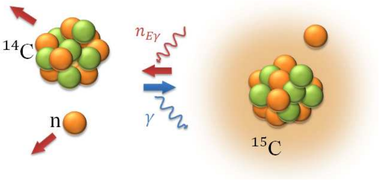
Inferring the cross section for the radiative capture of $^{14}\mathrm{C}(\mathrm{n},\gamma)^{15}\mathrm{C}$ from the Coulomb breakup of $^{15}\mathrm{C}$



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Outline

- Radiative capture in astrophysics
- The Coulomb breakup method
- Results for the breakup of $^{15}\mathrm{C}$
- Inferring the $^{14}\mathrm{C}(\mathrm{n},\gamma)^{15}\mathrm{C}$
- Conclusion and perspectives

Radiative capture in astrophysics

Radiative capture reaction : two nuclei fuse together and emit a γ :

$$b + c \rightarrow a + \gamma$$

Radiative capture reactions are abundant in stars ;

- $\mathrm{d(p,\gamma)^3He}$, $\mathrm{^3He(\alpha,\gamma)^7Be}$ in the pp chain
- $\mathrm{(n,\gamma)}$ reactions in the r and s processes
- $\mathrm{^{14}C(n,\gamma)^{15}C}$

Cross sections need to be known at low energies to constrain stellar models.

Their low values make such measurements very difficult at these energies :

$\Rightarrow$ Go deep underground (LUNA)

$\Rightarrow$ Use indirect methods such as the Coulomb breakup method

The Coulomb Breakup method

Idea : use the Coulomb breakup

$$a + T \to b + c + \gamma,$$

in which the projectile a breaks up colliding with a heavy target T.
Coulomb dominated $\Rightarrow$ due to the exchange of virtual photons.
$\Rightarrow$ can be seen as the time-reversed reaction of the radiative capture
$\Rightarrow$ use the Coulomb breakup to infer radiative-capture cross section.
But : [Baur, Bertulani and Rebel, NPA458, 188, 1986]

- nuclear contribution to the breakup,
- dynamical effects (post-acceleration effects),
- and E2 transitions,

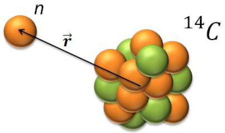
must be negligible.

Projectile structure

Two-body system : pointlike nucleon (f) loosely bound to a structureless core (c).

Internal hamiltonian :

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



Woods-Saxon potential :

$$V_{cf}(r) = \frac{-V_0}{1 + \exp\left(\frac{r-R}{a}\right)}.$$

^{14}C+n

$5/2^+$ -0.478 $0d(5/2)$

$1/2^+$ -1.218 $1s(1/2)$

The two-body projectile (P) colliding with the target (T) leads to the three-body Schrödinger equation :

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

where V_{cT} and V_{fT} simulate the P-T interaction.
Initial condition :

$$\Psi(\mathbf{r},\mathbf{R}) \underset{Z\to-\infty}{\longrightarrow} e^{iKZ}\Phi_0(\mathbf{r})$$

Dynamical eikonal approximation :
Factorize $\Psi = e^{iKZ}\hat{\Psi}$ and simplify the 3BSE to :

$$i\hbar v\dot{\hat{\Psi}}(\mathbf{r},b,Z) = [H_0 - \epsilon + V_{cT} + V_{fT}]\,\hat{\Psi}(\mathbf{r},b,Z),$$

with

$$\hat{\Psi}(\mathbf{r},b,Z) \underset{Z\to-\infty}{\longrightarrow} \Phi_0(\mathbf{r},b,Z) \text{ for each } b.$$

Choice of the reaction

The $^{14}\mathrm{C}(\mathrm{n},\gamma)^{15}\mathrm{C}$ reaction is a good case study :
Both the Coulomb breakup

$$^{15}\mathrm{C} +^{208}\mathrm{Pb} \rightarrow^{14}\mathrm{C} + \mathrm{n} +^{208}\mathrm{Pb},$$

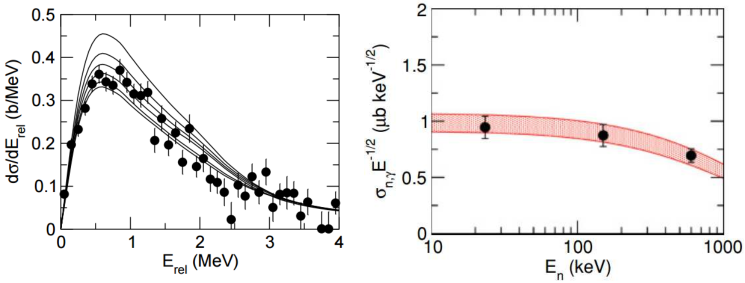
and the radiative capture

$$^{14}\mathrm{C} + \mathrm{n} \rightarrow \gamma +^{15}\mathrm{C},$$

have been measured accurately.
$\Rightarrow$ Results obtained with the Coulomb breakup method for the radiative capture can be validated by comparison with the direct measurements.
Dominant and peripheral E1 transition.

Summers and Nunes procedure [PRC 78, 011601 (2009)]

$$\frac{dB(\mathsf{E1})}{dE_{\mathsf{rel}}} \propto \left|\langle u_{\mathsf{p}}|r|u_{\mathsf{1s}}\rangle\right|^2 \;\text{with}\; u_{\mathsf{1s}}(r) \underset{r\to+\infty}{\longrightarrow} \text{ANC}\exp(-kr)$$



What about the description in the continuum ?

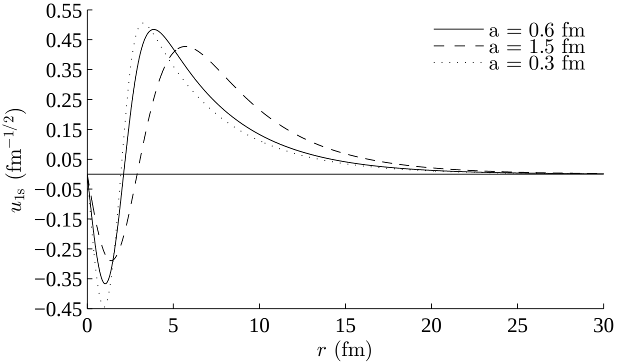
$$u_{\mathsf{p}}(r) \underset{r\to+\infty}{\backsim} \sin\left(kr - \frac{\pi}{2} + \delta_l\right)$$

Set of potentials

Potential	Strength		Radius		Diffuseness	
	V_s [MeV]	V_p [MeV]	R_s [fm]	R_p [fm]	a_s [fm]	a_p [fm]
1	52.814	52.814	2.959	2.959	0.6	0.6
2	52.814	42.787	2.959	2.959	0.6	0.6
3	52.814	38.415	2.959	2.820	0.6	1.5
4	52.814	0.0	2.820	2.959	0.6	0.6
5	38.415	52.814	2.959	2.959	1.5	0.6
6	38.415	42.787	2.959	2.959	1.5	0.6
7	38.415	38.415	2.959	2.820	1.5	1.5
8	38.415	0.0	2.820	2.959	1.5	0.6
9	59.122	52.814	2.959	2.959	0.3	0.6
10	59.122	42.787	2.959	2.959	0.3	0.6
11	59.122	38.415	2.959	2.820	0.3	1.5
12	59.122	0.0	2.820	2.959	0.3	0.6

Gives rise to different descriptions of the projectile in the bound state (1s) as well as in the continuum (p).

^{15}C Ground state



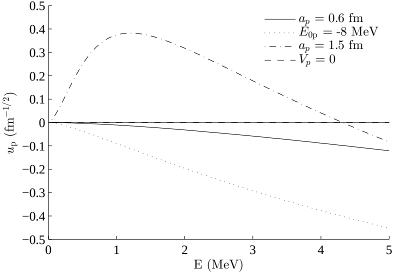
Diffuse potential wave function extends further away (larger ANC) while sharp potential wave function is shifted back to small distances (smaller ANC).

^{14}C-n continuum

s and d waves are constrained but not p waves

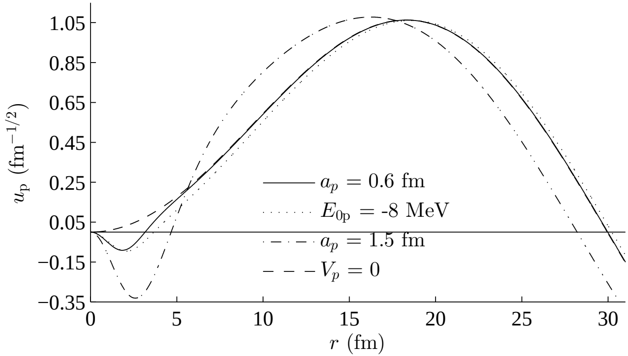
We consider 4 potentials :

- $V_p = V_s$ with $a = 0.6$ fm
- $V_p = V_s$ with $a = 1.5$ fm
- V_p set on $S_{\mathsf{n}}(^{14}\mathrm{C}) = 8$ MeV
- $V_p = 0$



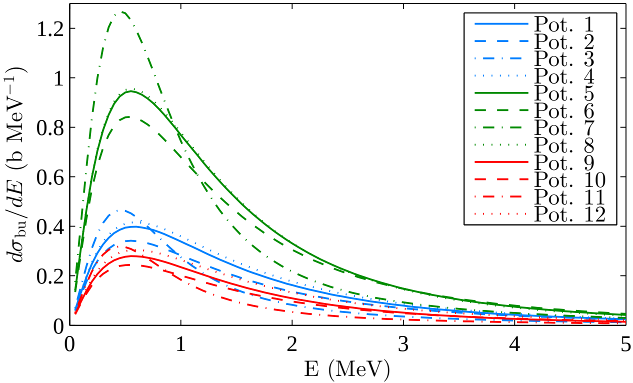
This choice of potentials results in significant variations of the phaseshifts of the wave functions.

^{14}C-n continuum



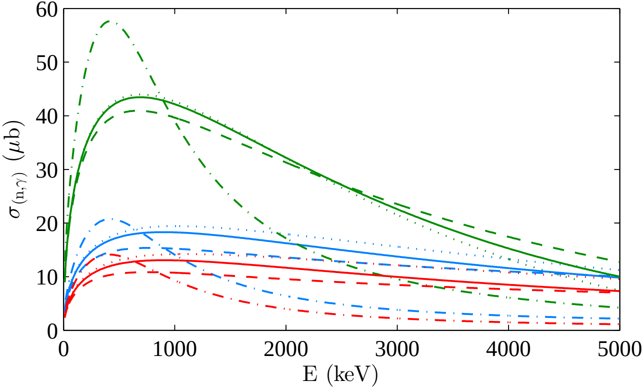
Diffuse potential wave function is significantly shifted + differences in the internal part.

$^{15}C + {}^{208}Pb$ @ 68 AMeV



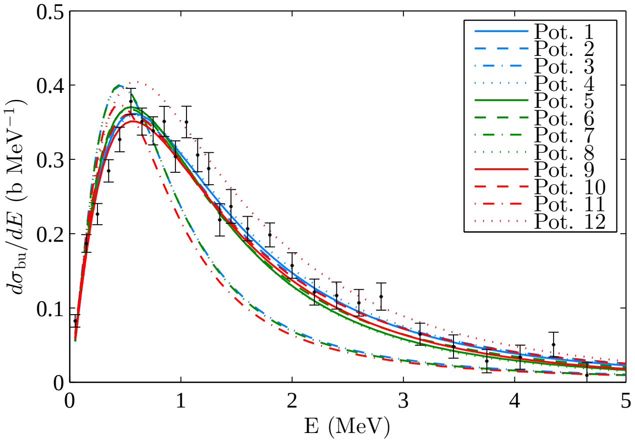
Large spread in the calculations due to the ANC (confirms Summers and Nunes PRC 78, 011601, 2008) **but also to** δ (new effect).

Capture cross sections computed using the same set of ^{14}C-n potentials



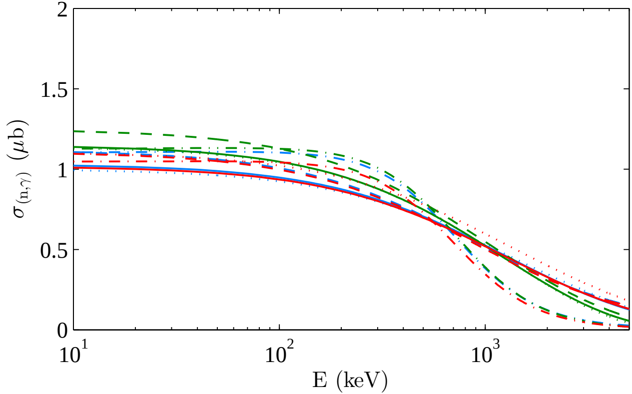
Large spread of the calculations, as observed for the breakup.

χ^2 fit



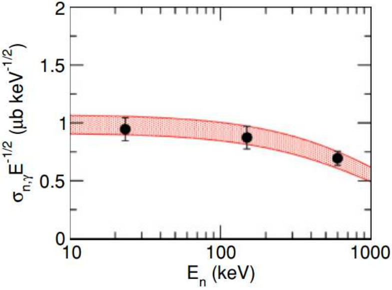
Most calculations agree with data (the unphysical diffuse potential has a wrong shape). The scaling factors now include a part due to the ANC **as well as a part due to** δ.

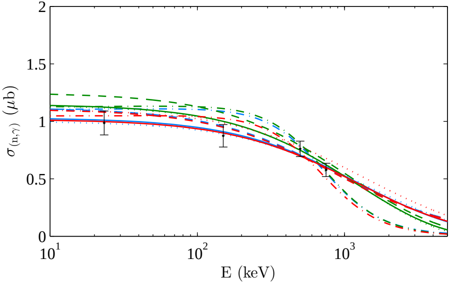
Scaling the (n,γ) cross sections using the fitting coefficients from the breakup



Too large variations in the inferred (n, γ) cross sections.

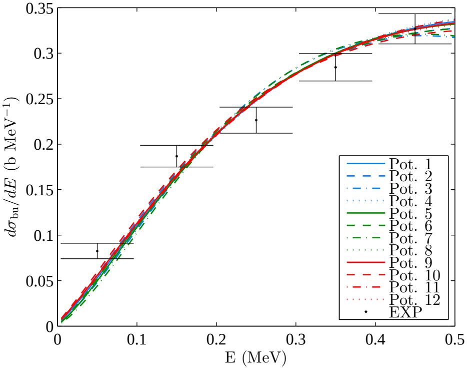
Comparison with experimental data





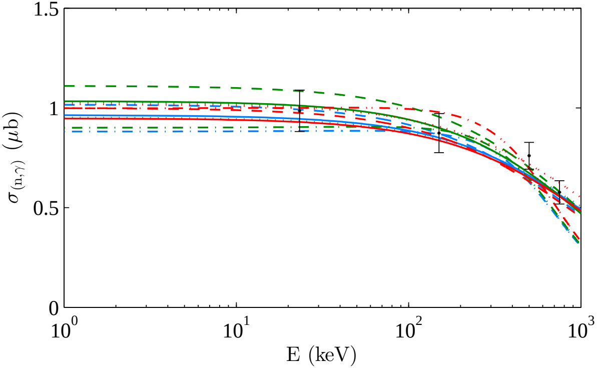
Direct measurements are overestimated + large spread.

Breakup fit at low energies (E < 0.5 MeV)



All curves are superimposed on each other and agree well with the breakup data.

(n,γ) cross sections from the breakup fit at low energies



Much better agreement with the data $\Rightarrow$ despite the (extreme) choice of potentials, Summers and Nunes method happens to work well.

Conclusion :

- The Coulomb breakup method to infer the radiative capture cross section is analysed for $^{14}\mathrm{C}(\mathrm{n},\gamma)^{15}\mathrm{C}$ with emphasis on the $\mathbf{^{14}C}$**-n continuum**.
- The procedure proposed by Summers and Nunes is shown to work well.
- Breakup and capture calculations are shown to be quite sensitive to the continuum, in addition to the ANC of the bound state.
- Capture cross sections can nevertheless be extracted if the fit is performed at low energies (energies of astrophysical interest).

Prospects :

- Forward angle data ?
- Does it remains valid in the **charged case** ?