^{6}Li breakup into $\alpha + \mathrm{d}$: a study case for electron-induced photodissociation to measure radiative-capture cross sections of astrophysical interest

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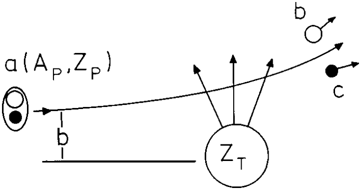
Coulomb breakup for astrophysical purposes

Measuring radiative-capture cross sections (p, γ), (d, γ), $(\alpha, \gamma)\ldots$
at astrophysical energies is difficult :
cross sections plummet due to Coulomb repulsion

Idea : use Coulomb breakup, e.g.,

$$^{6}\mathrm{Li} + \mathrm{Pb} \rightarrow \alpha + \mathrm{d} + \mathrm{Pb}$$

Reaction is Coulomb dominated $\Rightarrow$ seen as exchange of virtual photons



$\Leftrightarrow$ time reversed reaction of radiative capture $\mathrm{d}(\alpha, \gamma)^{6}\mathrm{Li}$
[Baur, Bertulani, and Rebel, NPA **458**, 188 (1986)]
[Baur & Rebel, Annu. Rev. Nucl. Part. Sci. **46**, 321 (1996)]

However. . .

1. We know that there are higher-order effects
   [Capel & Baye, PRC **71**, 044609 (2005)]
   [Esbensen, Bertsch, and Snover, PRL **94**, 042502 (2005)]

   ⇒ Coulomb breakup not exactly time-reversed radiative capture
2. Nuclear interaction is not always negligible
   [Hammache *et al.* , PRC **82**, 065803 (2010)]

   ⇒ not just photon exchange

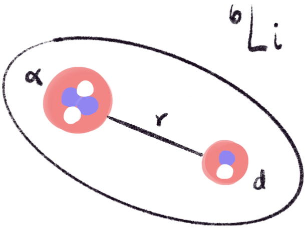
Here we reanalyse the Coulomb breakup of $^6\mathrm{Li}$ on Pb
@$26A$MeV [Kiener *et al.* PRC **44**, 2195 (1991)]
@$150A$MeV [Hammache *et al.* PRC **82**, 065803 (2010)]

using a dynamical model of breakup
[Baye, Capel, and Goldstein, PRL **95**, 082502 (2005)]

^{6}Li

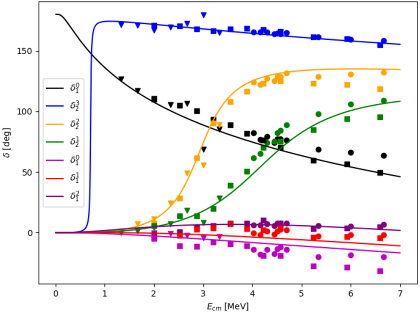
Formed mostly during BBN
by $\mathrm{d}(\alpha, \gamma)^6\mathrm{Li}$

Has a clear $\alpha + \mathrm{d}$ structure
⇒ can be described in 2-b model



We use the Woods-Saxon of
[Hammache *et al.* PRC **82**, 065803 (2010)]
reproduces experimental

- binding energy
- phaseshifts



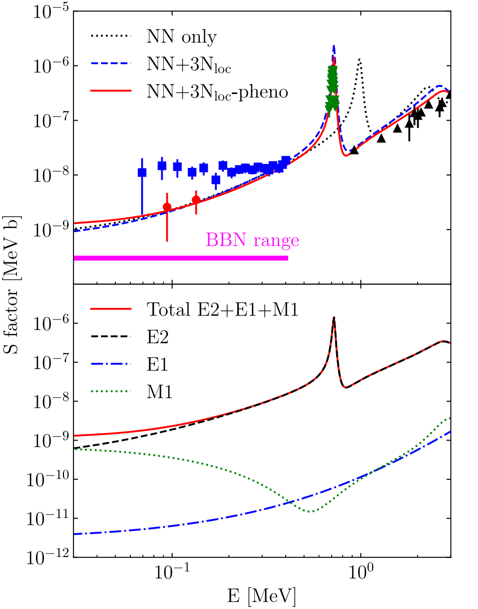
^{6}Li computed *ab initio*

$d(\alpha,\gamma)^6$Li computed *ab initio*
[Hebborn *et al.* PRL **129**, 042503 (2022)]
within NCSMC

Agrees with direct measurements
[**Robertson *et al.*** PRL **47**, 1867 (1981)]
[Mohr *et al.* PRC **50**, 1543 (1994)]
[LUNA PRL **113**, 042501 (2014)]

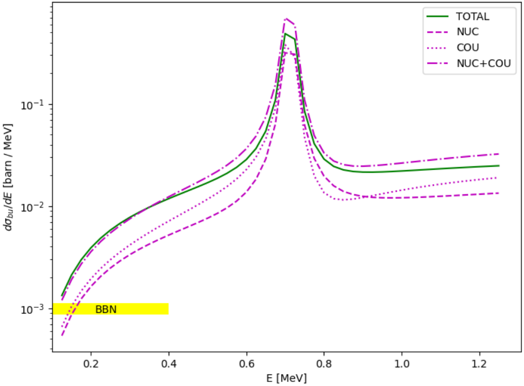
Disagrees with Coulomb breakup
[Kiener *et al.* PRC **44**, 2195 (1991)]
Why ?

Capture dominated by **E2**
negligible E1 ($N = Z$ nuclei)
and small M1



Coulomb breakup of ^{6}Li @ $26A$MeV

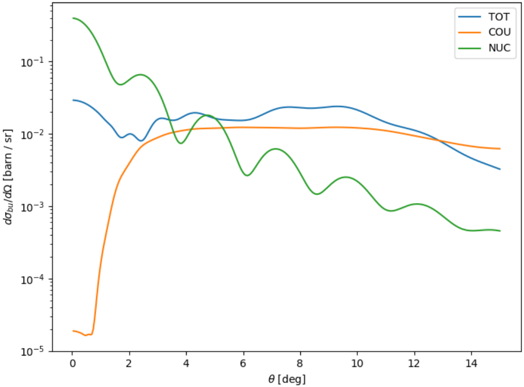
$$^6\mathrm{Li} + \mathrm{Pb} \rightarrow \alpha + \mathrm{d} + \mathrm{Pb} \text{ @ } 26A\mathrm{MeV}$$



- Reaction with equal Coulomb and nuclear contributions
  $\Rightarrow$ not purely Coulomb breakup
- Significant Coulomb-nuclear interferences @ $E > 0.4$ MeV
- Is there an angular range, where Coulomb dominated ?

Angular distribution @ $26A$MeV

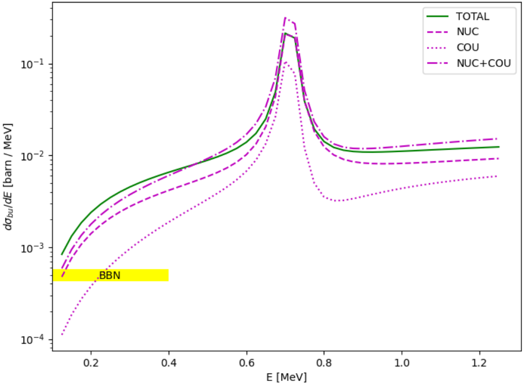
$^6\mathrm{Li} + \mathrm{Pb} \to \alpha + \mathrm{d} + \mathrm{Pb}$ @ $26A$MeV



- Reaction is Coulomb dominated at large angles ($\theta \geq 8°$)
- At forward angles, breakup is nuclear dominated
  Kiener measured at $\theta \lesssim 6°$ $\Rightarrow$ not Coulomb breakup
- α & d feel same acceleration : $a = \frac{F}{m} \propto \frac{Z}{A}$ & $\frac{Z_\alpha}{A_\alpha} = \frac{Z_\mathrm{d}}{A_\mathrm{d}}$
  $\Rightarrow$ no tidal force $\Rightarrow$ no Coulomb breakup

Coulomb breakup of ^{6}Li @ $150A$MeV

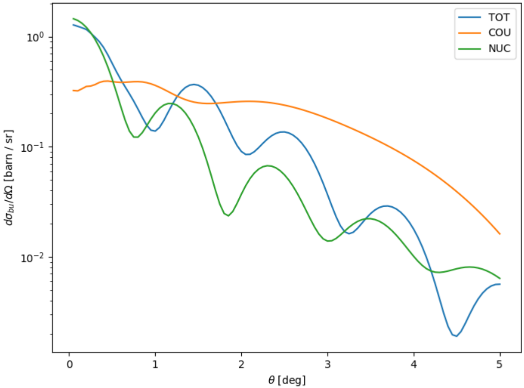
$$^6\text{Li} + \text{Pb} \rightarrow \alpha + \text{d} + \text{Pb @ } 150A\text{MeV}$$



- Reaction nuclear dominated at all energies
  $\Rightarrow$ not Coulomb breakup
- Significant Coulomb-nuclear interferences $\forall E$
- Confirms the analysis of [Hammache *et al.* PRC **82**, 065803 (2010)]

Angular distribution @ $150A$MeV

$$^6\mathrm{Li} + \mathrm{Pb} \rightarrow \alpha + \mathrm{d} + \mathrm{Pb} \text{ @ } 150A\mathrm{MeV}$$



- Reaction is nuclear dominated $\forall\theta$
  $\Rightarrow$ no Coulomb breakup [Hammache *et al.* PRC **82**, 065803 (2010)]
- Yet, reaction being peripheral (even nuclear dominated) data analysis confirms ANC, δ_{lJ} that control $\sigma_{(\mathrm{d},\gamma)}$

A first conclusion

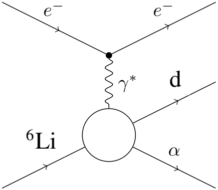
Coulomb breakup unsuited to infer $\mathrm{d}(\alpha,\gamma)^6\mathrm{Li}$:

- Nuclear contribution is very significant
- There are strong nuclear-Coulomb interferences
- Dynamical effects play a role

$\Rightarrow$ we need a method that

- is Coulomb dominated
  (no nuclear interaction)
- can be treated at first order
  (no dynamical effects)
- has high-enough cross sections
  larger than direct $\mathrm{d}(\alpha,\gamma)^6\mathrm{Li}$

Electron-induced photodissociation



Idea :
Use intense electron beam
to induce dissociation $^6\mathrm{Li}(e, e'\alpha)\mathrm{d}$
through the exchange of virtual photons

Pros :

- e-induced dissociation
  - no nuclear interaction
  - can be treated perturbatively (no dynamical effects)

  $\Rightarrow \sigma_{(\alpha,\gamma)} \propto \sigma_{(e,e'\alpha)}$
- $\sigma_{(e,e'\alpha)} \gg \sigma_{(\alpha,\gamma)}$

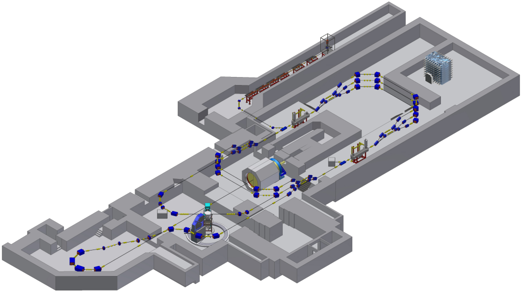
Cons :

- Need a facility with high intensity e beam…

MAGIX@MESA

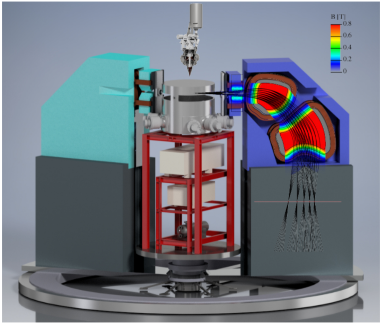
MESA

- Mainz Energy-recovering Superconducting Accelerator
- High-intensity e accelerator
- Provides e beam up to
  - 1mA
  - $E_e = 105$ MeV



MAGIX

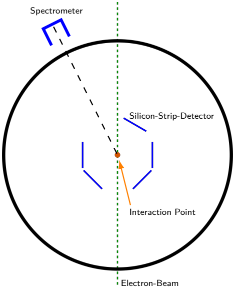
- MESA Gas-Internal target eXperiment
- Two spectrometers
  - $\frac{\Delta p}{p} < 10^{-4}$
  - $\Delta\theta_e \sim 1$ mrad



Experimental Setup : Phase 0

A1@MAMI

- Electron beam : $E_e = 330$ MeV
  20–30μA
- $^6\mathrm{Li}$ target
- Spectrometer @ $\theta_e \sim 22°$



Goals :

- Develop theoretical model of reaction (M. Sanjinez's PhD)
- Test α detection setup (Si strip detectors)
- Determine background
- Infer $\sigma_{(\alpha,\gamma)}$ @ $E \sim$ few MeV, where direct data exist

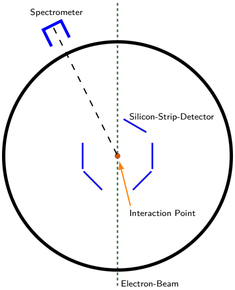
$\Rightarrow$ Test reaction model and analysis and compare to existing data

Experimental Setup : Phase 1

MAGIX@MESA

- Electron beam : $E_e = 50\text{–}105$ MeV
  1mA
- Li target enriched in ^{6}Li to measure
  - $^6\mathrm{Li}(e, e'\alpha)\mathrm{d}$
  - $^7\mathrm{Li}(e, e'\alpha)\mathrm{t}$

  with the same setup
- Spectrometer @ $\theta_e \sim 13°$



Goals :

- Infer $\sigma_{(\alpha,\gamma)}$ down to $E \sim 1$ MeV
- Compare results with existing data
- Determine background

Experimental Setup : Phase 2

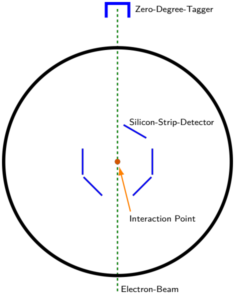
MAGIX@MESA with Zero-Degree Tagger

- Electron beam : $E_e = 50\text{–}105$ MeV
  1mA
- Li target enriched in $^6\mathrm{Li}$ to measure
  - $^6\mathrm{Li}(e, e'\alpha)\mathrm{d}$
  - $^7\mathrm{Li}(e, e'\alpha)\mathrm{t}$

  with the same setup
- Use deflection magnet
  to separate scattered e from beam
  (Zero-Degree Tagger)
- Acceptance $\theta_e = 0°\text{–}0.5°$

Goals :

- Infer $\sigma_{(\alpha,\gamma)}$ @ $E \lesssim 1$ MeV
- Improve statistical uncertainty for higher E



What's next ?

Extend the idea to other reactions :

- other (α, γ) :
  $^{24}\mathrm{Mg}(e, e'\alpha)^{20}\mathrm{Ne}$, $^{28}\mathrm{Si}(e, e'\alpha)^{24}\mathrm{Mg}$, $^{16}\mathrm{O}(e, e'\alpha)^{12}\mathrm{C}$
- neutron capture using $(e, e'\mathrm{n})$
  $^{7}\mathrm{Li}(e, e'\mathrm{n})^{6}\mathrm{Li}\ldots$

Tests of nuclear-structure models :

- α-d structure of $^{6}\mathrm{Li}$ (ANC)
  α-$^{12}\mathrm{C}$ structure of $^{16}\mathrm{O}$ (ANC)
  ...
- phaseshifts in continuum

$\Rightarrow$ test *ab initio* predictions [Hebborn *et al.* PRL **129**, 042503 (2022)]

See if this fits other reaction observables

- sub-Coulomb α transfer (ANC) [Brune *et al.* PRL 83, 4025 (1999)]
- phaseshifts from elastic scattering

Summary and prospect

- Coulomb breakup suggested as indirect method to infer radiative-capture at astrophysical energies
  But
  - for $N = Z$ nuclei, significant nuclear contribution
  - strong Coulomb-nuclear interferences
  - higher-order effects
- We suggest to use electron induced photodissociation
  - no nuclear interaction
  - perturbative $\Rightarrow \sigma_{(\alpha,\gamma)} \propto \sigma_{(e,e'\alpha)}$
  - JG|U is building MESA : high-intensity e accelerator
- Future :
  - Develop model of reaction (M. Sanjinez's PhD)
  - Benchmark the idea on $^{6}\mathrm{Li}(e, e'\alpha)\mathrm{d}$ @ MAMI
  - Then measure to lower energy @ MAGIX
  - Study cluster structure of nuclei

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MAGIX collaboration