Nuclear Astrophysics at MAGIX@MESA

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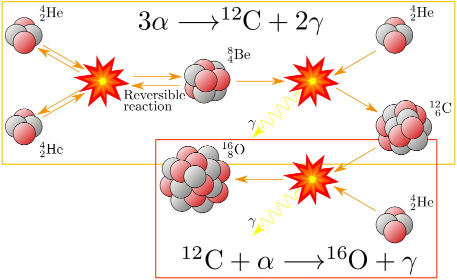
Helium Burning in stars



- Triple α process bridges the $A = 8$ gap
- C/O ratio affects stellar evolution and nucleosynthesis
- However $^{12}\mathrm{C}(\alpha, \gamma)^{16}\mathrm{O}$ impossible to measure directly :
  @ $T \sim 2\ 10^{8}$ K, Gamow peak @ $E \approx 300$ keV

[see also talk by R. J. deBoer]

^{12}C$(\alpha,\gamma)^{16}$O

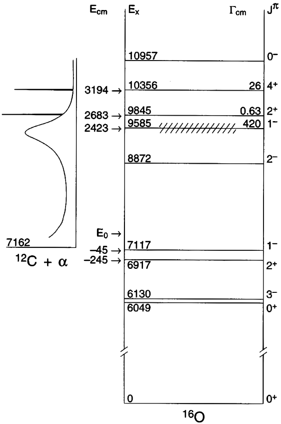
Dubbed as *the holy grail of nuclear astrophysics*
Not only because

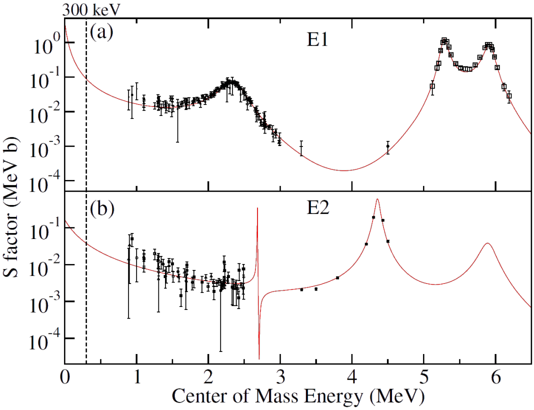
- key to the abundance of C, O and all heavier nuclei
- impossible to measure directly at relevant energies

But also because

- reaction mechanism is complex :
  - E1 capture is isospin forbidden
    ⇒ E1 and E2 transitions have similar amplitudes
  - interference between direct and resonant capture
  - influence of sub-threshold bound states
- the structure of ^{16}O is not simple
  ⇒ challenges theory to extrapolate “*high*”-energy data

Current status





[deBoer *et al.* RMP 89, 035007 (2017)]

- No data at $E \lesssim 0.9$ MeV whereas Gamow peak @ $E \approx 300$ keV
- Both E1 and E2 matter @ low E
- Need theoretical extrapolation (R-matrix theory)
- Significant influence of subthreshold 1^- and 2^+ bound states

A glimmer of hope…

Constraints on ^{16}O structure from e.g. transfer reactions
[Brune *et al.* PRL 83, 4025 (1999)]

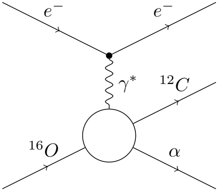
Significant progresses in α-cluster nuclear-structure models :

- on a lattice [Epelbaum *et al.* PRL 112 102501 (2014)]
- within shell model [Volya and Tchuvil'sky PRC 91 044319 (2015)]
- within AMD [Kanada-En'yo PRC 96, 034306 (2017)]

At astrophysical energy, ^{12}C$(\alpha,\gamma)^{16}$O dominated
by direct E1 and E2 captures towards the 0^+ ground state of ^{16}O

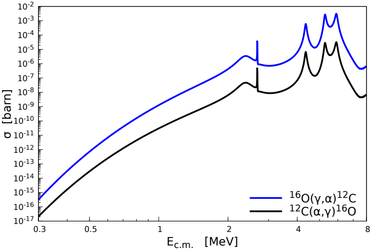
Photodissociation of ^{16}O, e.g. using an intense electron beam
can constrain the direct E1 and E2 transition towards ground state
[Friščić, Donelly and Milner, PRC 100, 025804 (2019)]

Photodissociation of ^{16}O with e beam



Idea :

Use intense electron beam
to induce dissociation $^{16}\mathrm{O}(e, e'\alpha)^{12}\mathrm{C}$
through the exchange of virtual photons



Courtesy of S. Lunkenheimer

Pros :

- e-induced dissociation
  can be treated perturbatively
  $\Rightarrow \sigma_{(\alpha,\gamma)} \propto \sigma_{(\gamma,\alpha)}$
- $\sigma_{(\gamma,\alpha)} \gg \sigma_{(\alpha,\gamma)}$
- $\neq$ Coulomb breakup (e.g. on Pb)
  - no nuclear interaction
  - no higher-order effects

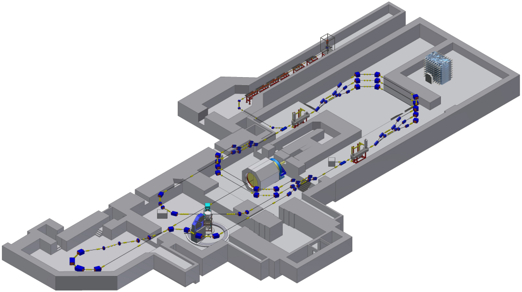
Cons :

- $\sigma_{(\gamma,\alpha)} \ll \sigma_{\text{Coul bu}}$
  but can be compensated with high intensity e beam

MAGIX@MESA

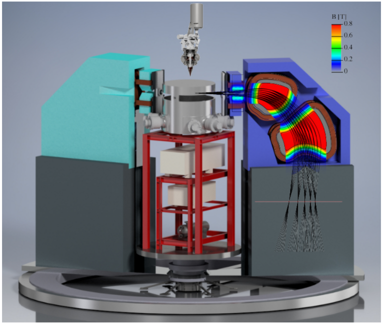
MESA

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



MAGIX

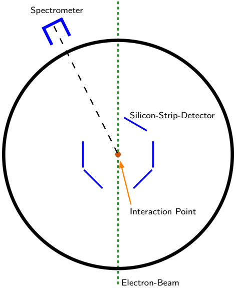
- MESA Gas-Internal target eXperiment
- Two spectrometers
  - $\frac{\Delta p}{p} < 10^{-4}$
  - $\Delta\theta_e \sim 1$ mrad



Experimental Setup : Phase 0

A1@MAMI

- Electron beam : $E_e = 195$ MeV
  100μA
- Windowless hypersonic jet target in vacuum



Goals :

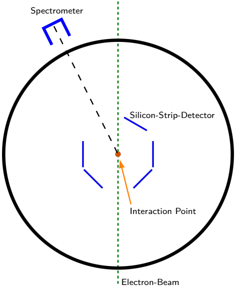
- Test Si strip detectors for α
- Infer $\sigma_{(\alpha,\gamma)}$ @ $E = 1.8$ MeV, where direct data exist

⇒ Test analysis and compare to existing data

Experimental Setup : Phase 1

MAGIX@MESA

- Electron beam : $E_e = 25\text{–}105$ MeV
  1mA
- Windowless hypersonic jet target in vacuum
- Spectrometer @ $\theta_e \sim 13°$



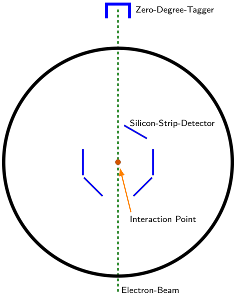
Goals :

- Infer $\sigma_{(\alpha,\gamma)}$ @ $E \gtrsim 0.9$ MeV
- Compare results with existing data
- Determine background

Experimental Setup : Phase 2

MAGIX@MESA with Zero-Degree Tagger

- Electron beam : $E_e = 25\text{–}105$ MeV
  1mA
- Windowless hypersonic jet target in vacuum
- Use deflection magnet
  to separate scattered e from beam
  (Zero-Degree Tagger)
- Acceptance $\theta_e = 0^\circ\text{–}0.5^\circ$



Goals :

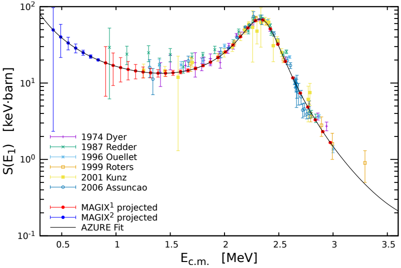
- Infer $\sigma_{(\alpha,\gamma)}$ @ $E \gtrsim 0.5$ MeV
- Improve statistical uncertainty for $E \gtrsim 0.9$ MeV

Results of simulations

Hypotheses

- e detector
  - **Phase 1 :**
    Spectrometer @ $\theta_e = 13°$
  - **Phase 2 :**
    Zero-Degree Tagger $\theta_e < 0.5°$
- α detectors
  - 5 Si striped detectors
    50×50 mm^2
  - @ 10 cm of O_2 jet
  - $\theta_\alpha = 30°, \pm 90°, \pm 120°$
- Target density : $2\ 10^{18}$ particle/cm^2
- Beam : $E_e = 105$ MeV @1mA
- Luminosity $\mathcal{L} \sim 10^{34}$ cm^{-2} s^{-1}
- Beam time : 4 weeks

Projections :



Courtesy of S. Lunkenheimer

Phase 1 :

- Infer $\sigma_{(\alpha,\gamma)}$ $E \gtrsim 0.9$ MeV

Phase 2 :

- Infer $\sigma_{(\alpha,\gamma)}$ $E \gtrsim 0.5$ MeV

What's next ? Test of nuclear-structure models

These precise measurements will provide stringent tests of nuclear-structure models :

- ^{12}C-α structure of ^{16}O ground state (ANC) and subthreshold states
- p- and d-wave phaseshifts

⇒ interpret capture in a potential model or EFT approach fitted to predictions of structure model

See if this fits other reaction observables

- sub-Coulomb α transfer (ANC) [Brune *et al.* PRL 83, 4025 (1999)] [Shen *et al.* PRL 124, 162701 (2020)]
- phaseshifts from elastic scattering [Tischhauser *et al.* PRC 79, 055803 (2009)]
- Coulomb breakup [Fleurot *et al.* PLB 615, 167 (2005)]

What's next ? Application to other reactions

- Using gas-jet target :
    - ^{15}N(p,γ)^{16}O
    - ^{18}O(p,γ)^{19}F
    - ^{16}O(α,γ)^{20}Ne $\rightleftharpoons$ ^{20}Ne(γ,α)^{16}O
    - ^{18}O(α,γ)^{22}Ne
- Extending to solid target :
    - ^{22}Ne(p,γ)^{23}Na
    - ^{22}Ne(α,γ)^{26}Mg
    - ^{20}Ne(α,γ)^{24}Mg $\rightleftharpoons$ ^{24}Mg(γ,α)^{20}Ne
    - ^{24}Mg(α,γ)^{28}Si
- Let's dream. . .
  ^{12}C + ^{12}C fusion

So, we'll reach for the *holy grail*
En route we'll add jewels to Guinever's crown and grab Excalibur. . .