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

Carl R. Brune

Ohio University

29 June 2016

The 2016 R-Matrix Workshop on Methods and Applications
June 27 – July 1, 2016
Inn & Spa at Loretto, Santa Fe, New Mexico, USA

Hydrostatic Fusion Stages

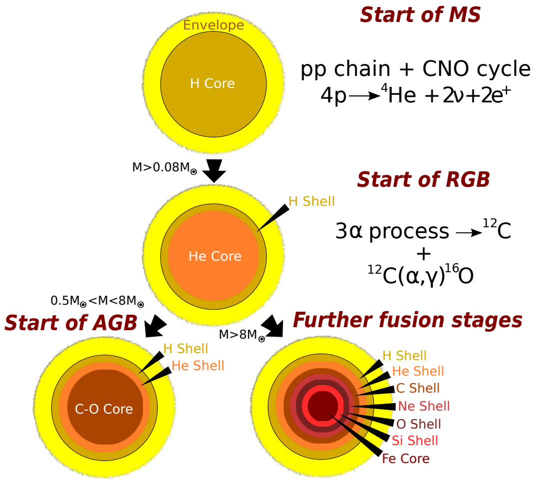
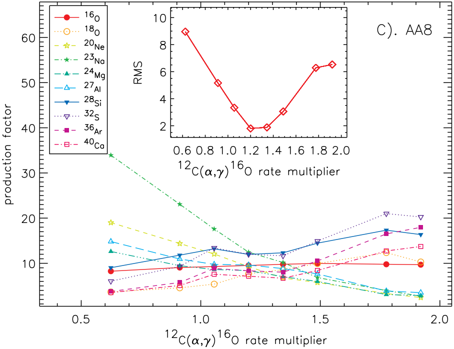


Figure courtesy of Dan Sayre.

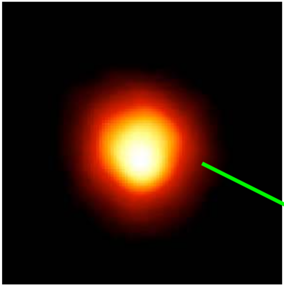
Sensitivity of Supernovae Isotope yields to $^{12}C(\alpha,\gamma)$



- Calculations by Tur, Heger, and Austin (2007).
- Uses Kepeler code developed by Weaver, Woosley, and collaborators.
- Varies $^{12}C(\alpha,\gamma)$ rate, starting from Buchmann (1996): $S(300 \text{ keV}) = 146$-keV-b.
- Preferred multiplier is 1.2, with an error for $\approx 25\%$.
- Other uncertainties: semiconvection, overshoot mixing, explosion mechanism,. . .
- Tail wagging the dog?

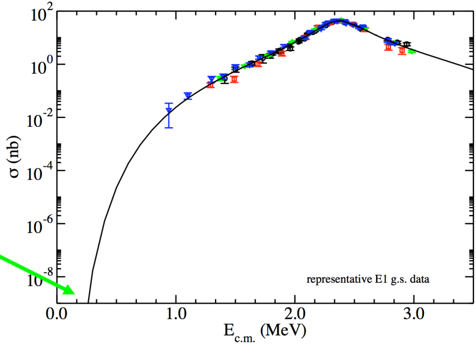
The Challenge

Red Giant



T=(1-3)x10^8 K

The Lab

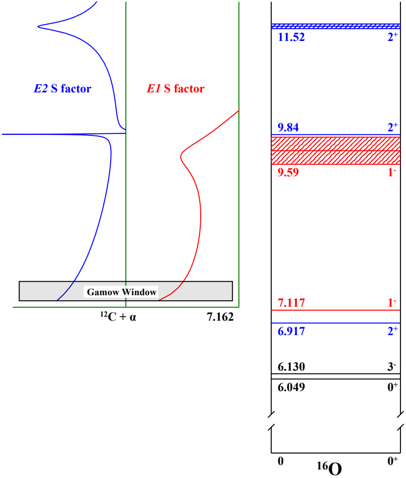


- Extrapolation to low energies is required. More challenging than the typical data evaluation problem.
- Experimental challenges: small cross sections ($E1$ surppressed).

$^{12}C(\alpha,\gamma)^{16}O$: Important Energy Levels

Physics: Subthreshold resonances and interference

Note: Combination of experiment and theory required to obtain $S(300)$. Subthreshold resonances along with their interference must be considered in the theory.



A partial level diagram

In Many Ways ^{12}C(α, γ) is Ideally Suited for R-Matrix Analysis

- The α and ^{12}C are spin zero.
- The density of levels is relatively low.
- High three-body thresholds (≈ 20 MeV).

- Can be treated as a single-channel problem to a reasonable approximation.
- If you are a student interested in how R-matrix works with a Coulomb force...

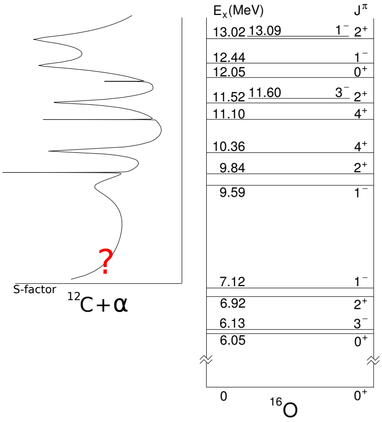
$^{12}C(\alpha,\gamma)$ has been a Mother of Invention for for the Phenomelogical R-Matrix

- Willie Fowler (1967) estimated the reaction rate considering just the subthreshold 1^- level, with Γ_γ taken from experiment and the reduced α width estimated from shell model calculations and transfer reactions.
- Fred Barker (1971) provided the first comprehensive R-matrix analysis: simultaneous description of $^{12}C(\alpha,\gamma)$, $^{12}C(\alpha,\alpha)$, and $^{16}N(\beta\alpha)$.
- Hybrid Model (Koonin *et al.*, 1974), K-matrix theory (Humblet *et al.*, 1976).
- Alternative parameterization (Brune, 2002).

Indirect Methods

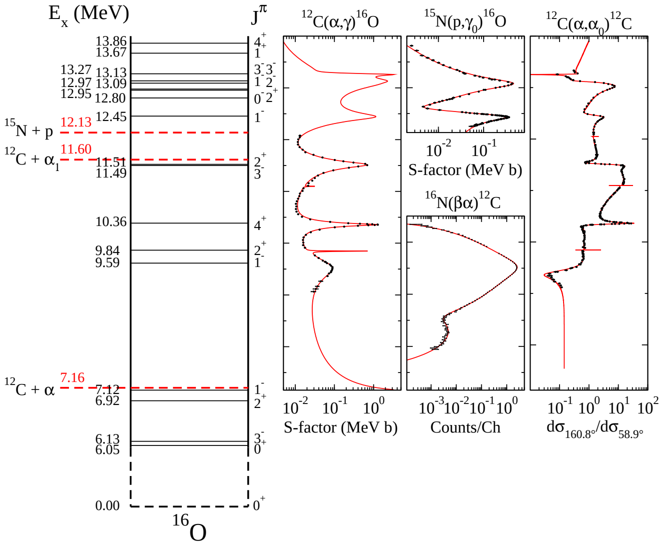
- Key R-matrix parameters are the γ_α for the subthreshold states (particularly the 1^- and 2^+). These quantities can also be expressed as Asymptotic Normalization Constants (ANCs).
- The 1^- ANC can be constrained by the $^{16}\mathrm{N}(\beta\alpha)$ spectrum.
- The ANCs can extracted from sub-Coulomb α transfer reactions, e.g $^{12}\mathrm{C}(^{6}\mathrm{Li}, d)$ and $^{12}\mathrm{C}(^{7}\mathrm{Li}, t)$. See Brune *et al.* (1999), Avila *et al.* (2015).
- Regarding transfer reactions, the upside is that the quantity of interest is directly proportional to the measured transfer cross section. However, one must consider additional systematic (theoretical) uncertainties.
- Note also that if the ANCs are assumed to be known, then we are determining $S(300\ \mathrm{keV})$ by *interpolation* rather than extrapolation.

The Motivation to Extend Analysis to Higher Energies



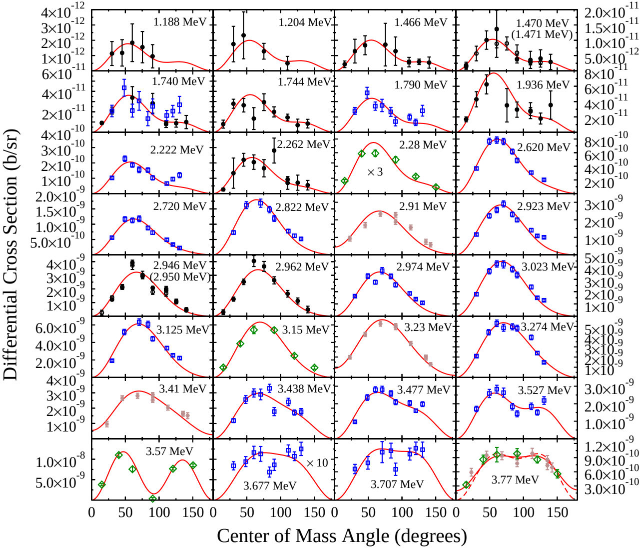
- $R_{cc'} = \sum_\lambda \frac{\gamma_c \gamma_{c'}}{E_\lambda - E}$ + background pole(s)
- By explicitly including higher-energy levels, the strength of the remaining background is diminished. This is advantageous if the higher-energy levels can be constrained by data.

Global *R*-Matrix Analysis



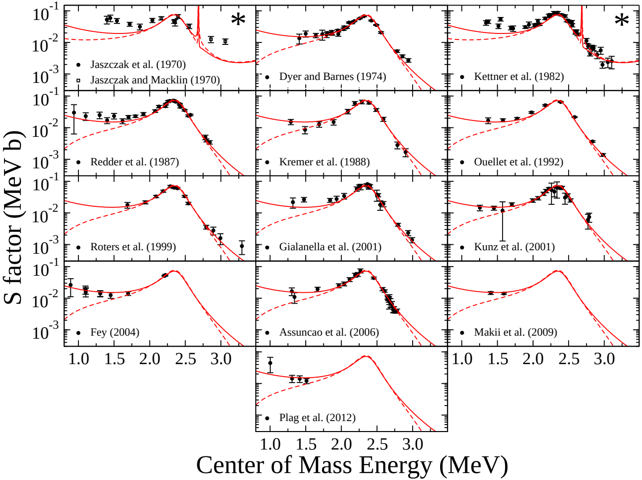
- James deBoer (leader), R.E. Azuma, A. Best, C.R. Brune J. Görres, S. Jones, M. Pignatari, D. Sayre, K. Smith, E. Uberseder, M. Wiescher.
- Bound state information (E_x, Γ_γ, ANCs) also fitted.

Fits to Ground-State $^{12}C(\alpha, \gamma)$ Angular Distributions



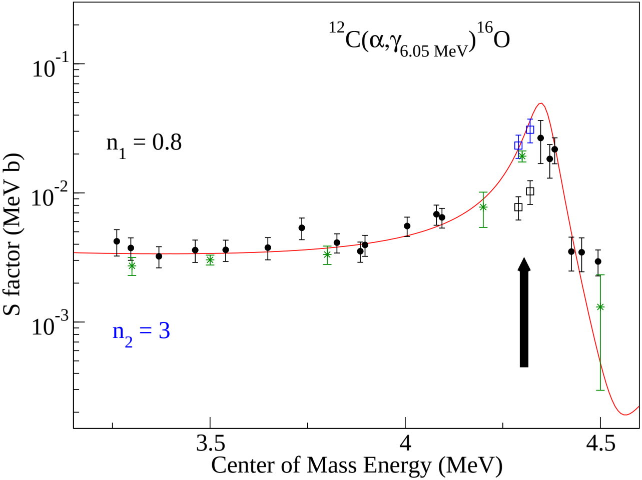
Dyer and Barnes (1974, green diamonds), Redder *et al.* (1987, brown stars), Assunção *et al.* (2006, black circles), Fey (2004, blue squares).

Interference in the $E1$ Ground-State Transition



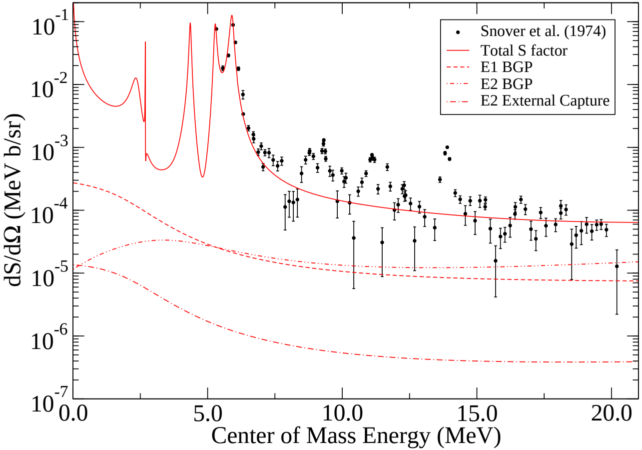
- Key additional inputs: explicit inclusion of higher 1^- resonances, bound-state ANC.
- $\Delta\chi^2 = 324$; note also $\Delta\chi^2(5\sigma) = 169$.

Transition to the 6.05-MeV State of ^{16}O



Matei *et al.* (TRIUMF, 2006, black/blue); Schuürmann *et al.* (Bochum, 2011, green stars).

Check of Ground-State S-factor Data at Even Higher Energies



- Differential S-factor data of Snover *et al.* at $\theta_{\text{lab}} = 52^{\circ}$.
- Background poles placed at $E_x = 40$ MeV.

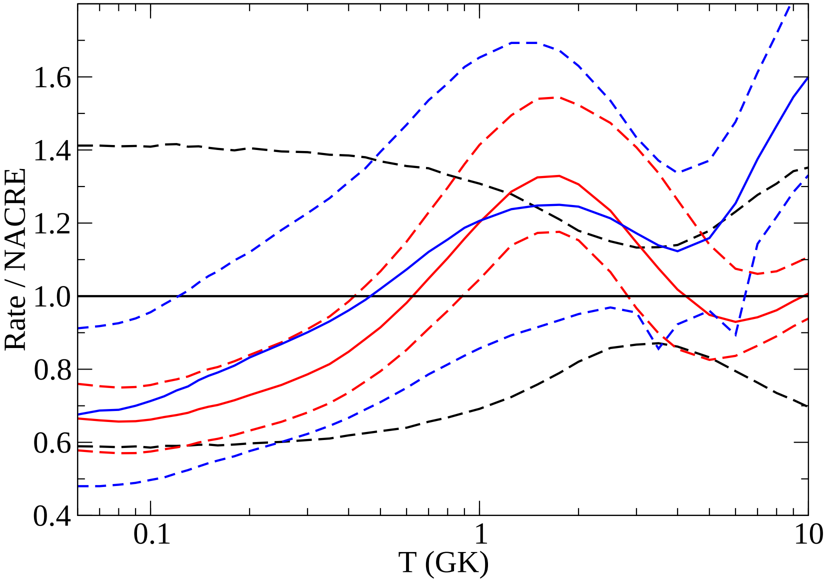
Summary of Results at $E = 300$ keV

- $E1$ ground-state S factor: 86 keV-b
- $E2$ ground-state S factor: 45 keV-b
- Cascade S factor: 7 keV-b

- Total S factor: 140 keV-b
- Estimated Uncertainty:

± 14	data (Monte Carlo)
$+18/-11$	model

Reaction Rate



Present result (red), Kunz *et al.* (blue), NACRE (black).

Future Work

- Direct Measurements:
  regular kinematics (especially low energies)
  inverse kinematics / recoil separator (cascades)
  inverse reaction: $^{16}O(\gamma, \alpha)$
- α transfer reactions
- Precision measurments are generally useful

- I would like to use this opportunity to urge
  Experimenters to report primary data with sufficient documentation
  R-Matrix Fitters to report their parameters and other information necessary to reproduce the fit

Thanks:

- Fred Barker, Gerry Hale, and Jean Humblet
  for answer my R-matrix and scattering theory
  questions in the mid 1990s
- Dick Azuma, Charlie Barnes, and Lothar Buchmann
  for various discussions regarding $^{12}\mathrm{C}(\alpha, \gamma)$
- Catalin Matei and Dan Sayre
  my Ph.D. students who worked on $^{12}\mathrm{C}(\alpha, \gamma)$
- Contemporary collaborators and students

Thank you for your attention.