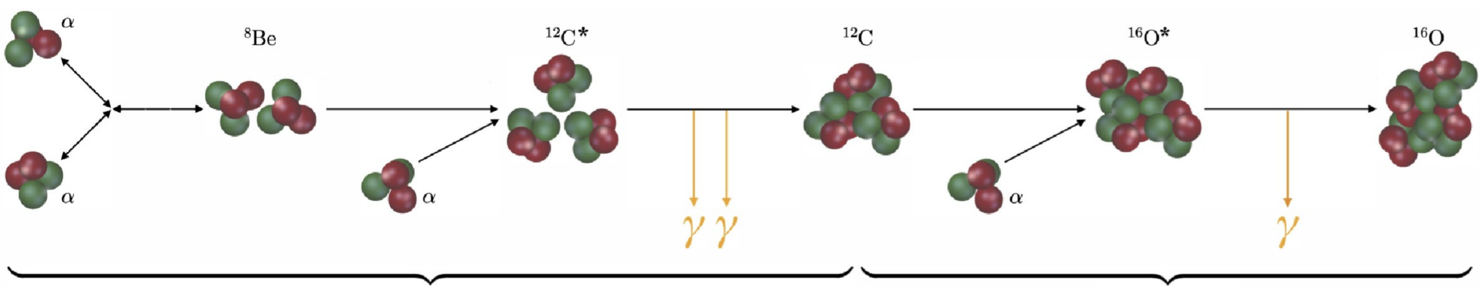
UNIVERSITY OF OSLO

Studying the astrophysically crucial $^{12}C(\alpha,\gamma)^{16}O$ reaction at high temperatures

Jeppe Thingholm[1,2], K. C. W. Li[1,2], V. W. Ingeberg[1,2], K. L. Malatji[3], L. M. Donaldson[3], R. Neveling[3], S. Sunniva[1,2] and P. Adsley[4,5]

NORWEGIAN NUCLEAR RESEARCH CENTRE

Helium Burning

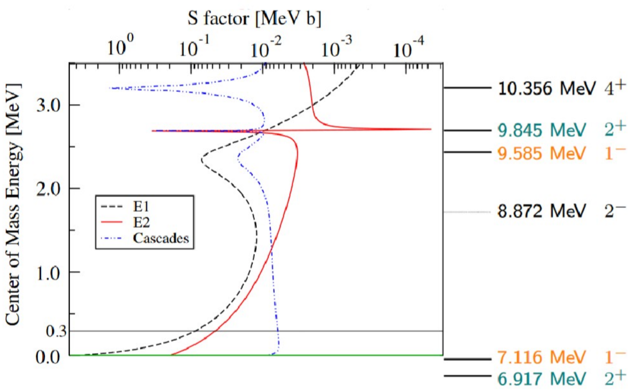


Helium burning consists of two major steps, the first being the triple-α process and the second the $^{12}C(\alpha,\gamma)^{16}O$ reaction. The triple-α process consists of three steps, the first being the fusion of two α particles to form the short lived ^{8}Be nucleus. Most of the formed ^{8}Be will quickly decay back to two α particles, but some will fuse with another α particle to form ^{12}C in an excited state, nearly always the Hoyle state. The excited ^{12}C will then perform two subsequent γ decays to the ground state [1]. The ^{12}C can then absorb another α particle, forming ^{16}O in an excited state. The excited ^{16}O will nearly always α decay, however, it may also undergo γ decay to a subthreshold state, forming a stable ^{16}O nucleus [2].

Importance of the $^{12}C(\alpha,\gamma)^{16}O$ reaction

After hydrogen and helium, the two most abundant elements are ^{12}C and ^{16}O, which are both produced from helium. The triple-α and $^{12}C(\alpha,\gamma)^{16}O$ reactions are both competing for the same α particles. Furthermore, ^{12}C and ^{16}O both take part in the CNO cycle. Thus the amount of ^{12}C and ^{16}O and the ratio between them plays a major role in stellar nucleosynthesis. With current models, using the current data and uncertainties of the $^{12}C(\alpha,\gamma)^{16}O$ reaction, results in a an uncertainty of around 50% for the final $^{12}C/^{16}O$ mass fraction. Thus our understanding of stellar evolution is highly dependent on our understanding of the $^{12}C(\alpha,\gamma)^{16}O$ reaction [2].

Structure of ^{16}O



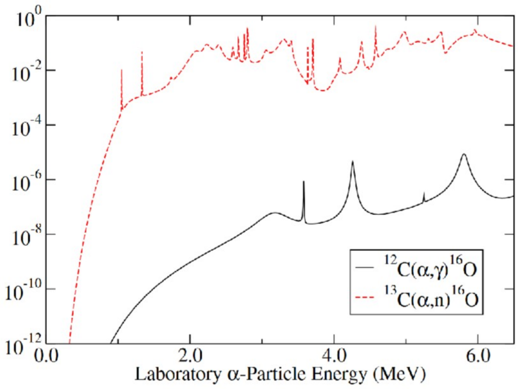
A comprehensive review of the $^{12}C(\alpha,\gamma)^{16}O$ reaction can found in Ref. [2]. The article by deBoer *et al.* contains an analysis of all available resonance scattering data on the formation of the ^{16}O compound nucleus, as well as relevant direct and transfer reactions probing the structure of ^{16}O. The analysis is performed using *R*-matrix code AZURE2.

- The *S*-factor is split into three different components, two of which are the direct $E1$ and $E2$ γ decay to the ground state. The third is the cascade where an above threshold state γ decays to a subthreshold state
- The figure also shows some of the excited levels in ^{16}O. The two lowest levels in the figure are subthreshold levels, as they are a few hundred keV too low to decay by other means than γ decay.
- The tails of the subthreshold state interact with the tails of broad higher lying states, resulting in complicated contributions at low energy (less than 1 MeV).

Difficulties measuring the $^{12}C(\alpha,\gamma)^{16}O$ reaction

Due to the difficulties in measuring the $^{12}C(\alpha,\gamma)^{16}O$ reaction, the structure of ^{16}O has also been studied using other reactions.

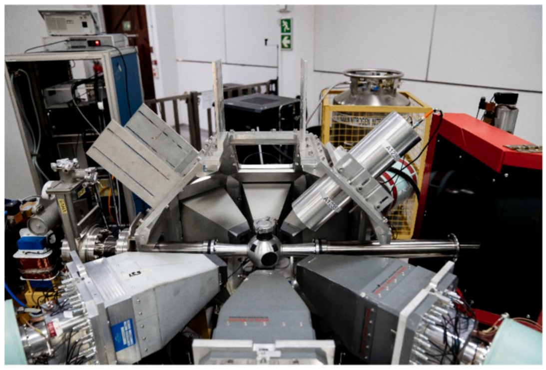
- The direct measurement of the $^{12}C(\alpha,\gamma)^{16}O$ reaction has proven difficult, especially at low energies where the cross sections are not experimentally accessible. Thus it is necessary to extrapolate down to stellar energies.
- Another big issue is the $^{13}C(\alpha,n)^{16}O$ reaction from the ^{13}C contaminant.



As the figure above shows, the cross section for the $^{13}C(\alpha,n)^{16}O$ reaction is several orders of magnitude higher than the $^{12}C(\alpha,\gamma)^{16}O$ reaction. This results in a high number of neutrons, even for an enriched ^{12}C target, which results in contaminant background events in the γ-ray detectors [2].

Experiment

The right figure shows the reaction chamber together with the detector mounting frame.



- The experiment will be based on the proposal in the article of deBoer *et al.* to measure the reaction at higher energies ($E_{CoM} \simeq$ 3–7 MeV), with focus on the off-resonance regions. This would help constrain not only the contributions from broad, higher-lying resonances, but also the subthreshold contributions which dominate medium stellar energies [2].
- To reduce contaminant background from neutrons, a self-supporting enriched ^{12}C target will be used, and a pulse-shape discrimination algorithm will be developed to remove most of the neutron events.
- At iThemba LABS, we will directly measure the $^{12}C(\alpha,\gamma)^{16}O$ reaction in the off-resonance regions, as well as at the resonance peaks for normalization. We will use 15 $LaBr_3$ detectors in close geometry, configured at θ = 45, 90 and 135 deg.

References

[1] H. O. U. Fynbo et al., Nature **433**, 136–139 (2005).

[2] R. J. deBoer et al., Rev. Mod. Phys. **89** (2017).

[1]Department of Physics, University of Oslo, N-0316 Oslo, Norway
[2]Norwegian Nuclear Research Centre, NO-0316 Oslo, Norway
[3]iThemba LABS, National Research Foundation, PO Box 722, Somerset West 7129, South Africa
[4]Department of Physics and Astronomy, Texas A&M University, College Station, Texas 77843, USA
[5]Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA