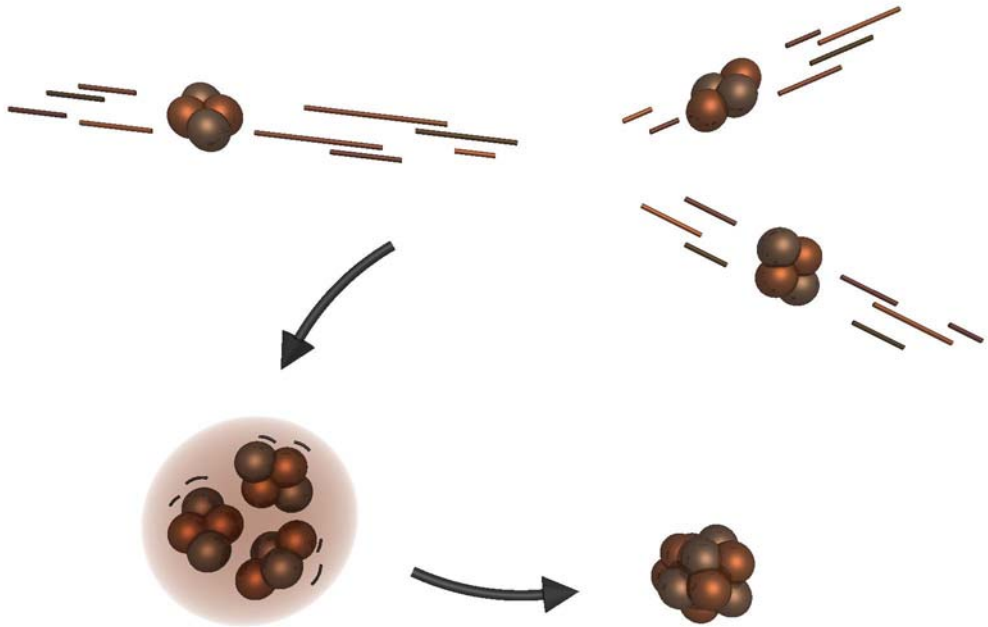
Status of the Triple Alpha reaction rate



Christian Aaen Diget
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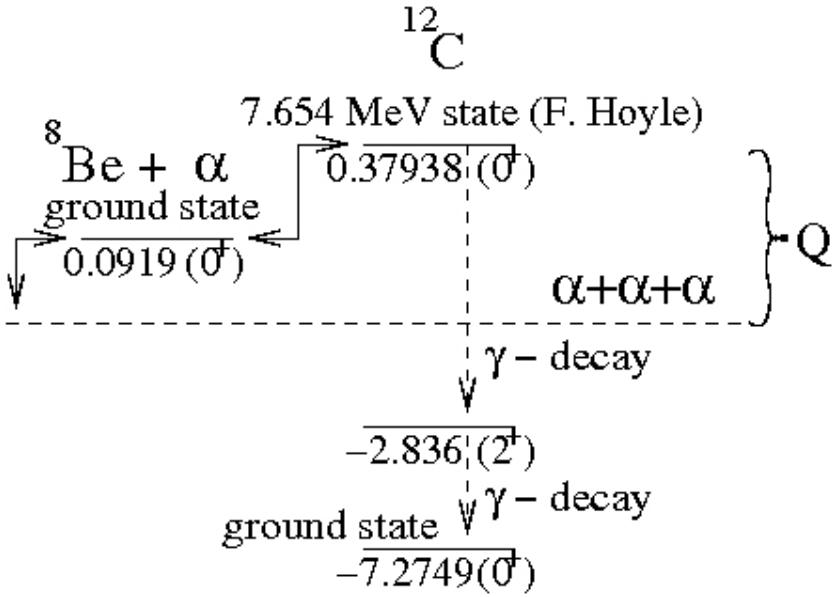
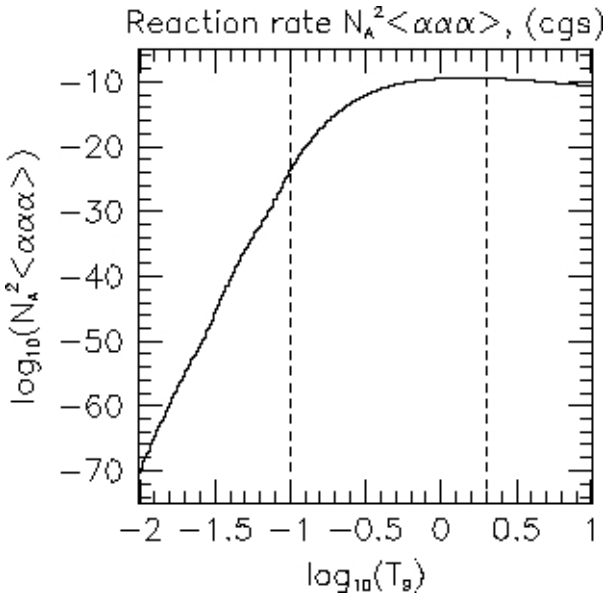
Status of the Triple Alpha reaction

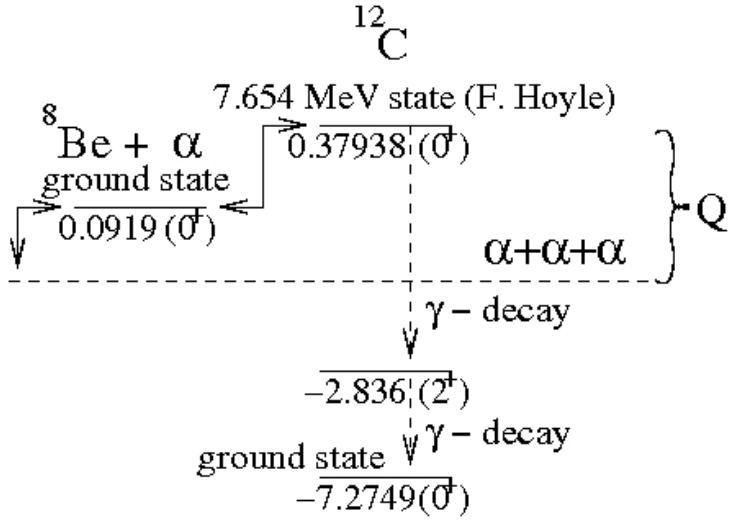
- Reaction rate at resonance ($T_9 \approx 0.1$–2).
- Reaction rate at very high or low temperatures.
- Present reaction rates and their physics input.





Reaction rate at resonance

- $T_9 \approx 0.1–2$.
- Both resonances within the Gamow window.



$$r_{3\alpha} \propto \Gamma_{rad} \exp\left(-\frac{Q}{kT}\right)$$

$$Q = E_r - 3m_\alpha c^2$$

$$\Gamma_{rad} = \Gamma_\gamma + \Gamma_\pi = \frac{\Gamma_\gamma + \Gamma_\pi}{\Gamma} \frac{\Gamma}{\Gamma_\pi} \Gamma_\pi$$

- Needed precision is 5–7% [Au05].
- Core-collapse supernovae and AGB stars.

[Au05] S.M. Austin, Nucl. Phys. A 758 (2005) 375c

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Most recent experiment				Contribution to rate uncertainty
[No76]	Q	=	$379.38 \pm 0.20\,\mathrm{keV}$	$(1.2\,\%)$
[Ma76]	$\frac{\Gamma_\gamma+\Gamma_\pi}{\Gamma}$	=	$(4.12 \pm 0.11)\,10^{-4}$	$(2.7\,\%)$
[Al77]	$\frac{\Gamma_\pi}{\Gamma}$	=	$(6.8 \pm 0.7)\,10^{-6}$	$(10\,\%)$
[St70]	Γ_π	=	$60.5 \pm 3.9\,\mu\mathrm{eV}$	$(6.4\,\%)$
			Total:	$(12\,\%)$

[Al77] D.E. Alburger Phys. Rev. C 16 (1977) 2394
[Ma76] R.G. Markham et al., Nucl. Phys. A 270 (1976)
[No76] J.A. Nolen and S.M. Austin Phys. Rev. C 13 (1976) 1773
[St70] P. Strehl, Z. Phys. 234 (1970) 416

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[Au05] S.M. Austin, Nucl. Phys. A 758 (2005) 375c (MSU & WMU)
[Cr05] H. Crannell et al., Nucl.Phys. A 758 (2005) 399c

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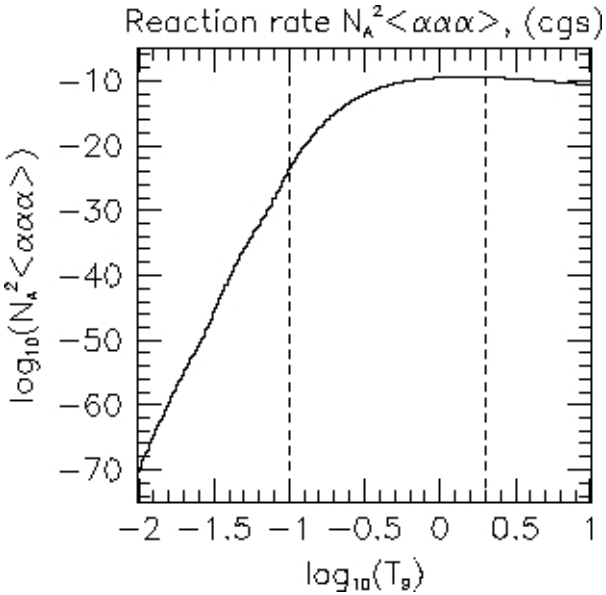
High or low temperatures (T9 < 0.1 or 2 < T9)

$r_{3\alpha}$ not dominated by resonant reaction through the 7.654 MeV state [Bu06].

- 7.654 MeV state still important.
- Other natural parity states.
- Direct reaction contributions.



^{8}Be	0^+		2^+	
^{12}C	0^+	1^-	2^+	3^-

Needed information on individual states:

- Resonance energy (E_r)
- Total width (Γ)
- Radiative width (Γ_{rad})

[Bu06] L.R. Buchmann and C.A. Barnes, Nucl. Phys. A (*in press*)

High temperatures (T9 > 2)

– States contributing to the high temperature reaction rate.

^{12}C	J^π	E_x	Γ	Γ_{rad}
[Aj90]	0^+	$7.654\,\mathrm{MeV}$	$8.3 \pm 1.0\,\mathrm{eV}$	$3.7 \pm 0.5\,\mathrm{meV}$
[Fy05]	0^+	$11.23 \pm 0.05\,\mathrm{MeV}$	$2.5 \pm 0.2\,\mathrm{MeV}$	unknown

– Interference between the two states results in 0^+ strength centered around the 10.3 MeV energy region.

– Small contribution to reaction rate, even for high value of Γ_{rad}.

[Aj90] F. Ajzenberg-Selove, Nucl. Phys. A 506 (1990) 1

[Fy05] H.O.U. Fynbo et al., Nature 433 (2005) 136

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[De87]	2^+	$9\,\mathrm{MeV}$	$0.56\,\mathrm{MeV}$	$0.2\,\mathrm{eV}$

– 2+ state at 9 MeV dominates the high T reaction rate, if included.

[Aj90] F. Ajzenberg-Selove, Nucl. Phys. A 506 (1990) 1
[De87] P. Descouvemont and D. Baye, Phys. Rev. C 36 (1987) 54
[Fy05] H.O.U. Fynbo et al., Nature 433 (2005) 136

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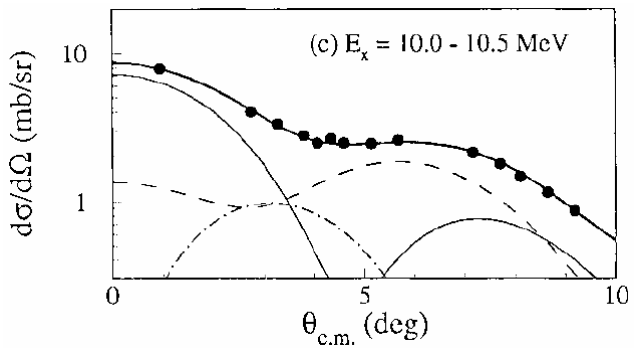
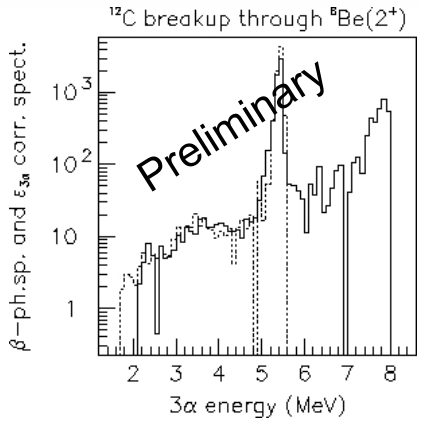
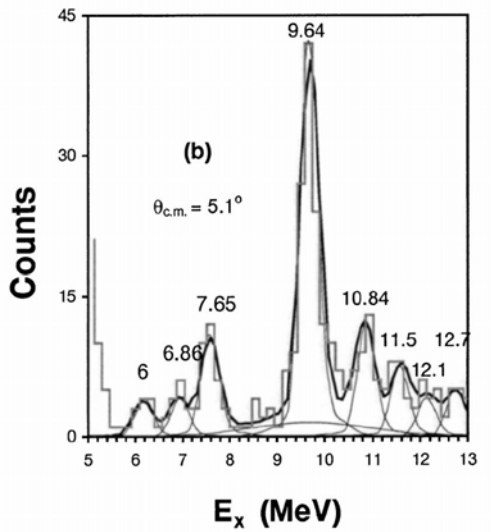
[De87]	2^+	$9\,\mathrm{MeV}$	$0.56\,\mathrm{MeV}$	$0.2\,\mathrm{eV}$
[BJ03]	2^+	$11.46 \pm 0.20\,\mathrm{MeV}$	$0.43 \pm 0.10\,\mathrm{MeV}$	
[It04]	2^+	9–$11\,\mathrm{MeV}$	$1\,\mathrm{MeV}$	







[Aj90] F. Ajzenberg-Selove, Nucl. Phys. A 506 (1990) 1

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[Fy05] H.O.U. Fynbo et al., Nature 433 (2005) 136

[It04] M. Itoh et al., Nucl. Phys. A 738 (2004) 268

[BJ03] Bency John et al., Phys. Rev C 68 (2003) 014305

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[It04]	2^+	9–$11\,\mathrm{MeV}$	$1\,\mathrm{MeV}$	
[Aj90]	3^-	$9.6\,\mathrm{MeV}$	$35 \pm 5\,\mathrm{keV}$	$0.3\,\mathrm{meV} < \Gamma_{rad} < 14\,\mathrm{meV}$
[Aj90]	1^-	$10.8\,\mathrm{MeV}$	$315 \pm 25\,\mathrm{keV}$	unknown

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[De87] P. Descouvemont and D. Baye, Phys. Rev. C 36 (1987) 54
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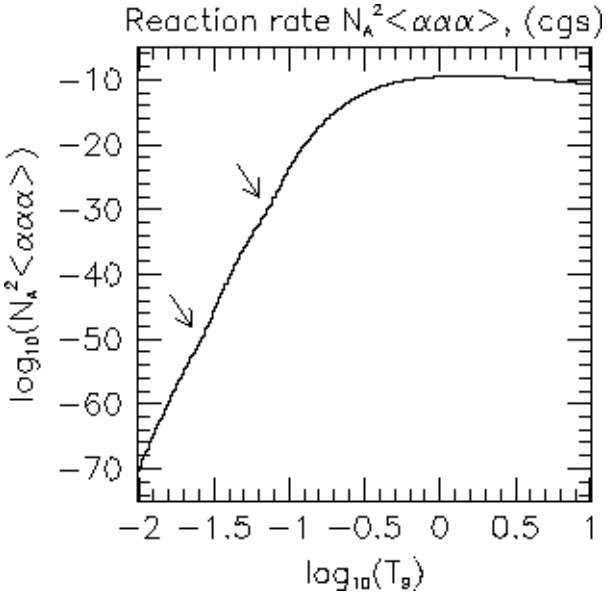
^{8}Be	J^π	E_x	Γ
[Ti04]	0^+	$92\,\mathrm{keV}$	$5.57 \pm 0.25\,\mathrm{eV}$
[Ti04]	2^+	$3\,\mathrm{MeV}$	$1513 \pm 15\,\mathrm{keV}$

[Aj90] F. Ajzenberg-Selove, Nucl. Phys. A 506 (1990) 1
[De87] P. Descouvemont and D. Baye, Phys. Rev. C 36 (1987) 54
[Fy05] H.O.U. Fynbo et al., Nature 433 (2005) 136
[It04] M. Itoh et al., Nucl. Phys. A 738 (2004) 268
[BJ03] Bency John et al., Phys. Rev C 68 (2003) 014305
[Ti04] D.R. Tilley et al., http://www.tunl.duke.edu/nucldata/ourpubs/08_2004.pdf

Low temperatures ($T_9 < 0.1$)

- Significant contributions:

  Only 0^+ strength.
- Low energy tail of 7.654 MeV state [No85].
- Low energy tail of ^{8}Be(gs).



- Non-Breit-Wigner effects:
- Interference with higher lying state (strength at 10.3 MeV) [Fy05].
- R-Matrix description of threshold effects (form of low energy tails of ^{12}C and ^{8}Be states) [Fy05].
- Direct L=0 E2 capture to the 4.44 MeV state [La86].

[Fy05] H.O.U. Fynbo et al., Nature 433 (2005) 136
[La86] K. Langanke et al., Z. Phys. A 324 (1986) 147
[No85] K. Nomoto et al., Astron. Astrophys. 149 (1985) 239

Summary of present 3α reaction rates

3α rate contributions	An99 NACRE	CF88	Fy05	La86
Low T non-BW effects.	%	%	Interference between 7.654 MeV& 11.2 MeV states. R-Matrix description of threshold effects. (^{12}C and ^{8}Be)	Direct L=0 E2 capture to 4.44 MeV ^{12}C state
7.654 MeV ^{12}C 0^+ state.	√	√	√	√
0^+ strength at 10.3 MeV in ^{12}C	%	%	Interference between 7.654 MeV& 11.2 MeV states.	%
2^+ state at 9.1 MeV	√	%	%	%
3^- state at 9.6 MeV	√	%	%	%
1^- state at 10.8 MeV	%	%	%	%
2^+ state at 3 MeV in ^{8}Be	%	%	%	%

[An99] C. Angulo et al., Nucl. Phys. A 656 (1999) 3

[CF88] G.R. Caughlan W.R. Fowler, At. Data Nucl. Data Tab. 40 (1988) 283

[Fy05] H.O.U. Fynbo et al., Nature 433 (2005) 136

[La86] K. Langanke et al., Z. Phys. A 324 (1986) 147

N.B.: Not [CF85]

Thank you for your attention