

# CARBON AND OXYGEN BURNING TOWARDS ASTROPHYSICAL ENERGIES

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Journée Andromède du 18/01/2022

Emma MONPRIBAT

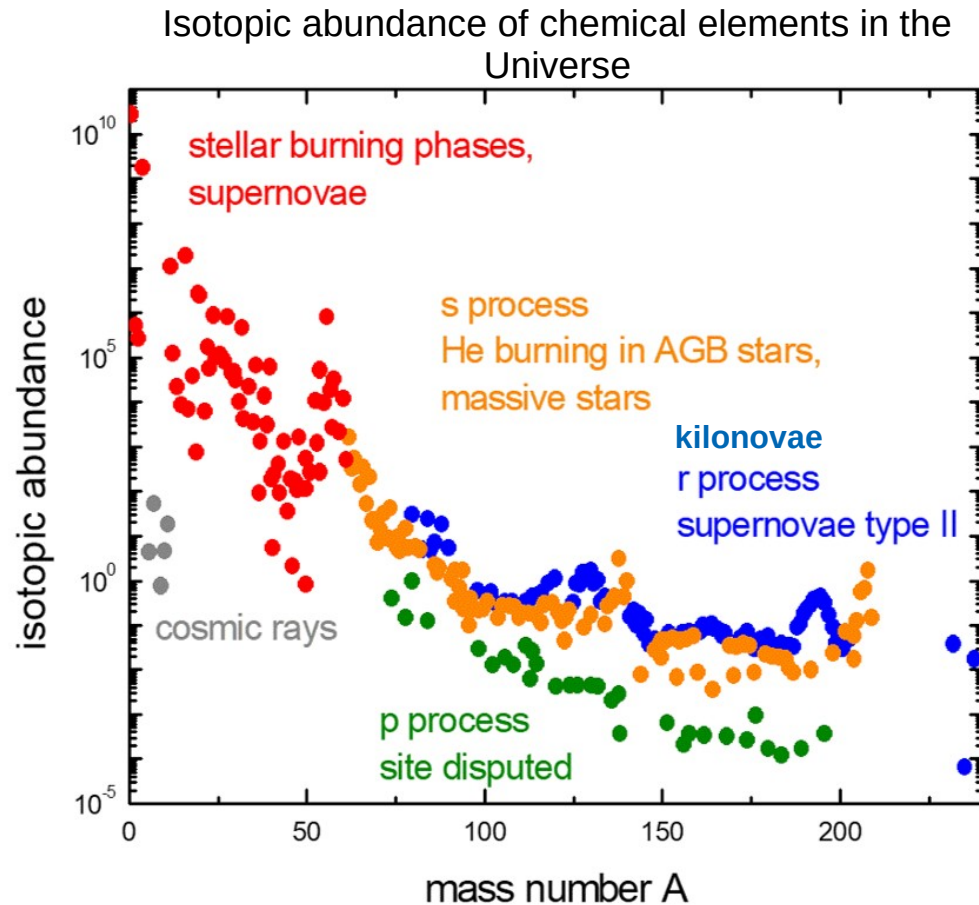
Pour la collaboration STELLA

IPHC, France



# Isotopic abundance and stellar nucleosynthesis

- Origin of chemical elements => **nucleosynthesis**
- Stellar evolution
  - $M_i < 8 M_\odot$  => white dwarf, may generate Type Ia supernova
  - $M_i = 8 - 10 M_\odot$  => burning under degenerate condition, carbon flash
  - $M_i > 10 - 12 M_\odot$  => burning in a non-degenerate core
- C-burning and O-burning => “**key phases**” of stellar evolution
  - Intermediate mass stars, massive stars, type Ia supernova..
  - $^{12}\text{C} + ^{12}\text{C}$ ,  $^{12}\text{C} + ^{16}\text{O}$  and  $^{16}\text{O} + ^{16}\text{O}$



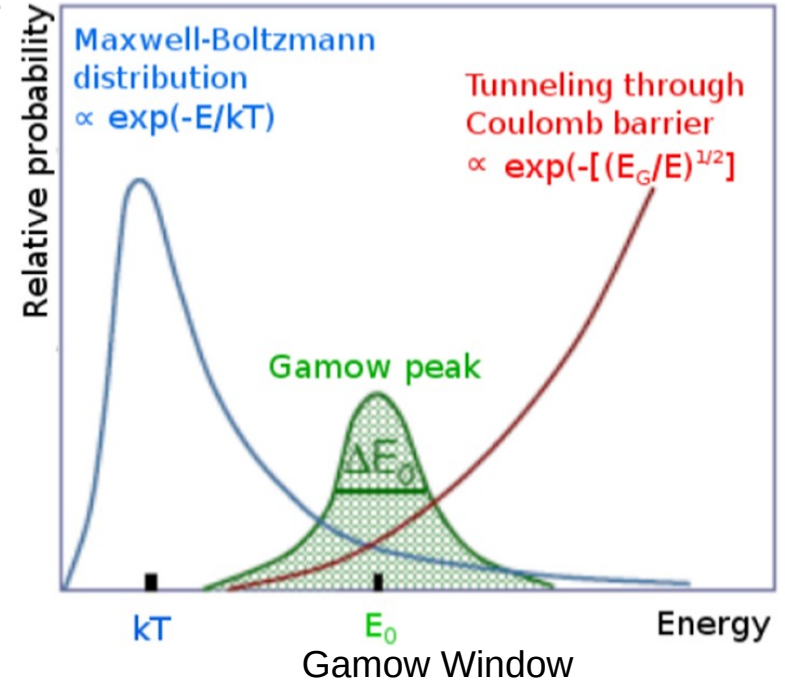
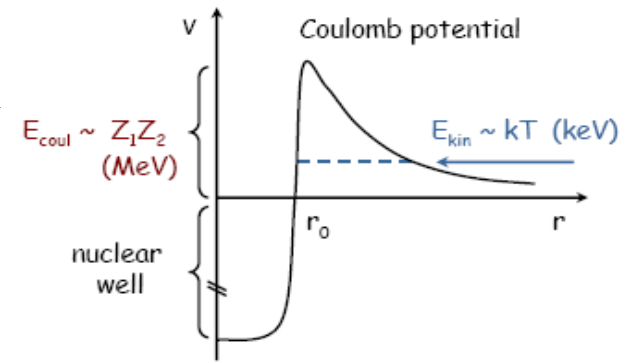
# Astrophysical context

- Energy available from thermal motion
  - $kT \sim 1 - 10^2$  keV (1 keV for the Sun)
  - **Maxwell-Boltzmann distribution**
  - Stars: fusion of charged species => Coulomb barrier
  - During static burning:  $kT \ll E_{\text{Coul}}$
- Reaction occurs through **tunneling**
  - Highest fusion probability => **Gamow window**
  - Cross section :

$$\sigma(E) = \frac{1}{E} e^{-2\pi\eta} S(E)$$

with  $S(E)$  the astrophysical S-factor

- **Reaction rates**



# Deep sub-barrier cross section

- What do we know about nuclear fusion ?

- **Fusion hindrance**

- Measured cross sections lower than theoretical predictions
- Observed in many systems

(Jiang *et al.*, PRL **93**, 2004)

- Nucleons are fermions => Pauli repulsion

(Simenel *et al.*, INPC 2016, Fusion17, PRC **95**, 2017)

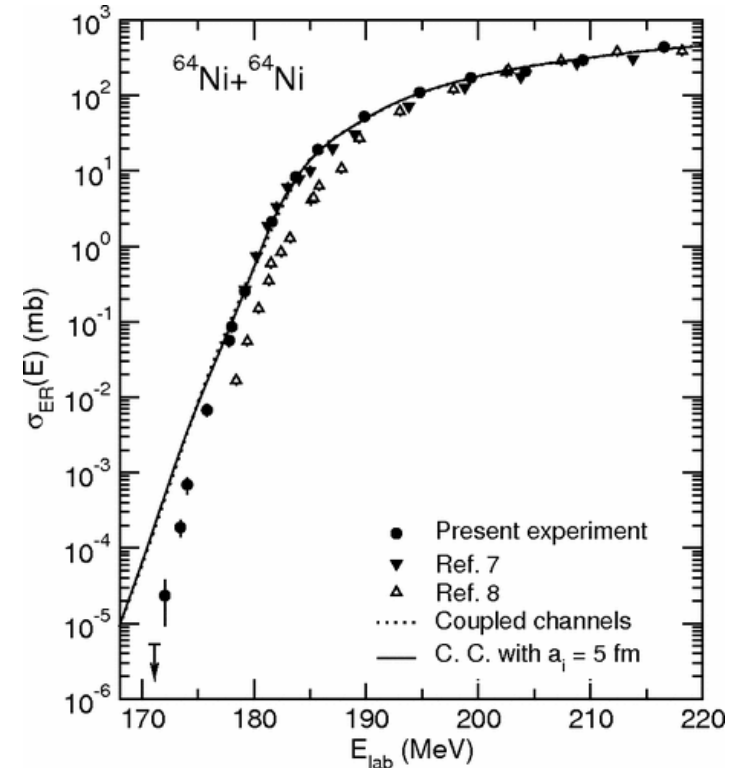
- **Resonance**

- Local increase of cross section
- Molecular configuration of nuclei

(Jenkins & Courtin, Journal of Physics G: Nuclear and Particle Physics, **42**, 2015)

- $^{12}\text{C}+^{12}\text{C}$  system known to present many resonances

(Almqvist *et al.*, PRL **4**, 1960)



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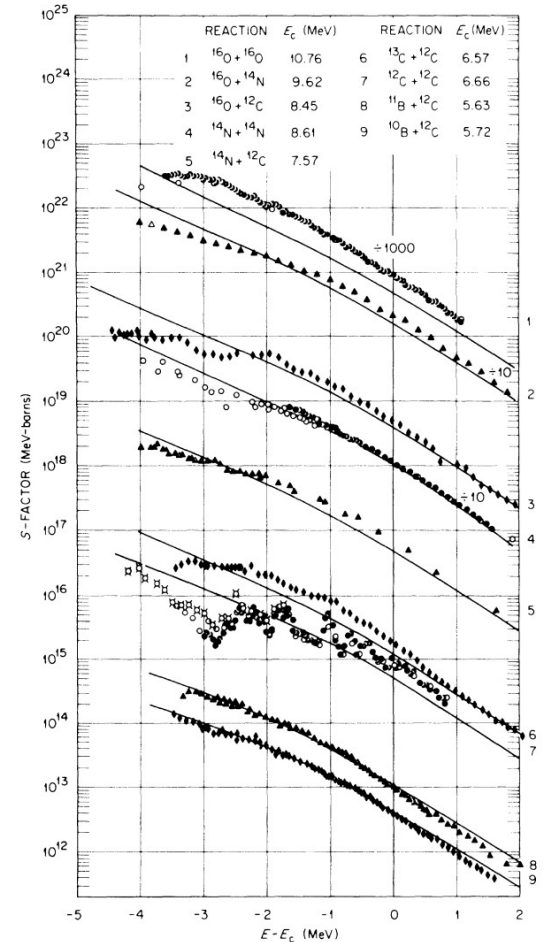
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# The (incomplete yet) complex story of $^{12}\text{C}$ fusion

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- (Heine, *Nuclei: Exotics and Stars*, *Nuclei In the Cosmos* 2021)

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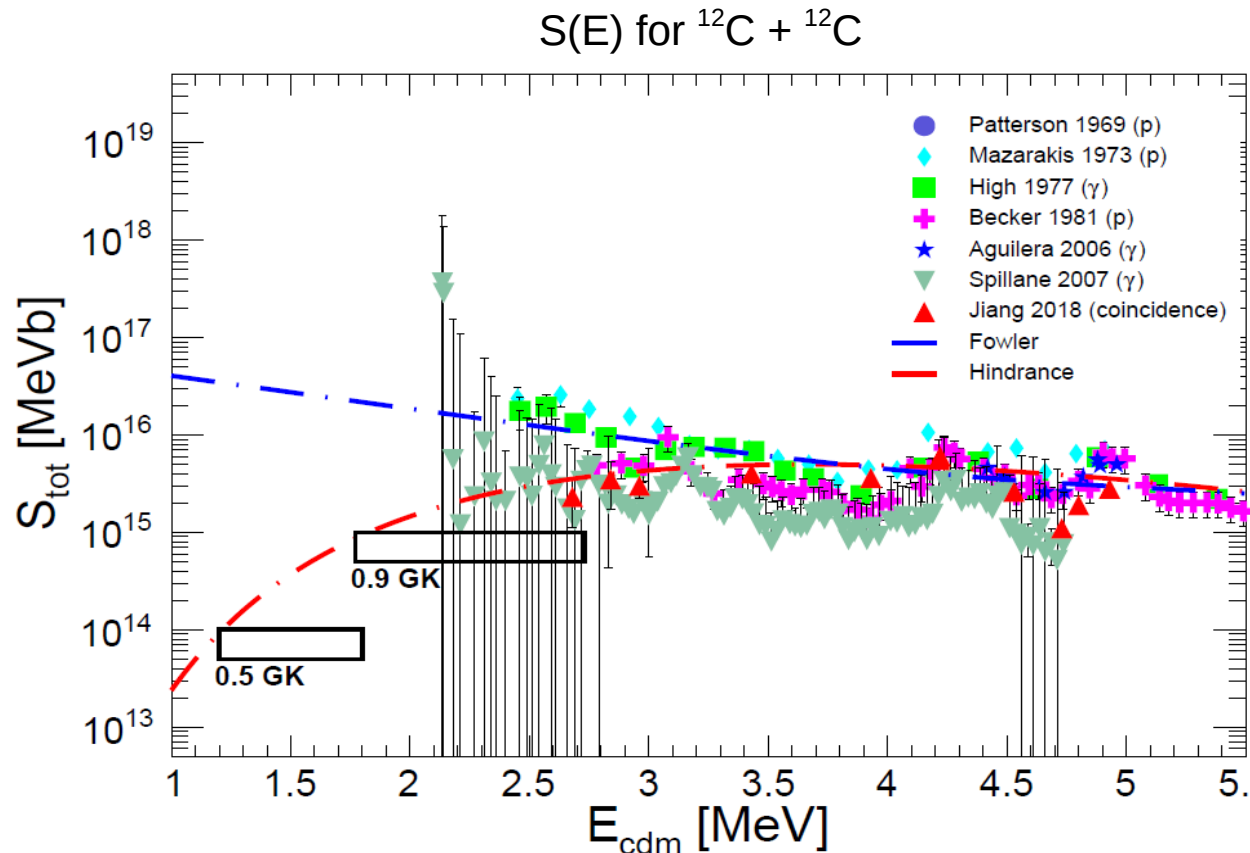
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← Publication on STELLA apparatus

← Publication from the first run of STELLA at Andromède

(Heine, *Nuclei: Exotics and Stars, Nuclei In the Cosmos* 2021)

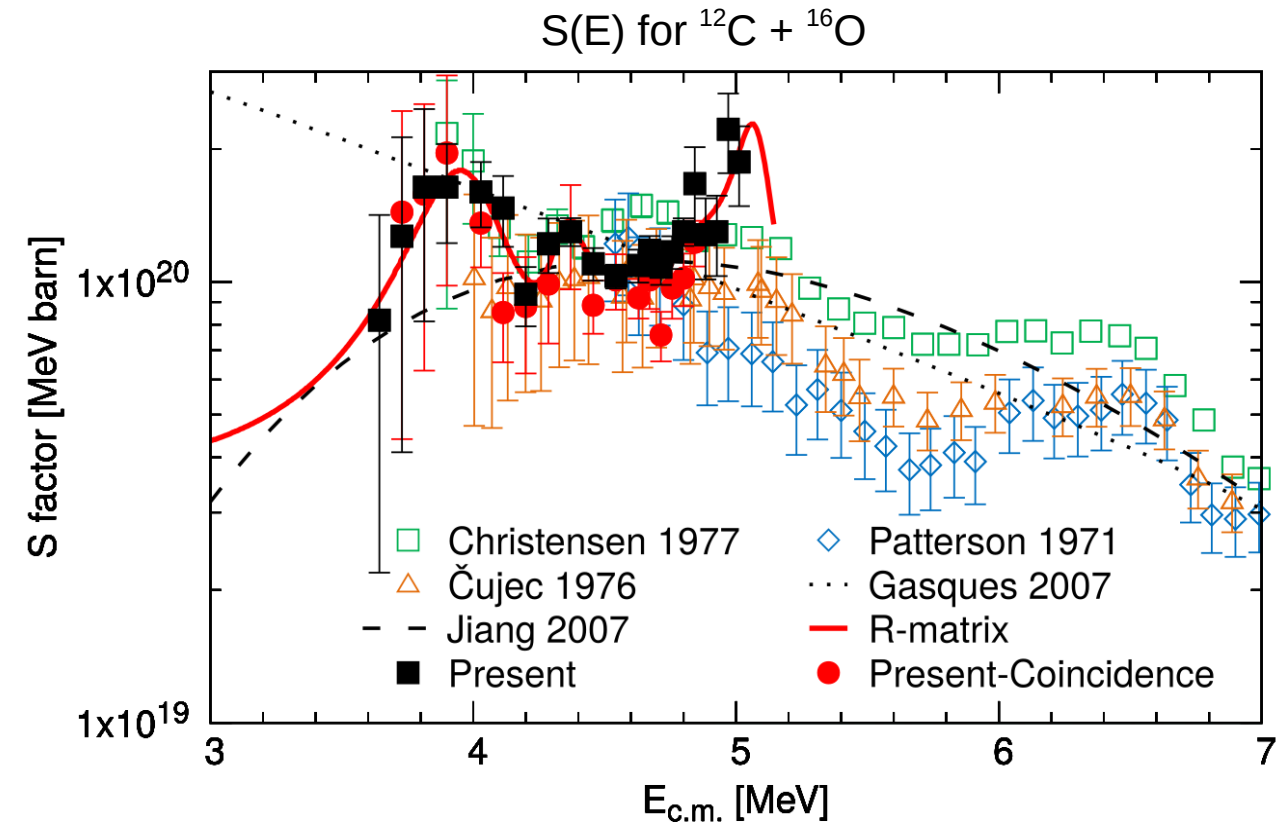
# Brief history of $^{12}\text{C} + ^{12}\text{C}$



- Detection of particles or gamma rays
- Extrapolations with different trends
- At low energies => large uncertainties or no data
- **Experimental challenges**
  - Low cross sections ( $\sim$ pb)
  - Background
- Jiang et al. => **coincidence method**  
(Jiang et al., NIMA 682, 2012)



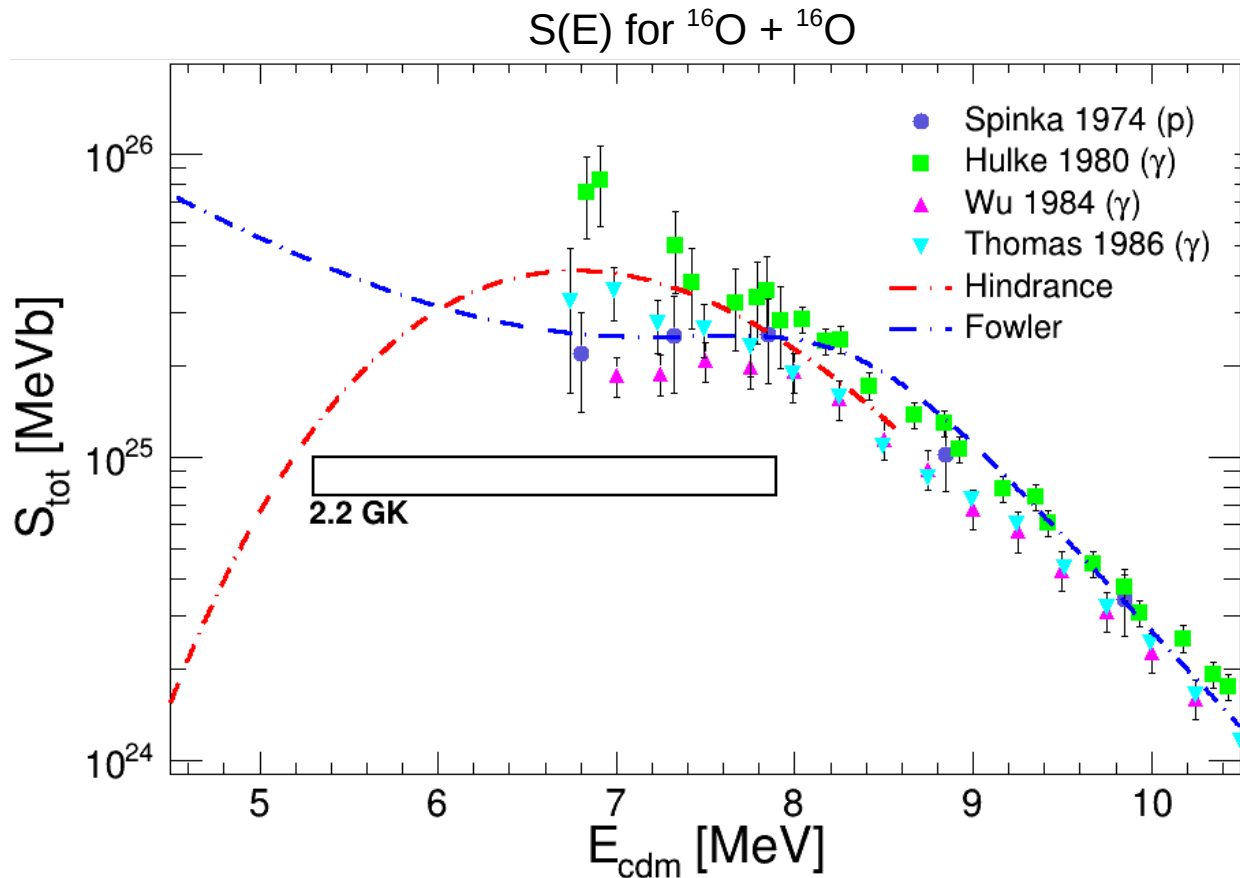
# State of art for $^{12}\text{C}+^{16}\text{O}$



(Fang *et al.*, PRC **96**, 2017)

- Detection of particles or gamma rays
- Extrapolations with different trends
- At low energies => large uncertainties
- **Experimental challenges**
  - Low cross sections ( $\sim$ pb)
  - Background
- Use of the coincidence method for highest energies

# State of art for $^{16}\text{O} + ^{16}\text{O}$



- Detection of particles or gamma rays
- Extrapolations with different trends
- $E_{\text{cdm}} = 6,7 - 8,5$  MeV  $\Rightarrow$  disagreement between experimental data
- At low energies  $\Rightarrow$  no experimental data
- **Experimental challenges**
  - Exit channels
  - Oxygen target

# Conclusion

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- $^{12}\text{C} + ^{12}\text{C}$ ,  $^{12}\text{C} + ^{16}\text{O}$  and  $^{16}\text{O} + ^{16}\text{O} \Rightarrow$  fusion reactions important for nuclear physics but also for astrophysics
- Direct application to astrophysics: determination of reaction rates (Monpriat et al., A&A)
- Experimental challenges
  - Low cross sections, background...
  - Need of specific detection method, very efficient tools and high intensity beam

**$\Rightarrow$  the answer: the STELLA at Andromède experiment**

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<sup>1</sup> Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France

<sup>2</sup> University of Strasbourg Institute of Advanced Studies (USIAS), Strasbourg, France

And thank you for your attention !

# Bibliography

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- C.L. Jiang et al ., Physical Review C, 97 :012801, 2018.
- C.L. Jiang et al ., Nuclear Instruments and Methods in Physics Research A, 682 :012, 2012.
- M. Heine et al. , Nuclear Instruments and Methods in Physics Research A, 903 :01, 2017.
- Page web de l'accélérateur andromède, 15/05/2020, <http://ipnwww.in2p3.fr/ANDROMEDE ?lang=fr>.
- G. Fruet et al ., Physical Review Letters, 124 :192701, 2020.
- C.L. Jiang et al ., Physical Review Letters, 93 :012701, 2004
- C. Simenel et al ., EPJ Web of Conferences 163, 00055, 2017
- C.L. Jiang et al ., Physical Review C, 75 :015803, 2007.
- E. Almqvist et al ., Physical Review Letters, 4 :515, 1960.

# Bibliography

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- L.R. Gasques et al. , Physical Review C, 76 :035802, 2007.
- C. Illiadis, Nuclear Physics of Stars. Wiley-VCH, 2015.
- Thielemann, F. K., Arnould, M., & Truran, J. W. 1986, in Advances in Nuclear Astrophysics, ed. E. Vangioni-Flam, J. Audouze, M. Casse, J.-P. Chieze, & J. Tran Thanh Van, 525–540
- Bucher, B., Tang, X. D., Fang, X., et al. 2015, Phys. Rev. Lett., 114, 251102
- Choplin, A., Maeder, A., Meynet, G., & Chiappini, C. 2016, A&A, 593, A36 [arXiv:1606.02752]
- Caughlan, G. R. & Fowler, W. A. 1988, Atomic Data and Nuclear Data Tables, 40, 283
- Jenkins, D. & Courtin, S. 2015, Journal of Physics G: Nuclear and Particle Physics, 42, 034010, and references therein.
- G. Fruet, Structure des ions lourds et nucléosynthèse dans les étoiles massives : la réaction  $^{12}\text{C} + ^{12}\text{C}$ . PhD thesis, University of Strasbourg, 2018.
- X. Fang et al., Physical Review C, 96 :045804, 2017

# Bibliography

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- C.E. Rolfs and W.S. Rodney. *Cauldrons in the Cosmos*. The University of Chicago Press, 1988.
- P. Eggenberger et al ., *Astrophys Space Sci*, 316 :43, 2008.
- W.A. Fowler et al ., *Annu Rev. Astro. Astrophysics*, 13 :69, 1975.
- L.J. Patterson et al ., *The Astrophysical Journal*, 157 :367, 1969.
- M. Mazarakis et al ., *Physical Review C*, 7 :1280, 1973.
- M.D. High and B. Cujec, *Nuclear Physics A*, 282 :181, 1977.
- H.W. Becker et al ., *Z. Phys.A - Atom and Nuclei*, 28 :305, 1981.
- E.F. Aguilera et al ., *Physical Review C*, 73 :064, 2006.
- T. Spillane et al ., *Physical Review Letters*, 98 :122, 2007.
- C.L. Jiang et al ., *Physical Review C*, 97 :012801, 2018
- R.G. Stokstad et al., *Physical Review Letters*, 37 : 888, 1976