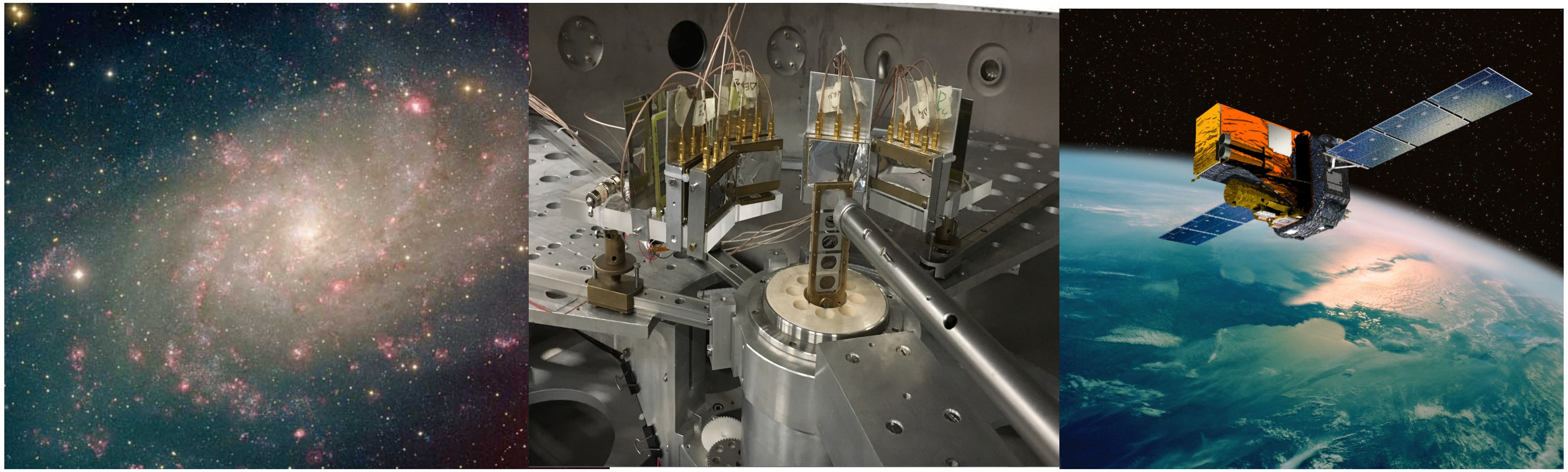
Direct and Indirect Measurements in Nuclear Astrophysics



Aurora Tumino

Outline

- Nuclear Physics in Astrophysics
- Feature of thermonuclear reactions and experimental requirements in direct mesurements
- Indirect measurements
- Direct vs. Indirect measurements: 12C+12C fusion as case study

Nuclear Astrophysics

Rich & Diverse Interdisciplinary Field bringing together

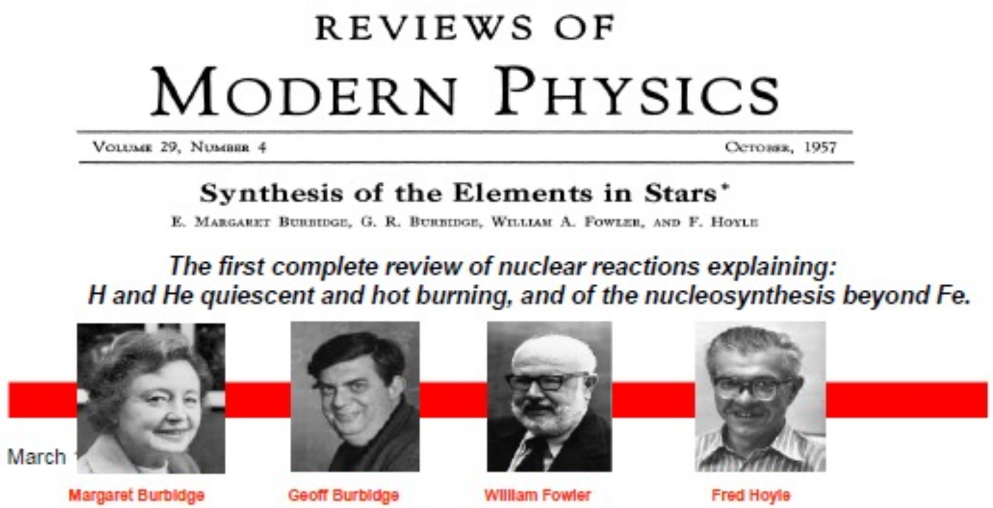
- Modelers
- Observers
- Nuclear physicists: Experimentalists as well as Theorists

Nucleosynthesis in 1900

... to the seminal **B^{2}FH** review paper of 1957,

the basis of the modern nuclear astrophysics

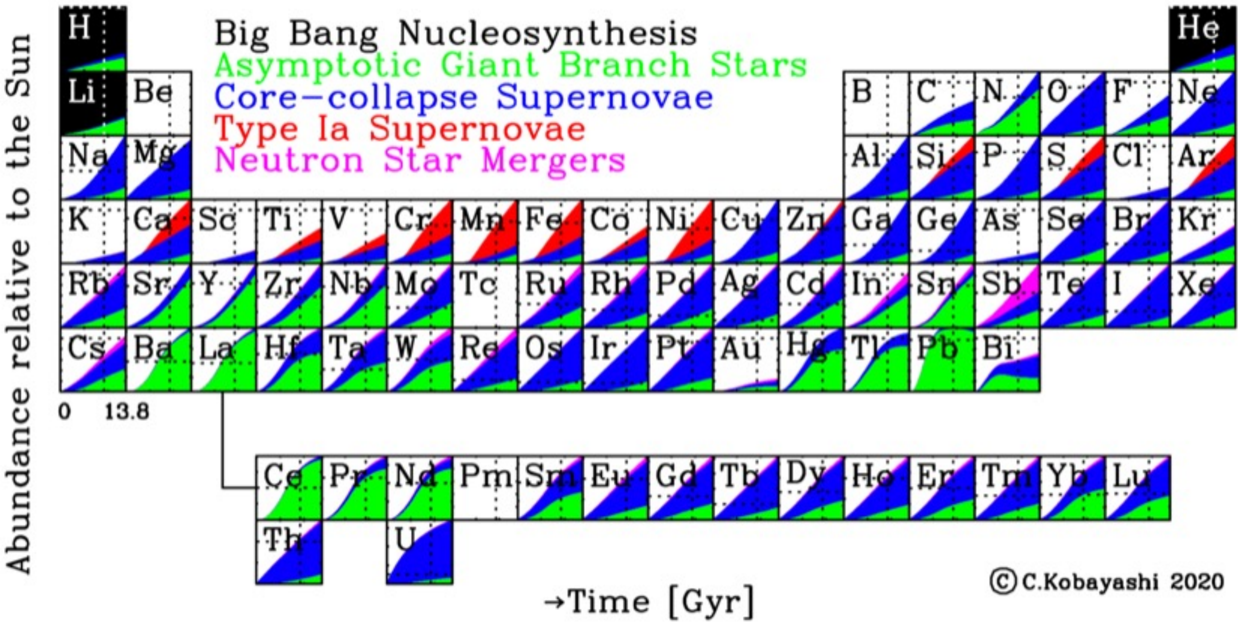
this work has been considered as the greatest gift of astrophysics to modern civilization



Nuclear reactions responsible for both ENERGY PRODUCTION and CREATION OF ELEMENTS in 4 ways/environments:

Where the elements are made...we WISH we knew that!
Here is the "current belief" in terms of nucleosynthetic source of elements in the Solar System

Each element in this periodic table is color-coded by the relative contribution of nucleosynthesis sources



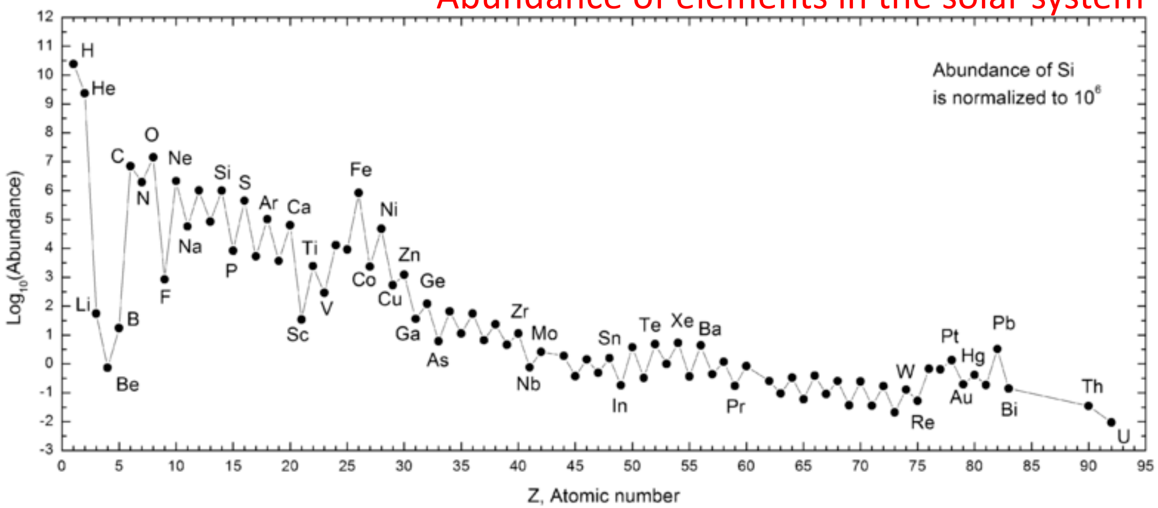
In [astronomy](), a "metal" is any element other than hydrogen or helium, the only elements that were produced in significant quantities in the Big Bang. Thus, the [metallicity]() of a [galaxy]() or other object is an indication of stellar activity after the Big Bang.

Where's the Nuclear Physics?

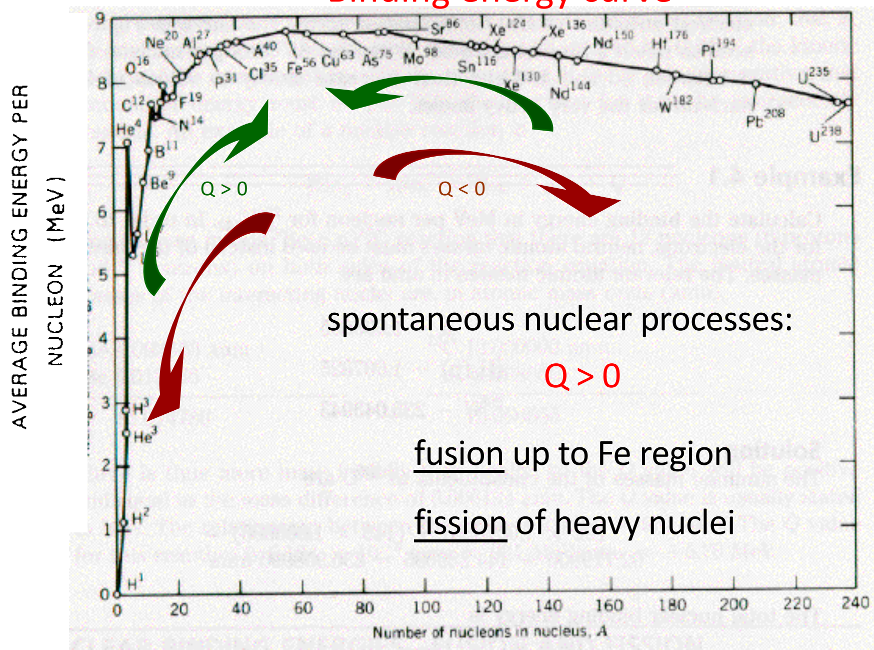
H burning → conversion of H to He
He burning → conversion of He to C, O …
C, O and Ne burning → production of A: 16 to 28
Si burning → production of A: 28 to 60
s-, r- and p-processes → production of A>60
Li,Be, and B from cosmic rays

- Big Bang Nucleosynthesis does not go beyond Li due to missing stable nuclei of mass number 5 or 8
- Odd-even staggering of abundances (Oddo-Harkins rule)
- Larger alpha-nuclei abundance, particularly those connected to particular values of Z and N (so called magic numbers,2,8,20,28,50 …) which are significant with regard to the structure of nuclei … at least up to Fe
- Broad peak around Fe

Abundance of elements in the solar system

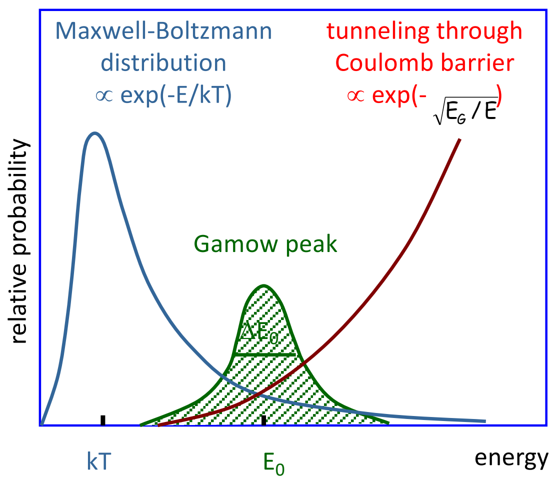


Binding energy curve



Nuclear Astrophysics

Astrophysical energies for reactions between charged particles are determined by the Gamow peak: the most effective energy region for thermonuclear reactions



The Gamow energy $E_0 = f(Z_1, Z_2, T)$ varies depending on the reaction and/or the temperature, usually from tens to hundreds of keV, but also MeV.

Examples: $T \sim 15\times10^6$ K ($T_6 = 15$)

reaction	Coulomb barrier (MeV)	E_0 (keV)	area under Gamow peak ~ $\langle\sigma v\rangle$
p + p	0.182	5.9	7.0×10^{-6}
$\alpha + {}^{12}C$	2.242	56	5.9×10^{-56}
${}^{16}O + {}^{16}O$	10.349	237	2.5×10^{-237}

$kT \ll E_0 \ll E_{coul}$

10^{-18} barn $< \sigma < 10^{-9}$ barn   major experimental challenges

General features: Quiescent vs. Explosive Burning

Feature	**Quiescent Burning** (e.g., Main Sequence, Red Giant)	**Explosive Burning** (e.g., Supernovae, X-ray Bursts)
Temperature (T)	$10^6 - 10^8$ K	$ > 10^9$ K
Energy (E_0)	$10\ \mathrm{keV} - 1\ \mathrm{MeV}\ (E_0 \ll E_{Coul})$	$\sim \mathrm{MeVs}\ (E_0 \leq E_{Coul})$
Cross-Section (σ)	$10^{-18}\ \mathrm{barn} < \sigma < 10^{-9}\ \mathrm{barn}$	$10^{-6}\ \mathrm{barn} < \sigma < 10^{3}\ \mathrm{barn}$
Interaction Time (τ)	$\sim \langle\sigma v\rangle^{-1} \sim 10^9$ years	$\sim \langle\sigma v\rangle^{-1} \sim$ seconds
Unstable Species	**DO NOT** play significant role	**DO** play significant role

Shared Experimental Challenges

- **Low Signal-to-Noise Ratio** (Common across both due to low cross-sections or low beam intensities)
- **Unknown Nuclear Properties** (Especially for exotic, unstable nuclei)
- **Low Beam Intensities** (Particularly for Radioactive Ion Beams - RIBs, which are several orders of magnitude lower than stable beams)

Experimental Requirements

- **Extrapolation Procedures** (Crucial for quiescent, less so for explosive) using $S(E) = E\sigma(E)\exp(2\pi\eta)$
- **High Beam Intensities / RIBs production & acceleration** (High for quiescent, RIBs essential for explosive)
- **Ultra Pure Targets**
- **Long Measurements High Detection Efficiency** (Essential for both)
- **Storage Rings**

Experimental approach: alternative solutions

- Underground experiments to reduce (cosmic) background: LUNA (LNGS Italy), Felsenkeller (Germany), CASPAR (USA), JUNA (China), particularly suited to perform gamma spectroscopy

- Surface experiments:

    inverse kinematics: accelerating heavier nuclei into lighter targets.

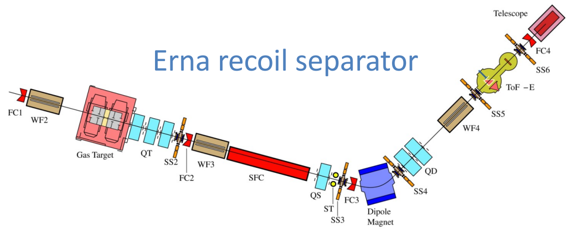
    coincidence experiments (g-g, g-particle, …) ;

    recoil separators: to separate reaction products from unreacted beam and disperse them according to their mass-to-charge-state ratio;

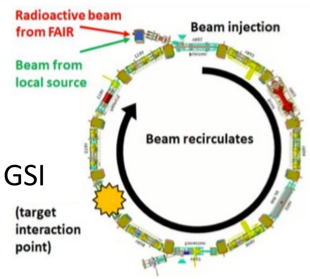
    storage rings: to overcome beam intensity limitations. Recirculate the beam many times for repeated target interactions.

    …

Erna recoil separator



Cryring GSI



- Use indirect methods: Coulomb Dissociation (CD), Asymptotic Normalization Coefficients (ANC), Trojan Horse Method (THM) …

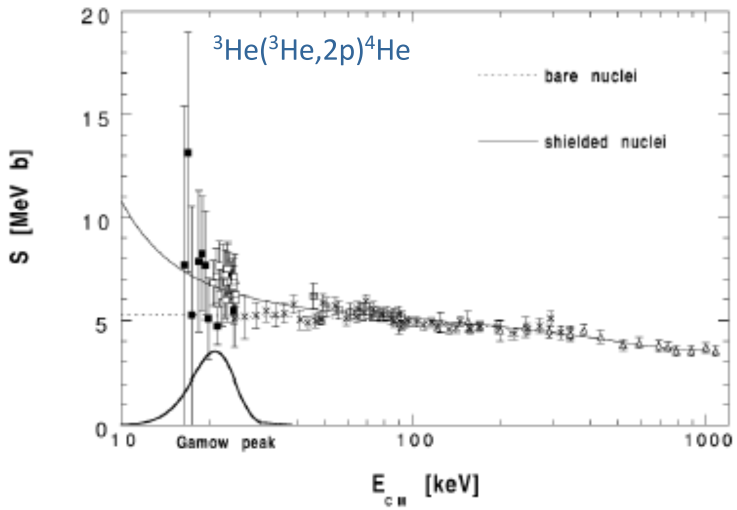
Dedicated Talks for some of these items already this afternoon

To give you the feeling what low signal-to-noise ratio means

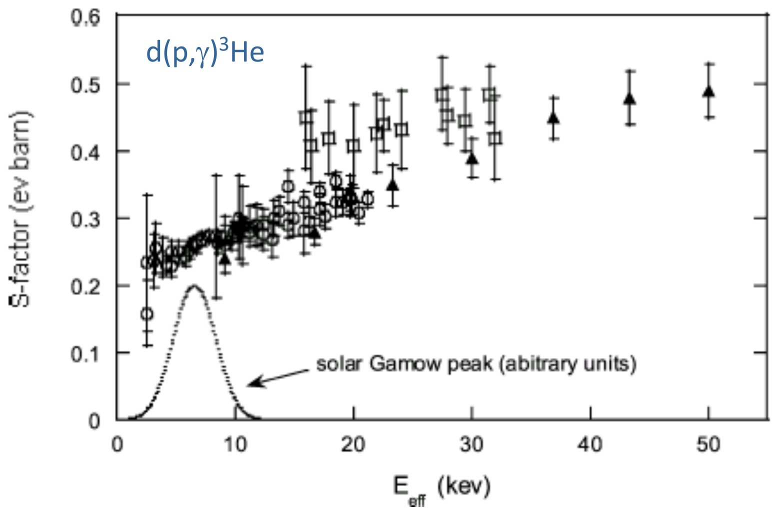
LUNA – Phase I: 50 kV accelerator (1992-2001)

investigate reactions in solar pp chain

R. Bonetti et al.: Phys. Rev. Lett. 82 (1999) 5205



C. Casella et al.: Nucl. Phys. A706 (2002) 203-216



@ lowest energy:

σ ~ 20 fb → 1 count/month

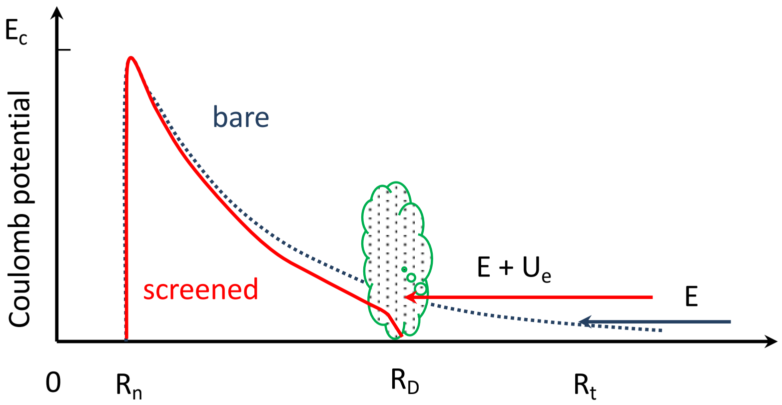
@ lowest energy:

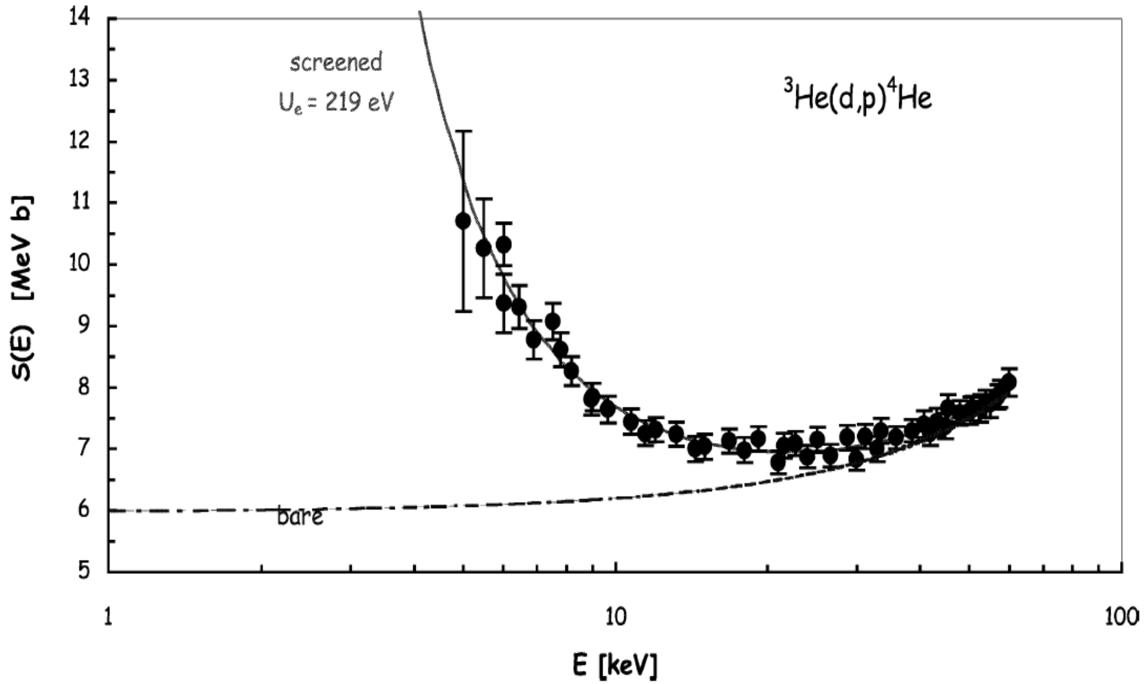
σ ~ 9 pb → 50 counts/day

only two reactions studied directly at the Gamow peak

…but… intrinsic limitation at astrophysical energies → → → → Electron Screening

S(E) experimental enhancement due to the electron screening $S(E)_s = S(E)_b \exp(\pi\eta U_e/E)$

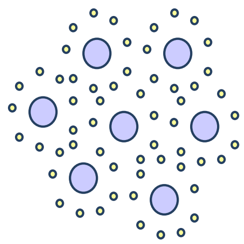




Electron Screening

In astrophysical plasma:

- the screening, due to free electrons in plasma, can be different
→ we need $S(E)_b$ to evaluate reaction rates



Debye-Hückel radius

$R_D \sim (kT/\rho)^{1/2}$

A theoretical approach to extract the electron screening potential U_e in the laboratory is needed

… however, experimental studies of reactions involving light nuclides have shown that the observed exponential enhancement of the cross section at low energies were in all cases significantly larger
(about a factor of 2)
than it could be accounted for from available atomic-physics model, i.e. the adiabatic limit $(U_e)_{ad}$ … screening yet to be fully understood

→ No way to measure $S(E)_b$ from direct experiments at energies where screening is important

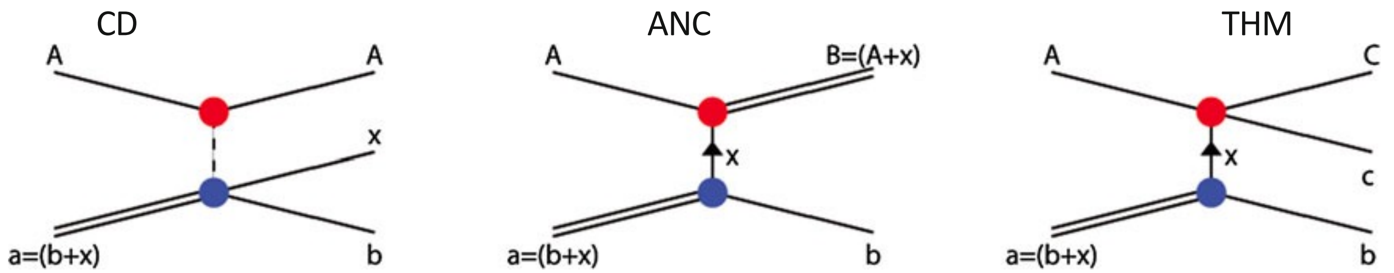
$S_b(E)$-factor extracted from extrapolation of higher energy data

Indirect Methods for Nuclear Astrophysics

- to measure cross sections at never reached energies (no Coulomb suppression), where the signal is below current detection sensitivity
- to get independent information on U_e
- to overcome difficulties in producing the beam or the target (radioactive ions, neutrons..)

Coulomb Dissociation (CD), Asymptotic Normalization Coefficient (ANC) and Trojan Horse Methods (THM)

They share some common features: the astrophysically relevant two-body reaction at low energies is replaced by a high-energy reaction usually with a three-body final state. In all cases a virtual particle (photon γ or nucleus x) is transferred between the two subsystems in the reaction.



Quite straightforward experiment, no Coulomb suppression, no electron screening but …

Entrance channel

A+a

Several reaction mechanisms link the two channels

Reaction products

C+c+…

The reaction theory is needed to select only one reaction mechanism. However, nowadays powerful techniques and observables for careful data analysis and theoretical investigation.

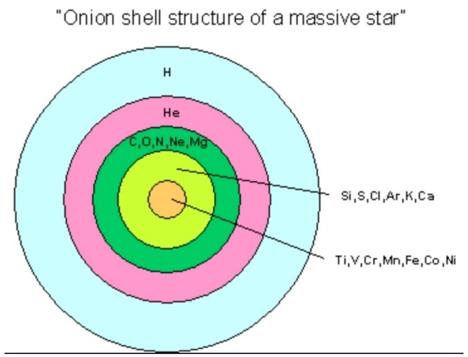
C-burning

Relevant temperature T ~ 0.1-1.2 GK

It powers scenarios that influence the fate of stars, such as:

- Late evolutionary stages of massive stars (> 8 $M_{\odot}$). It influences M_{up}, threshold in mass for hydrostatic carbon burning to occur (relevant T ~ 1 GK)
- Superbursts from accreting neutron stars (T ~ 0.15-0.7 GK): C-fusion triggers (?) the ignition in the burning ashes of hydrogen and helium on the surface of accreting neutron stars
- Type Ia supernovae (0.15-0.7 GK and ρ ~ (2- 5) 10^9 g/cm^3): interpreted as the consequence of explosive carbon burning ignited near the core of the white dwarf star in a binary system

the C/O ratio influences the nucleosynthesis and, in turn, the resulting light curve



12C+12C fusion

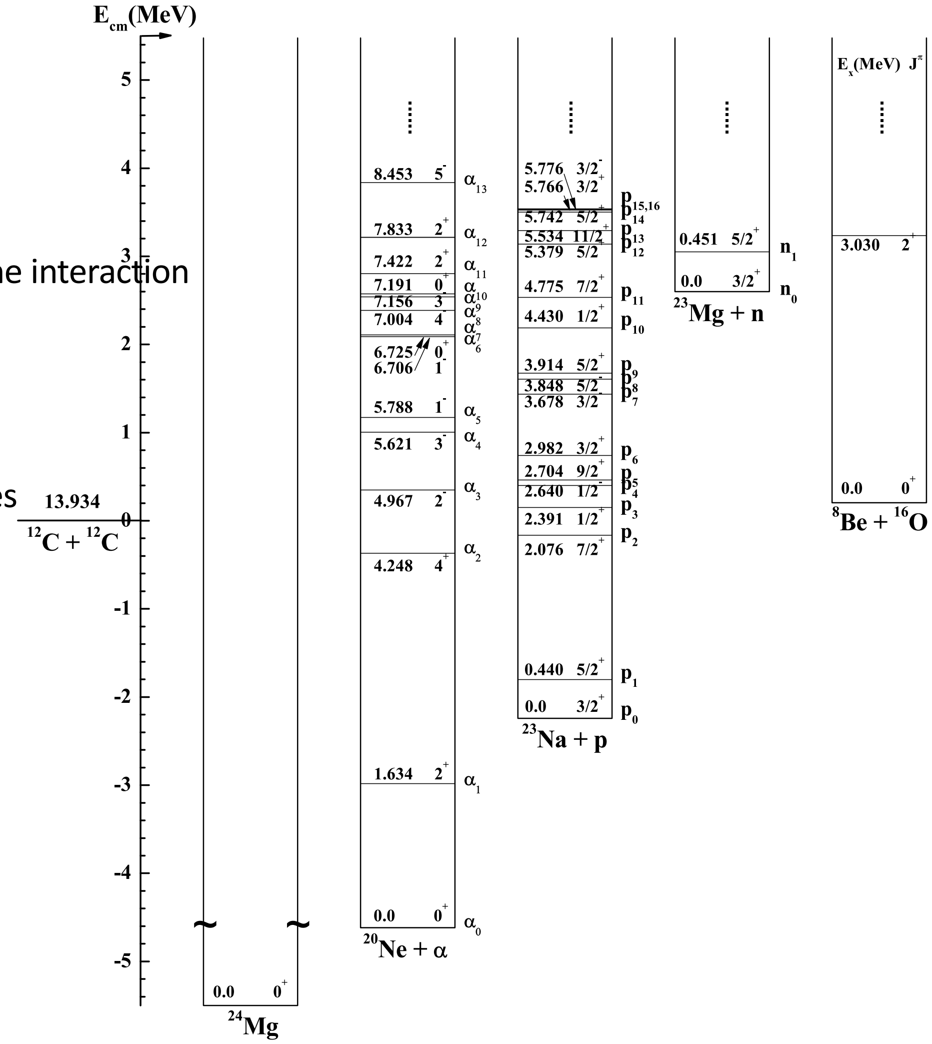
Carbon burning temperature from 0.1 to 1.2 GK $\rightarrow$ E_{cm} from 1 to 3 MeV

Principal reactions:

$^{12}C(^{12}C,\alpha)^{20}Ne$	+ 4.617 MeV
$^{12}C(^{12}C,p)^{23}Na$	+ 2.241 MeV
$^{12}C(^{12}C,n)^{23}Mg$	- 2.599 MeV
$^{12}C(^{12}C,\gamma)^{24}Mg$	+13.933 MeV
$^{12}C(^{12}C,2\alpha)^{16}O$	-0.20 MeV

The most frequent results of the interaction

Considerable efforts to measure the $^{12}C+^{12}C$ cross section at astrophysical energies



M.G. Mazarakis & W.E. Stephensen, Phys. Rev. C 7 1280 (1973)

K. U. Kettner *et al.*, Phys. Rev. Lett. 38, 337 (1977)

H.W. Becker et al., Z. Phys. A 303, 305 (1981)

L. Barron-Palos et al., Nucl. Phys. A 779, 318 (2006)

E.F. Aguleira et al.,Phys. Rev. C 73, 064601 (2006)

T. Spillane et al., Phys. Rev. C 73, 064601 (2006)

T. Spillane et al., Phys. Rev. Lett. 98, 122501 (2007)

B. Bucher et al., Phys. Rev. Lett. 114, 251102 (2015)

C.L. Jiang et al., Phys. Rev. C 97 012801 (2018)

J. Zickefoose et al., Phys. Rev. C 97, 065806 (2018)

A. Tumino et al., Nature (2018)

G. Fruet et al. PRL, 124 192701 (2020)

W.P. Tan et al. PRL, 124 192702 (2020), W.P. Tan et al. PRC (2024)

L. Morales-Gallegos et al. EPJ A (2024) ….

12C+12C: recent experiments

Jiang et al. 2018: down to $E_{c.m.}$ = 2.84 MeV and 2.96 MeV for the p and α channels, respectively, using a sphere array of 100 Compton-suppressed Ge detectors in coincidence with silicon detectors.

Fruet et al. 2020: down to $E_{c.m.}$=2.16 MeV using the particle-γ coincidence technique and thin C-target. Charged particles were detected using annular silicon strip detectors, while γ-ray detection was accomplished with an array of LaBr3(Ce) scintillators. Only the p_1 and α_1 channels. Total S* factor reconstructed taking not observed branchings from the literature

Tan et al. 2020 and 2024: down to $E_{c.m.}$=2.2 MeV using the particle-γ coincidence technique and thick target. In particular, p and αs were detected using a silicon detector array, and γ-rays with HPGe detectors. Only the p_1 and α_1 channels. Total S* factor reconstructed taking not observed branchings from the literature.

Tumino et al. 2018: THM measurement down to 0.8 MeV for the $p_{0,1}$ and $\alpha_{0,1}$ channels. Coincidence experiment using the $^{14}N+^{12}C$ reaction at 30 MeV of beam energy.

Morales Gallegos et al. 2023: down to $E_{c.m.}$ = 2.4 MeV and 2.9 MeV for the p and α channels, respectively, using telescopes (GASTLY modules) made up of CI+Si detectors and thick target. Problems with background at the lowest energies.

Most of direct measurements: particle-γ concidence technique to overcome limitations due to target purity and beam-induced/cosmic rays background but no access to the ground state transitions

ground state transitions are crucial, as these channels contribute significantly at stellar energies

Our Experiment with theTHM

$^{12}C(^{12}C,\alpha)^{20}Ne$ and **$^{12}C(^{12}C,p)^{23}Na$** reactions via the <u>Trojan Horse Method</u> applied to the **$^{12}C(^{14}N,\alpha^{20}Ne)^{2}H$** and **$^{12}C(^{14}N,p^{23}Na)^{2}H$** three-body processes

^{2}H from the ^{14}N as spectator s

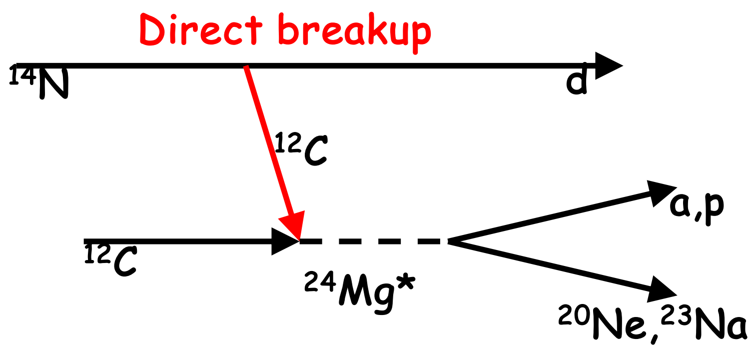
Observation of ^{12}C cluster transfer in the $^{12}C(^{14}N,d)^{24}Mg^{*}$ reaction (R.H. Zurmûhle et al. PRC 49(1994) 5)

<u>QUASI-FREE MECHANISM</u>

✓ only ^{12}C - ^{12}C interaction

✓d = spectator

$$E_{QF} = E_{14N}\,\frac{m_{^{12}C}}{m_{^{14}N}}\cdot\frac{m_{^{12}C}}{m_{^{12}C}+m_{^{12}C}} \;-10.27\ \text{MeV}$$



E_{14N} =30 MeV> E_{Coul} ⇒ **<u>NO Coulomb barrier in the entrance channel</u>**

<u>NO electron screening</u>

PWIA

$$\frac{d^3\sigma}{d\Omega_B d\Omega_b dE_B} \propto \mathrm{KF}\,\left|\Phi(p_{xs})\right|^2 \left[\frac{d^2\sigma_{xA\to bB}}{dE_{xA}\,d\Omega}\right]^{\mathrm{HOES}}$$

kinematical factor

momentum distribution of *s* inside *a*

Nuclear cross section for the A+x→C+c reaction

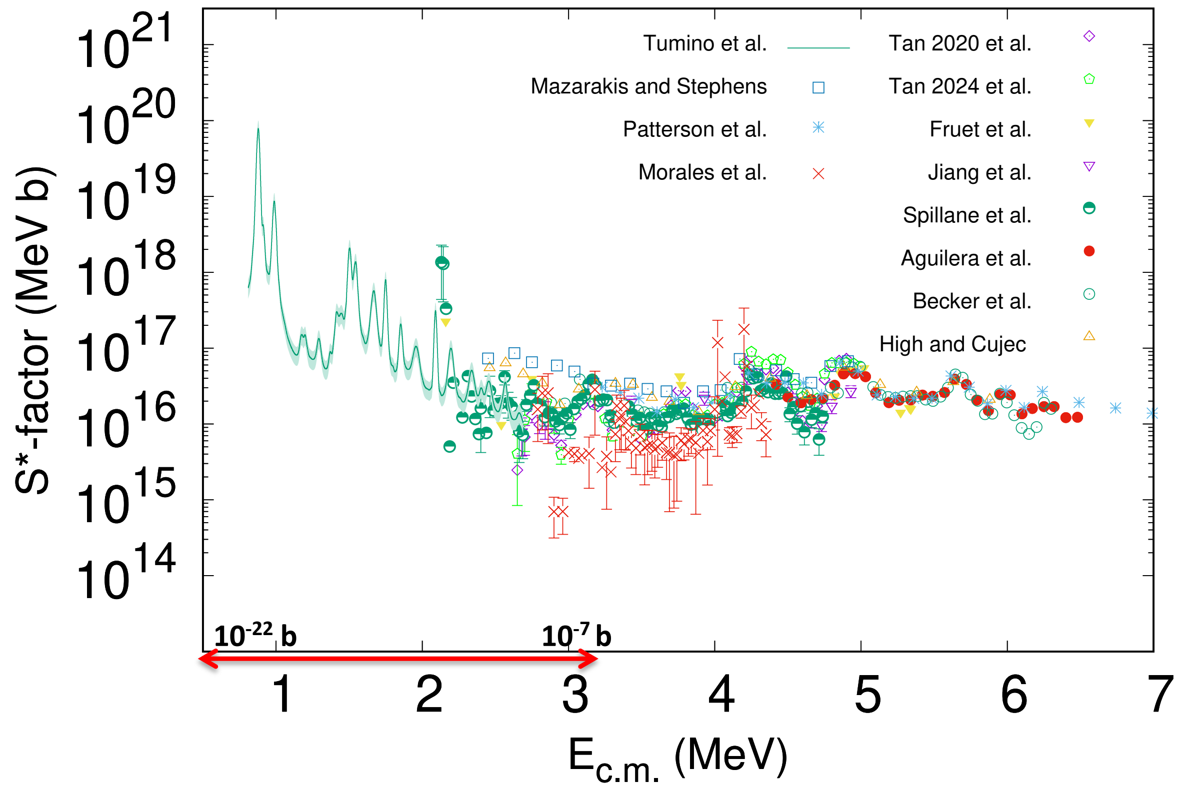
$$\frac{d^2\sigma_{xA\to c'}}{dE_{xA}\,d\Omega_s} = \mathrm{NF}\sum_i (2J_i+1)\left|\sqrt{\frac{k_{c'}}{\mu_{c'}}}\,\frac{\sqrt{2P_{c'}}\,M_i(p_{xA}R_{xA})\,\gamma^i_{xA}\gamma^i_{c'}}{D_i(E_{xA})}\right|^2$$

From the modified R-matrix approach assuming non-interfering resonances

R-matrix fits on all channels at the same time in the full energy range of interest

12C+12C comprehensive figure

$^{12}C + ^{12}C \rightarrow \alpha + ^{20}Ne$
$^{12}C + ^{12}C \rightarrow p + ^{23}Na$



Next step:

- direct data below 2 MeV (LUNA MV, Stella collaboration …)
- improve the normalization of THM data to direct ones with larger overlap

nature
International journal of science

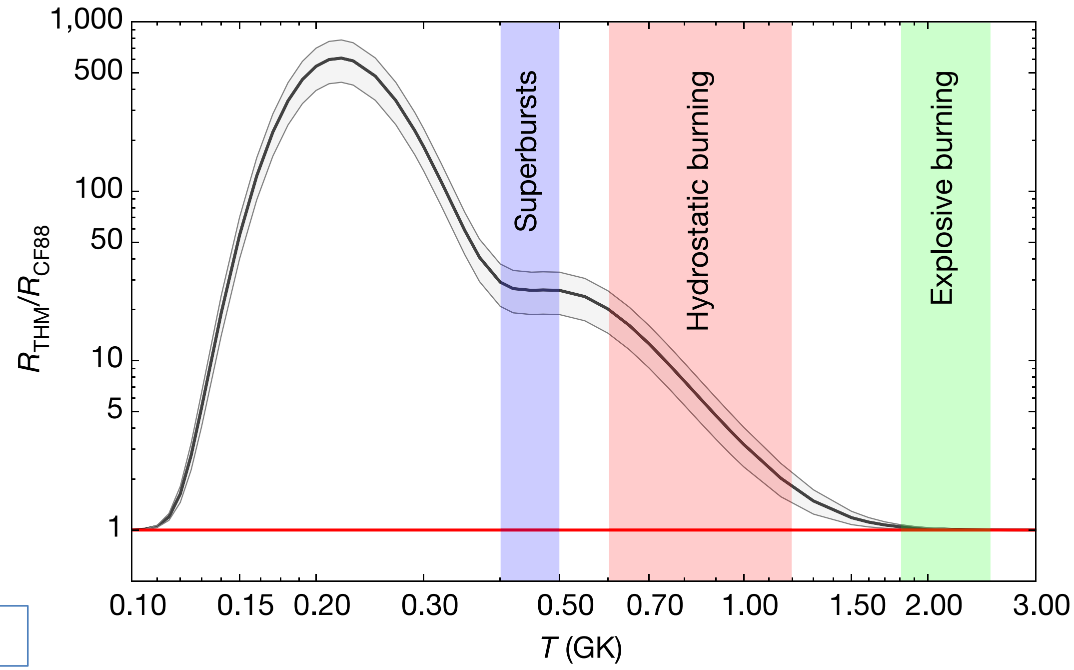
Letter | Published: 23 May 2018

An increase in the $^{12}C + ^{12}C$ fusion rate from resonances at astrophysical energies

A. Tumino, C. Spitaleri, M. La Cognata, S. Cherubini, G. L. Guardo, M. Gulino, S. Hayakawa, I. Indelicato, L. Lamia, H. Petrascu, R. G. Pizzone, S. M. R. Puglia, G. G. Rapisarda, S. Romano, M. L. Sergi, R. Spartá & L. Trache

Nature **557**, 687–690 (2018) | Download Citation

12C+12C Reaction Rate



Color shadings mark typical regions for C-burning

Compared to CF88, the present rate increases from a factor of 1.18 at 1.2 GK to a factor of more than 25 at 0.5 GK

Conclusions

Nuclear Astrophysics a fascinating and active field

Nuclear physics is a fundamental pillar of Nuclear Astrophysics

Direct measurements are becoming more and more accurate

Indirect methods are unique tools to investigate reactions on energy ranges difficult to study otherwise.

However, when possible, a joint work with direct and indirect measurements is the best choice to ensure accurate normalization and reaction rates for astrophysical applications

Thank you for your attention!