

What's Nuclear Astrophysics for a nuclear physicist?



Nuclear Astrophysics

Rich & Diverse Interdisciplinary Field bringing together

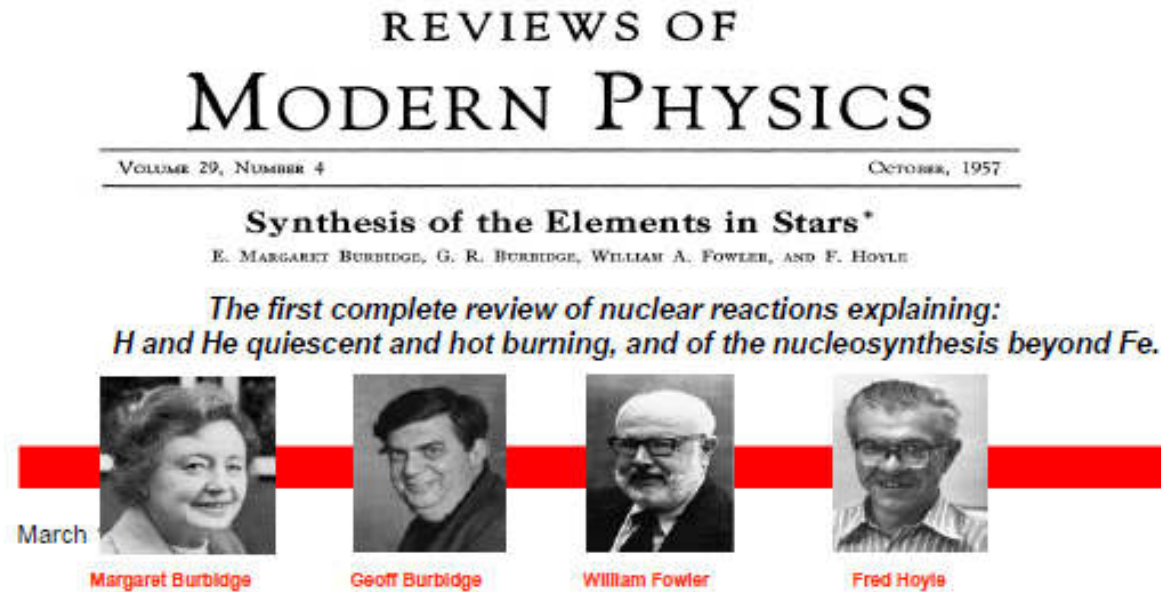
- Modelers
- Observers
- **Nuclear physicists**: Experimentalists as well as Theorists

Outline of my talk

- Nuclear physics in the abundance curve
- Features of thermonuclear reactions
- Experimental approaches
- Physics cases

... from the seminal **B²FH** 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



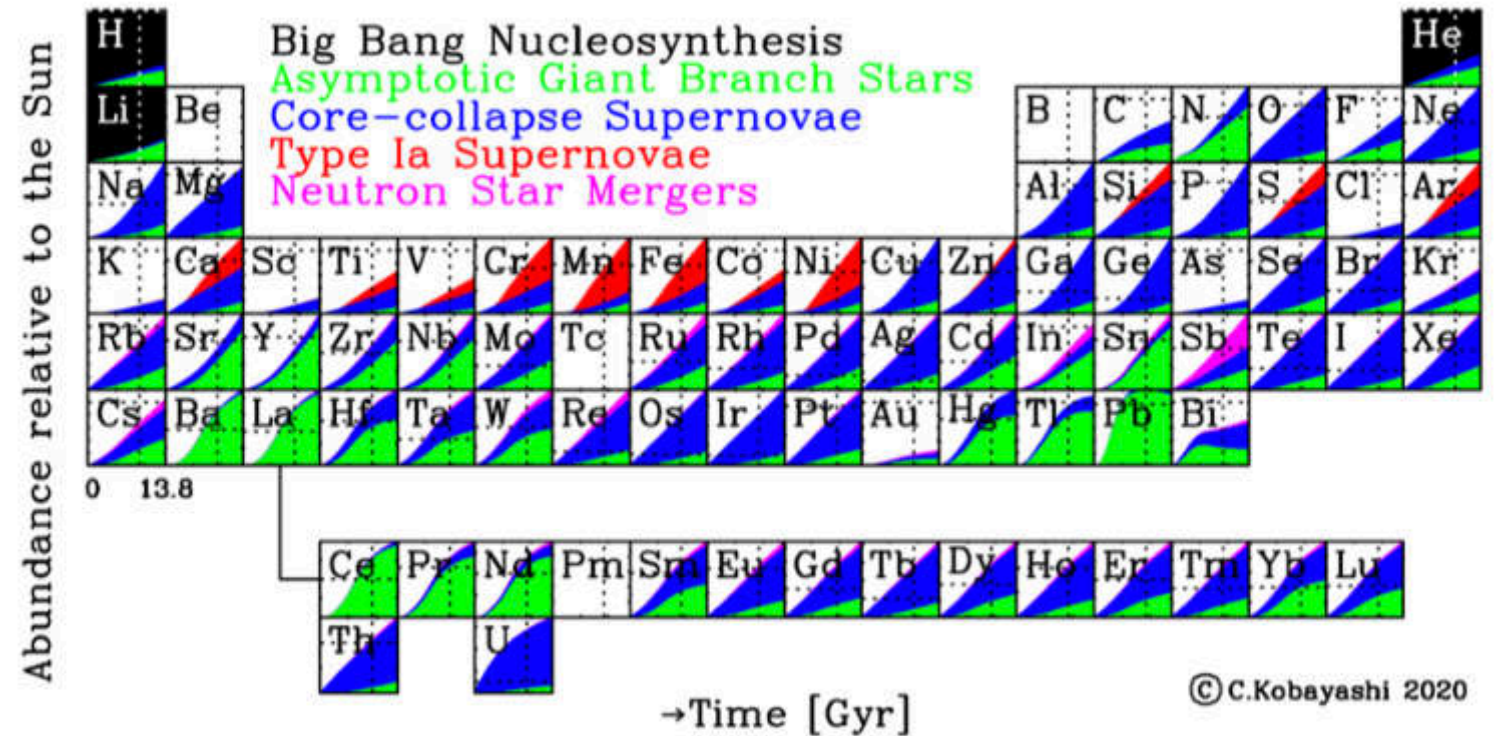
Nuclear reactions responsible for both ENERGY PRODUCTION and
CREATION OF ELEMENTS in 4 ways/environments:

- **Cosmological nucleosynthesis**: creation in the Big Bang
- **Stellar nucleosynthesis**: synthesis of elements by fusion in stars
- **Explosive nucleosynthesis**: synthesis of elements by neutron and proton capture reactions in supernovae
- **Galactic nucleosynthesis**: synthesis of elements by cosmic ray spallation reactions

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 \rightarrow conversion of H to He

He burning \rightarrow conversion of He to C, O ...

C, O and Ne burning \rightarrow production of A: 16 to 28

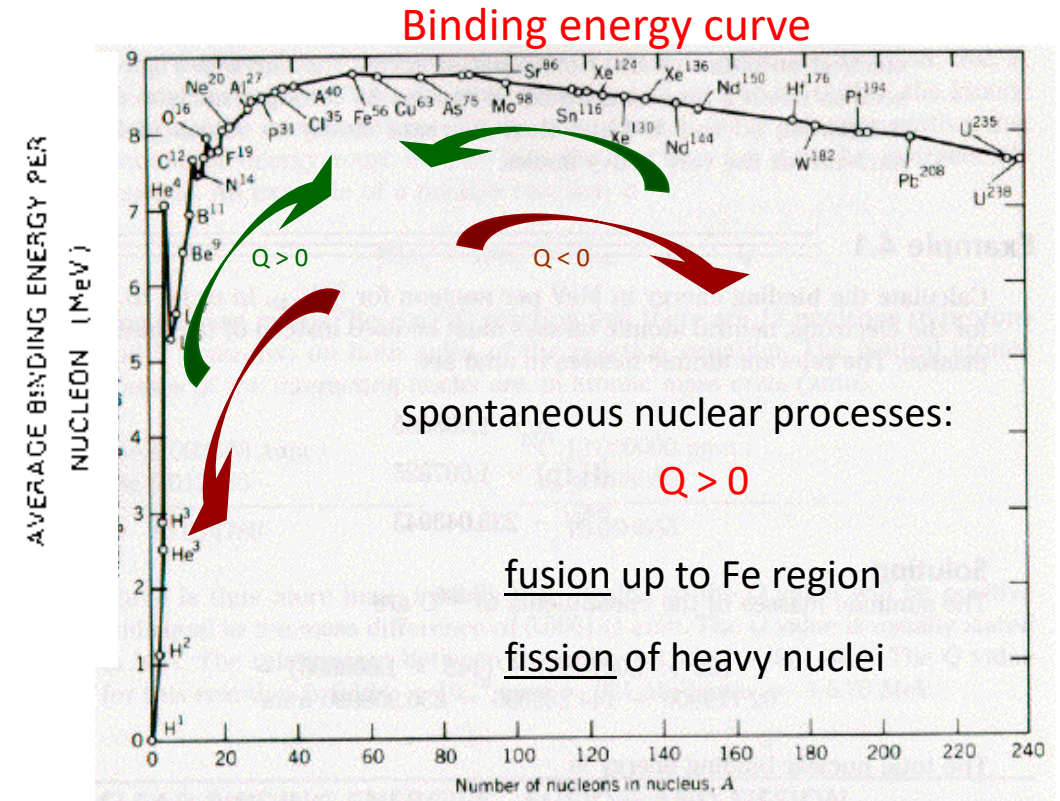
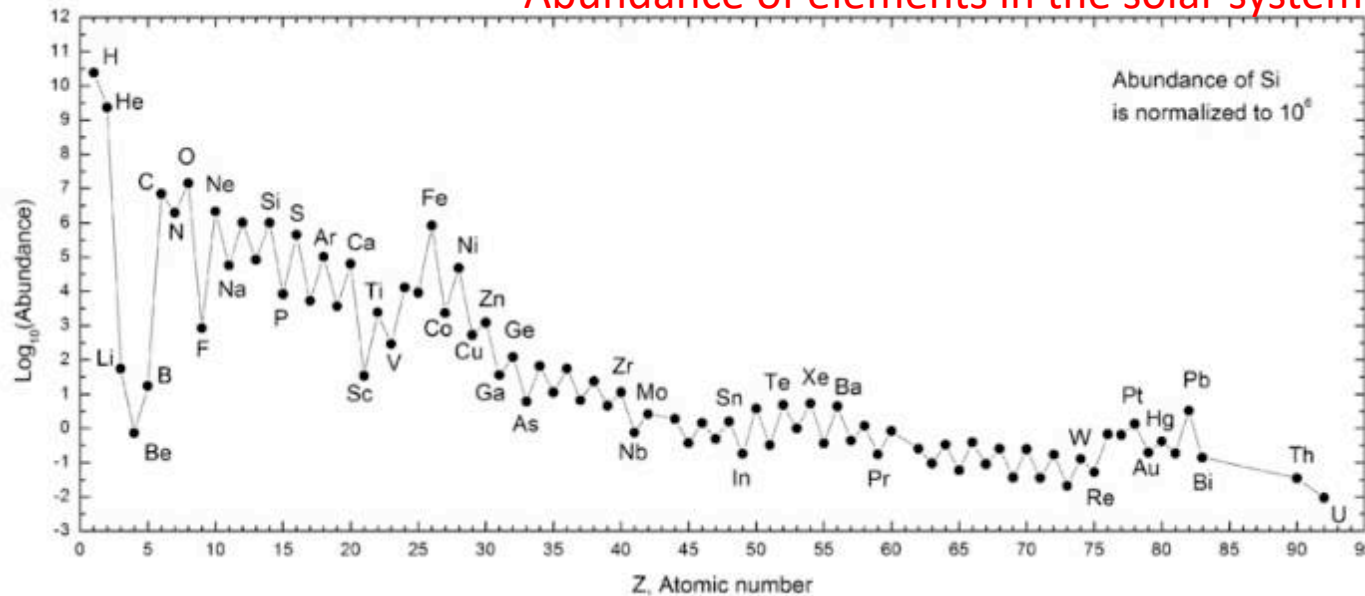
Si burning \rightarrow production of A: 28 to 60

s-, r- and p-processes \rightarrow 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
- Larger alpha-nuclei abundance
- Broad peak around Fe

Abundance of elements in the solar system

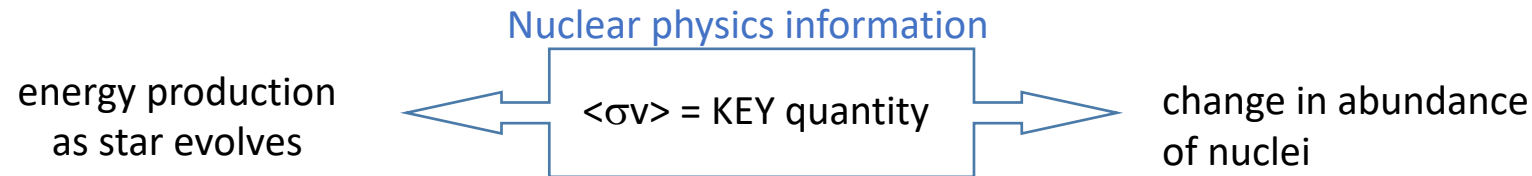


for a nuclear reaction



Total reaction rate: $R_{12} = (1+\delta_{12})^{-1} N_1 N_2 \langle \sigma v \rangle_{12}$ reactions $\text{cm}^{-3} \text{s}^{-1}$, N_i number density

Energy production rate: $\epsilon_{12} = R_{12} Q_{12}$ reaction Q-value: $Q_{12} = [(m_1 + m_2) - (m_3 + m_4)]c^2$



to be determined from experiments and/or theoretical considerations

a) velocity distribution

interacting nuclei in plasma are in **thermal equilibrium** at temperature T

also assume **non-degenerate** and **non-relativistic** plasma

\Rightarrow **Maxwell-Boltzmann velocity distribution**



stars = cooking pots of the Universe

b) cross section

no nuclear theory available to determine reaction cross section a priori

cross section depends sensitively on:

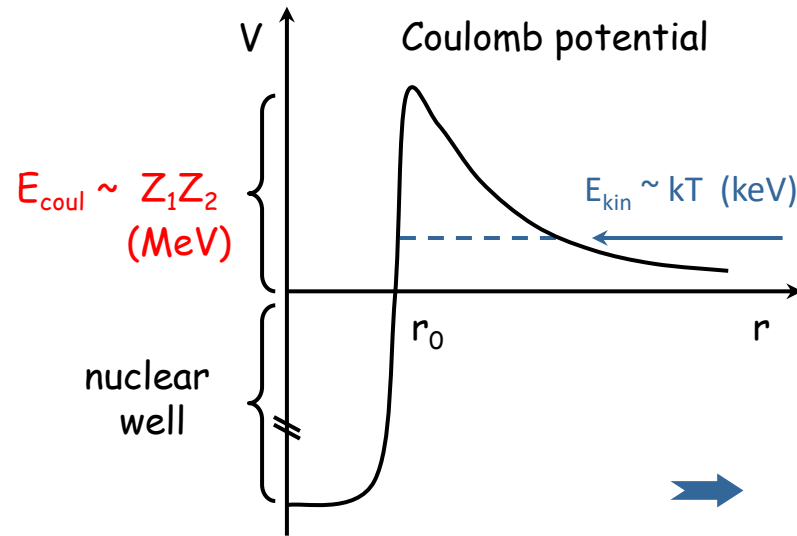
- the **properties of the nuclei** involved
- the **reaction mechanism**

in practice, need **experiments** AND **theory** to determine stellar reaction rates

Nuclear reactions between charged particles

charged particles → **Coulomb barrier**

energy available: from **thermal motion**

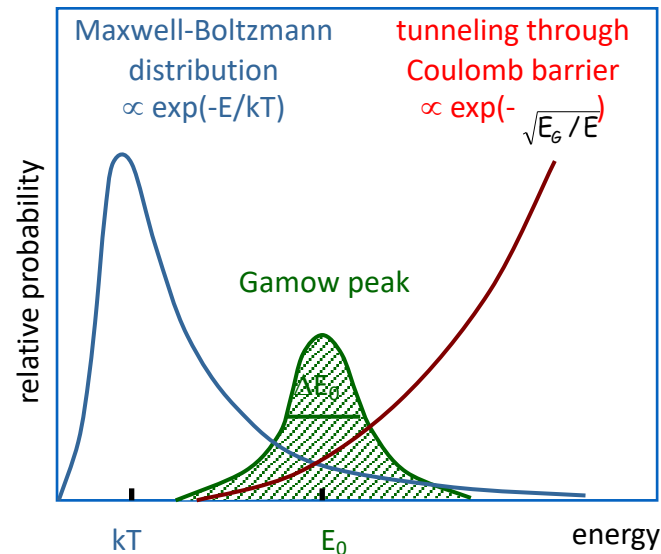
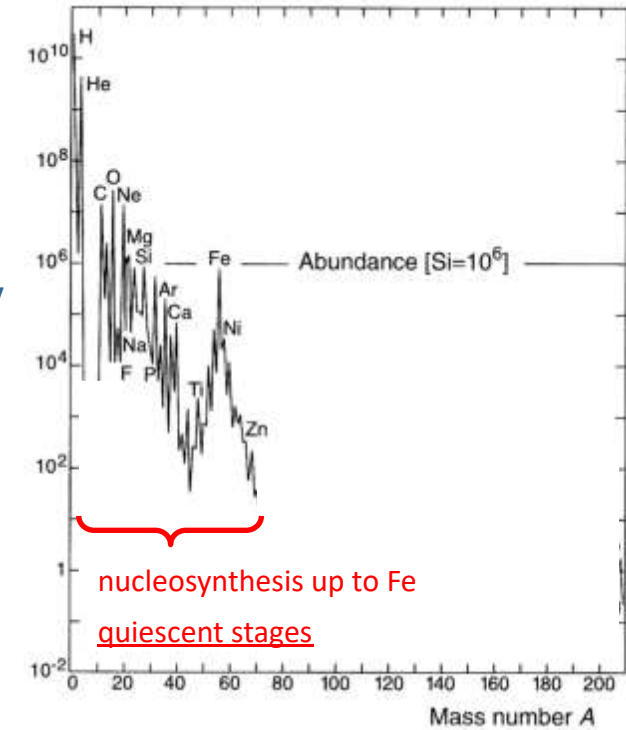


during static burning: $kT \ll E_{\text{Coul}}$

$T \sim 15 \times 10^6 \text{ K}$ (e.g. our Sun) $\Rightarrow kT \sim 1 \text{ keV}$

reactions occur through **TUNNEL EFFECT**

tunneling probability $P \propto \exp(-2\pi\eta)$



Gamow peak: **most effective energy region** for thermonuclear reactions

It is where measurements should be carried out

Gamow energy:

$$E_0 = f(Z_1, Z_2, T)$$



varies depending on reaction and/or temperature

Examples: $T \sim 15 \times 10^6 \text{ K}$ ($T_6 = 15$)

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

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

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



STRONG sensitivity
to Coulomb barrier



separate stages:

H-burning
He-burning
C/O-burning ...

neutron captures

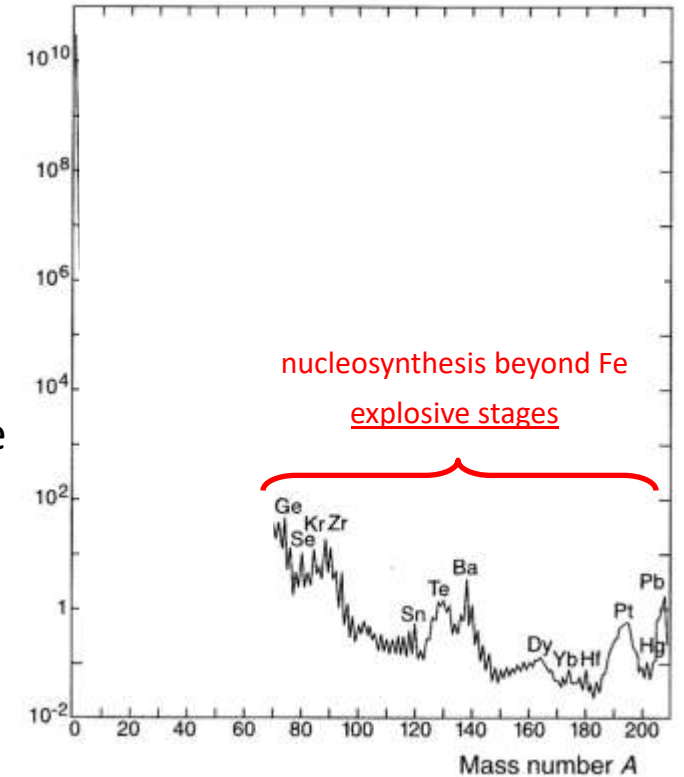
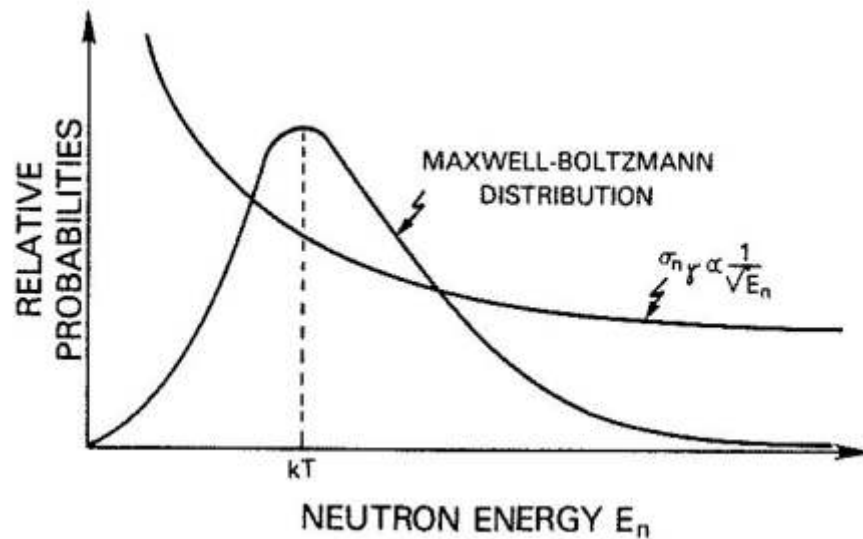
NO Coulomb barrier

neutrons produced in stars are quickly **thermalised**

$E_0 \sim kT = \text{relevant energy}$ (e.g. $T \sim 1\text{-}6 \times 10^8 \text{ K} \Rightarrow E_0 \sim 30 \text{ keV}$)

Typically $\sigma \sim \frac{1}{v}$
s-wave neutrons: $\rightarrow \langle \sigma v \rangle \sim \text{const} = \langle \sigma_T v_T \rangle \rightarrow$

accounts for **almost flat** abundance
distribution beyond iron peak



neutron-capture cross sections can be measured **directly** at the relevant energies

Features - General Overview

Quiescent burning stages

$$T \sim 10^6 - 10^8 \text{ K} \Rightarrow E_0 \sim 10 \text{ keV} - 1 \text{ MeV} \ll E_{\text{coul}}$$

$$\Rightarrow 10^{-18} \text{ barn} < \sigma < 10^{-9} \text{ barn}$$

$$\Rightarrow \text{average interaction time } \tau \sim \langle \sigma v \rangle^{-1} \sim 10^9 \text{ y}$$

unstable species DO NOT play significant role

Explosive burning stages

$$T > 10^8 \text{ K} \Rightarrow E_0 \sim \text{MeVs} \leq E_{\text{coul}}$$

$$\Rightarrow 10^{-6} \text{ barn} < \sigma < 10^{-3} \text{ barn}$$

\Rightarrow Extrapolation may not be needed

$$\Rightarrow \text{average interaction time } \tau \sim \langle \sigma v \rangle^{-1} \sim \text{seconds}$$

\Rightarrow unstable species DO play significant role

Main Issues

- poor signal-to-noise ratio

- unknown nuclear properties

- low beam intensities (several o.d.m. lower than for stable beams)

Requirements

Extrapolation procedure (?)

long measurements

ultra pure targets

high beam intensities

high detection efficiency

...

RIBs production and acceleration

large area detectors

high detection efficiency

Storage rings

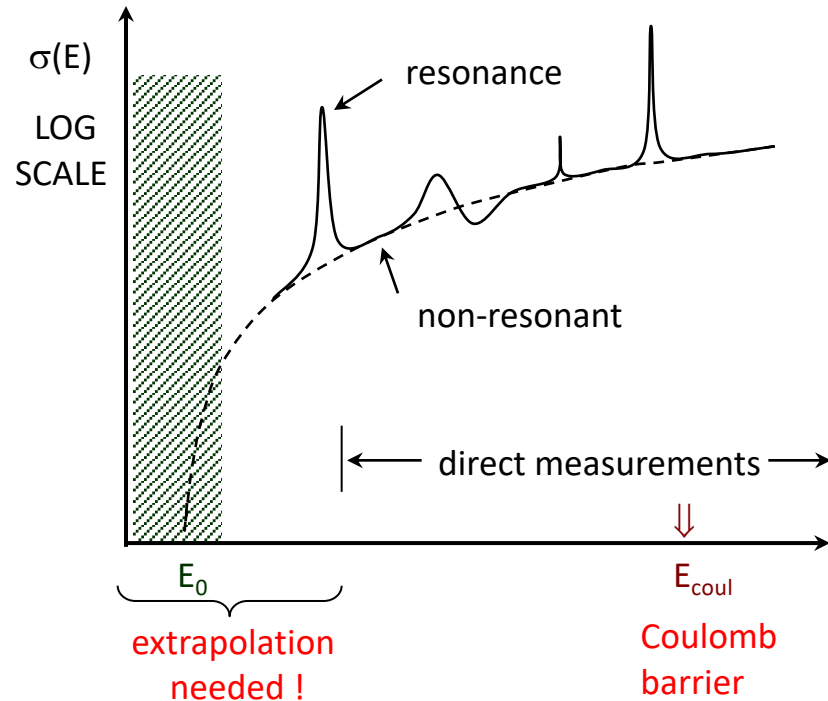
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Experimental approach: extrapolation

measure $\sigma(E)$ over as wide a range as possible, then extrapolate down to E_0 !

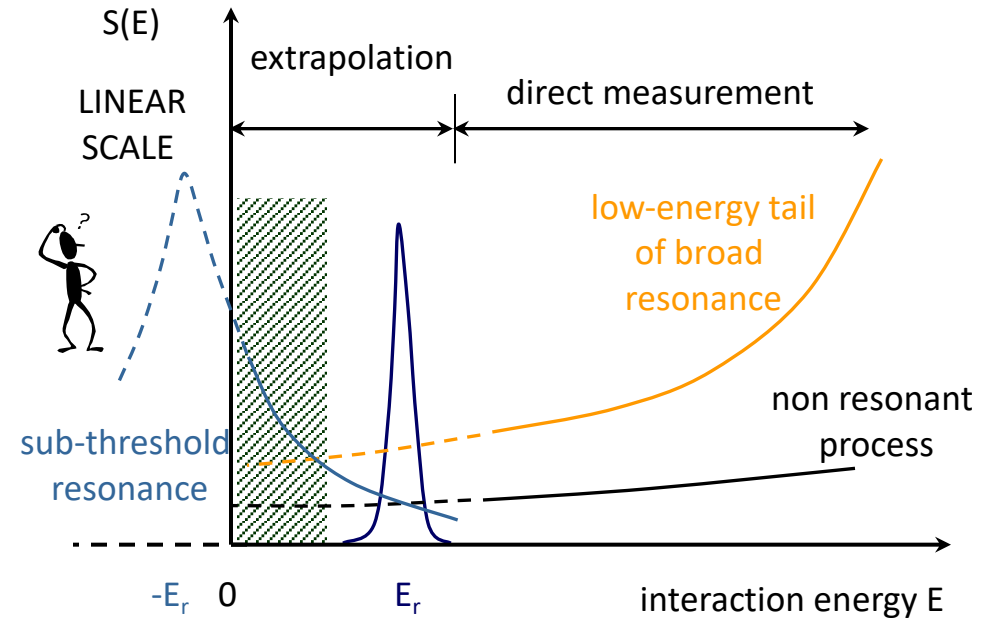
CROSS SECTION

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



S-FACTOR

$$S(E) = E\sigma(E) \exp(2\pi\eta)$$



DANGER OF EXTRAPOLATION !

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;

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

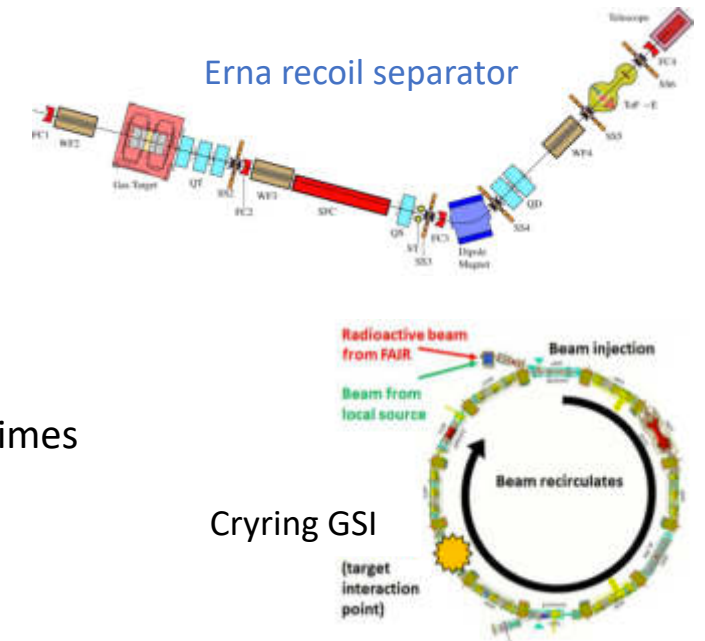
recoil separators, separate reaction products from unreacted beam and

disperse them according to their mass-to-charge-state ratio;

storage rings: to overcome beam intensity limitations. The beam is recirculated many times and therefore has repeated chances to interact with the target;

...

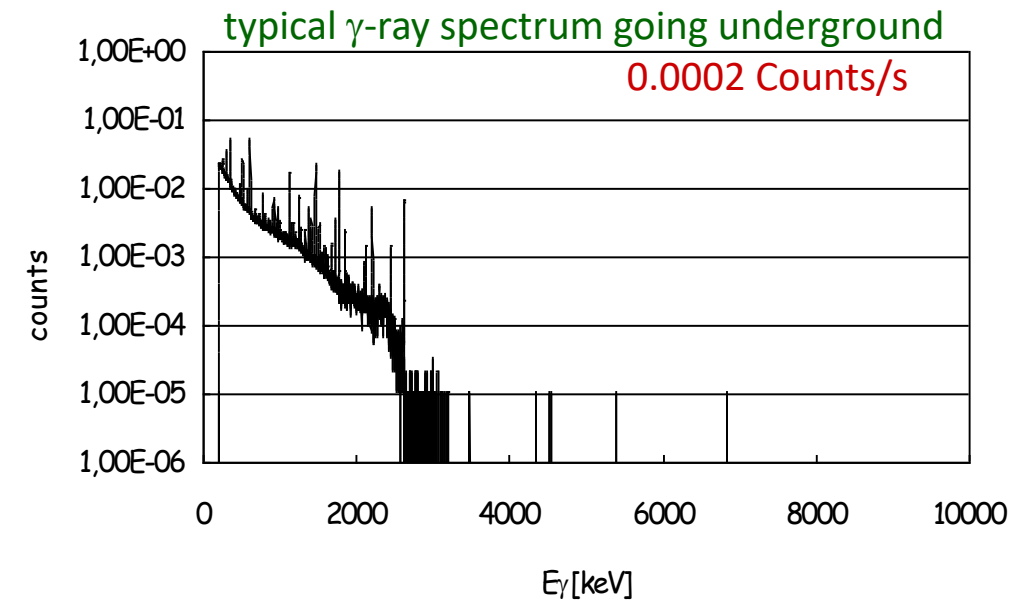
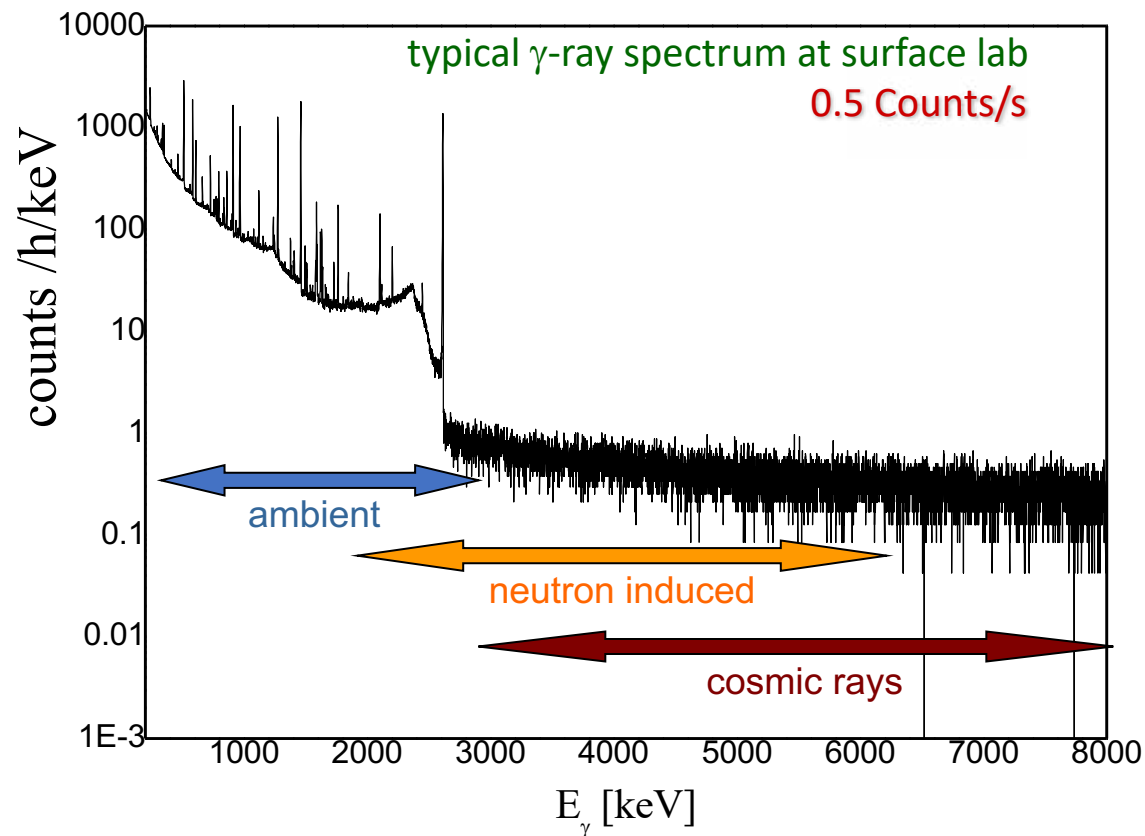
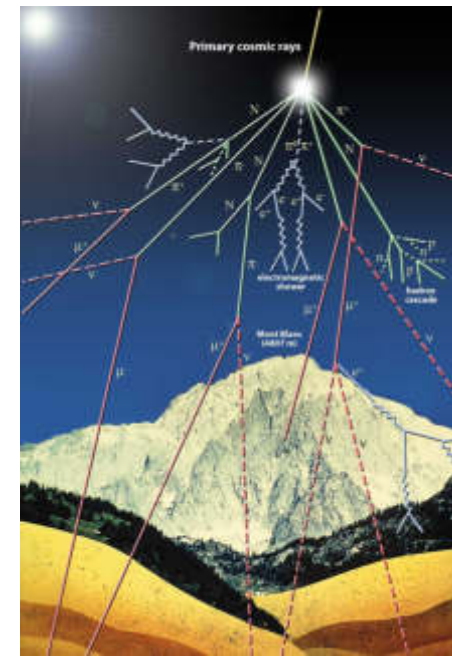
- Use indirect methods: Coulomb Dissociation (CD), Asymptotic Normalization Coefficients (ANC), Trojan Horse Method (THM)



Dedicated Talks for these topics in the next SNAQs - here only tastes for some of them

Main Sources of Background:

- **natural radioactivity** (mainly from U and Th chains and from Rn)
- **cosmic rays** (muons, ^1_3H , ^7Be , ^{14}C , ...)
- neutrons from **(a,n)** reactions and **fission**



ideal location: **underground** + low concentration of U and Th

the advantage is evident for high Q-value capture reactions, less evident for low Q-value reactions

LUNA= Laboratory for Underground Nuclear Astrophysics

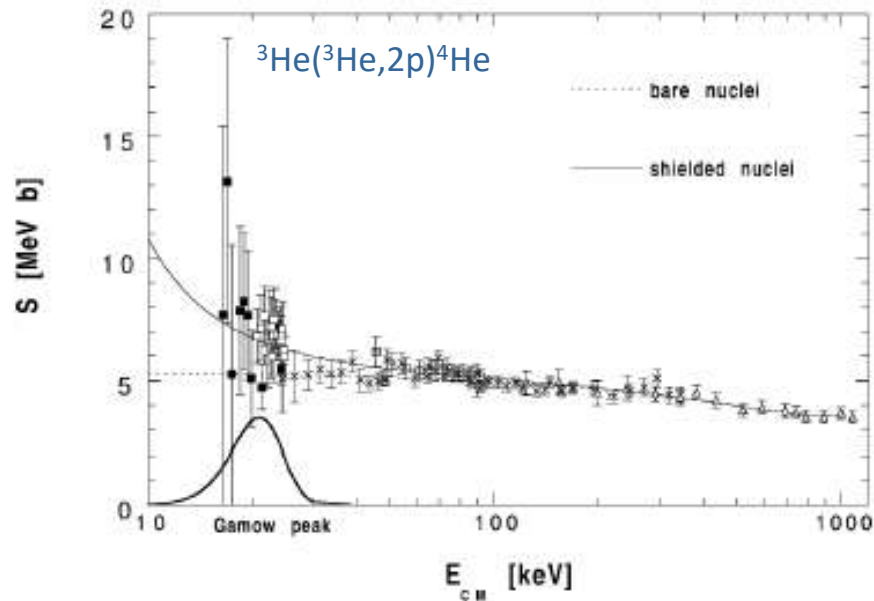


LUNA – Phase I: 50 kV accelerator (1992-2001)

investigate reactions in solar pp chain



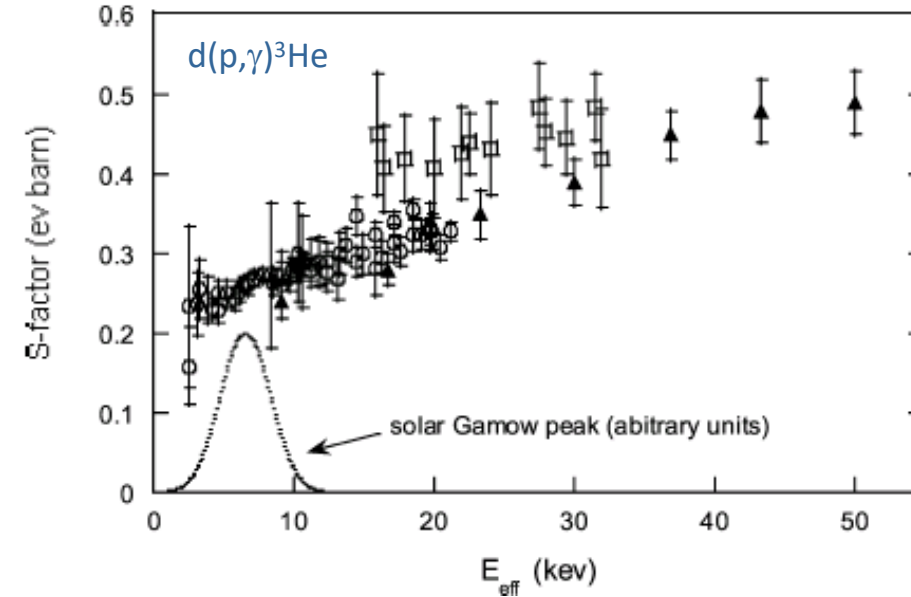
R. Bonetti et al.: Phys. Rev. Lett. 82 (1999) 5205



@ lowest energy:

$\sigma \sim 20 \text{ fb} \rightarrow 1 \text{ count/month}$

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



@ lowest energy:

$\sigma \sim 9 \text{ pb} \rightarrow 50 \text{ counts/day}$

only two reactions studied directly at the Gamow peak

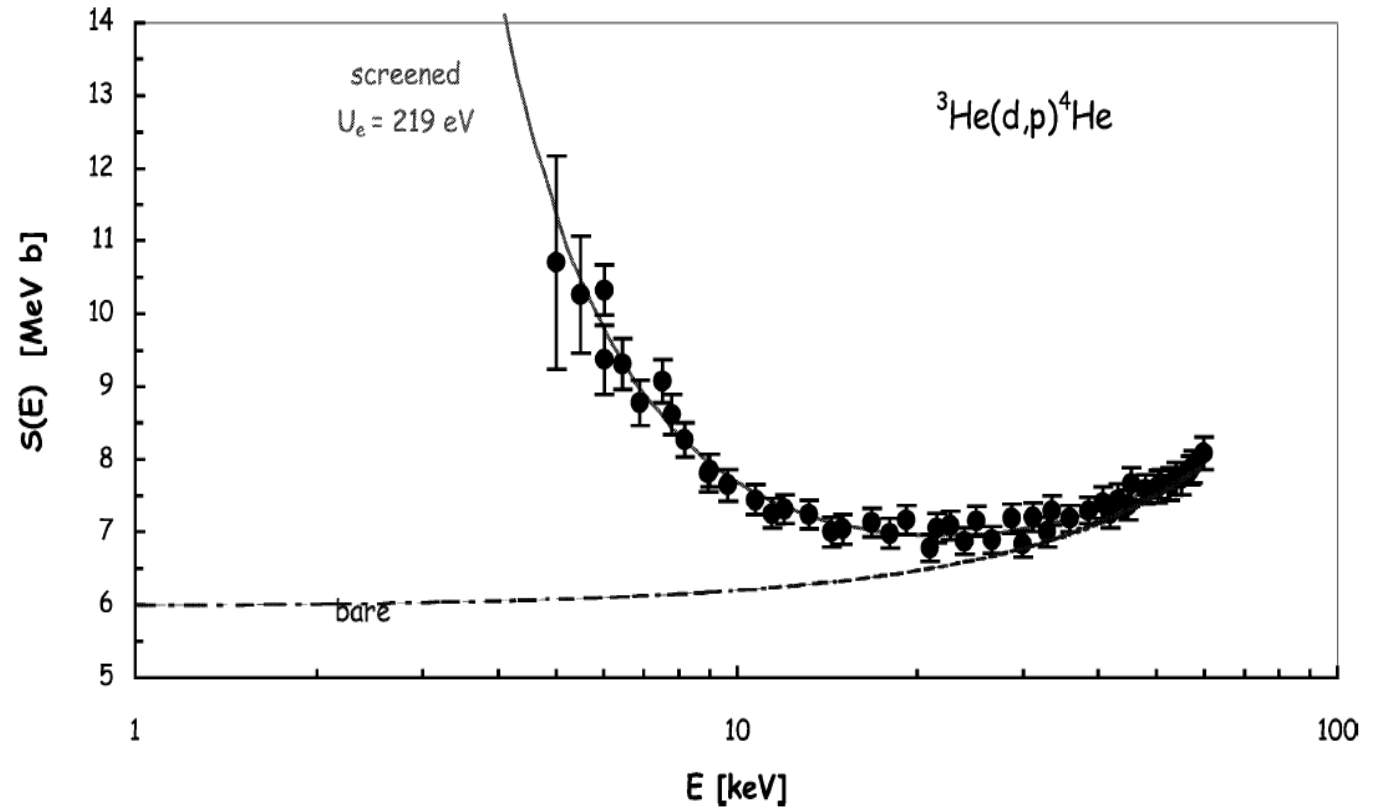
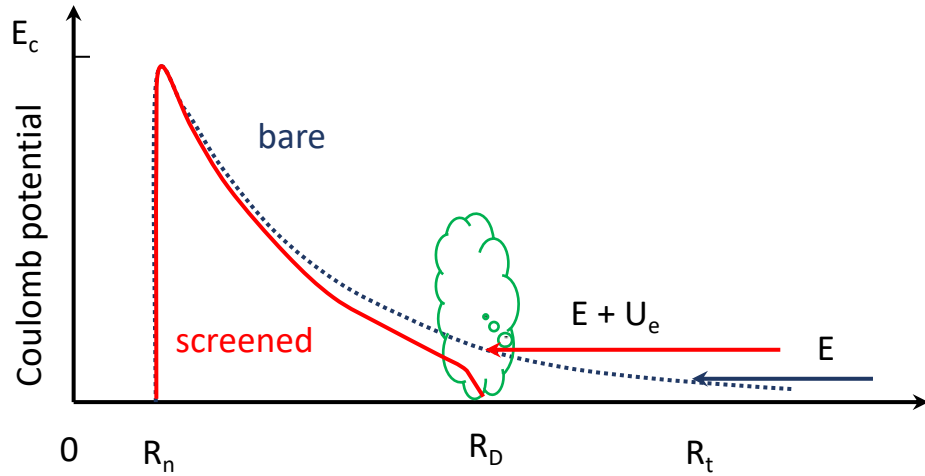
...but... intrinsic limitation at astrophysical energies

→ → → →

Electron Screening

$S(E)$ experimental enhancement due to the electron screening

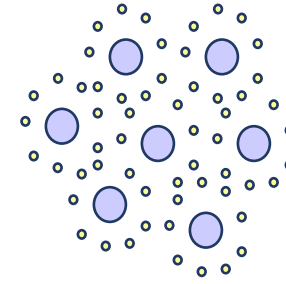
$$S(E)_s = S(E)_b \exp(\pi\eta U_e/E)$$



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

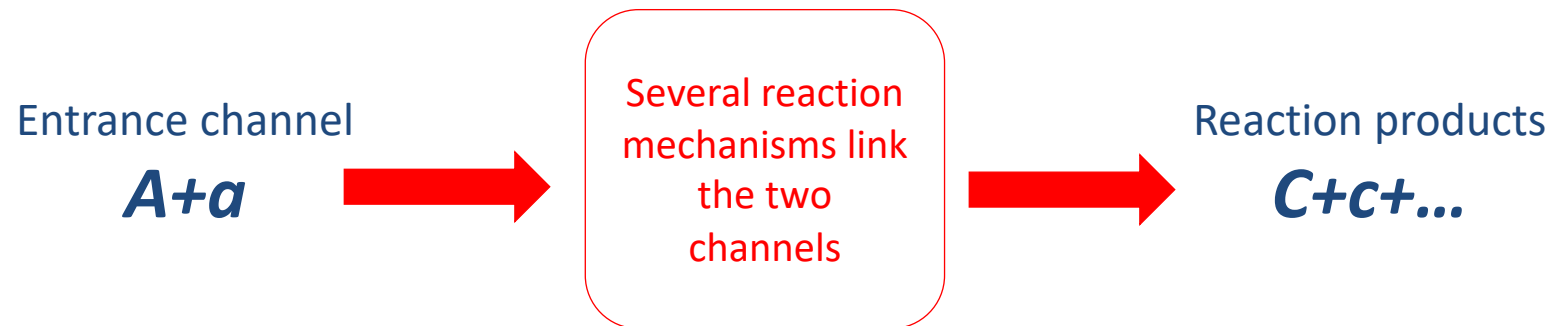
→ No way to measure $S(E)_b$ from direct experiments at energies where screening is important

$S_b(E)$ -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..)

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



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

Coulomb Dissociation in short

to determine the absolute $S(E)$ factor of a radiative capture reaction $A+x \rightarrow B+\gamma$ studying the reversing photodisintegration process $B+\gamma \rightarrow A+x$

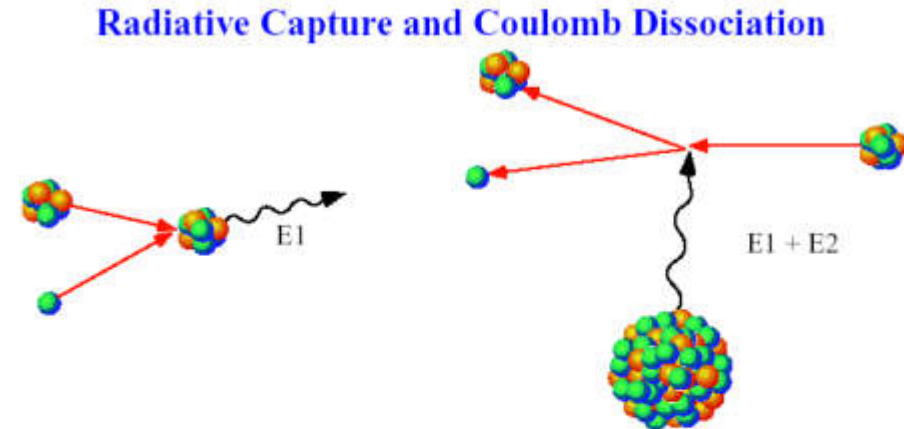
- Breakup of fast projectile by Coulomb field of a high-Z nucleus.
- Detailed balance \Rightarrow S-factor for radiative capture. Inverse cross section is larger.
- Advantages: possibility to use thick targets, large $\sigma \Rightarrow$ high rates.
- Issues: Nuclear breakup if E_γ is large, contributions of other multipoles.

$$\frac{d^2 \sigma}{d\Omega dE_\gamma} = \frac{1}{E_\gamma} \frac{dn_{\pi,\lambda}}{d\Omega} \sigma_{\pi,\lambda}^{\text{photo}}$$

Early and forthcoming Experiments

$^{13}\text{N}(p,\gamma)^{14}\text{O}$, $^7\text{Be}(p,\gamma)^8\text{B}$, breakup of ^8B , ^{14}O

GSI, NSCL: $^7\text{Be}(p,\gamma)^8\text{B}$, $^8\text{Li}(n,\gamma)^9\text{Li}$, $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$

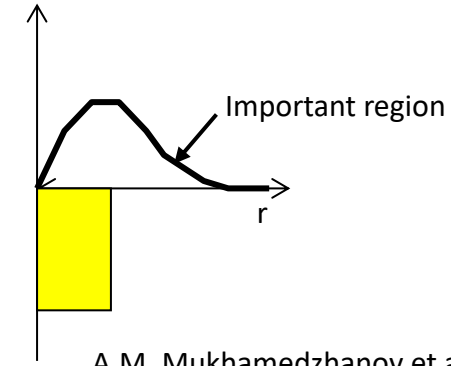


ANCs in short

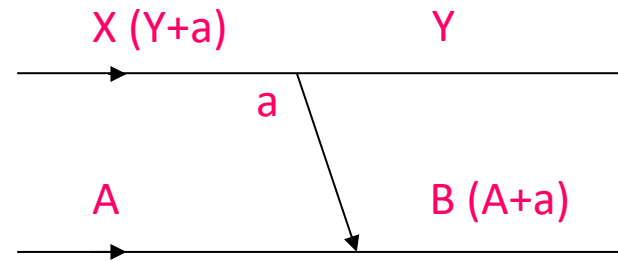
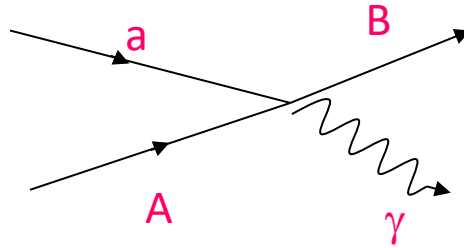
... to determine the $S(0)$ factor of the radiative capture reaction, $A+x \rightarrow B+\gamma$ studying a peripheral transfer reaction into a bound state of the B nucleus

$S(E=0)$ for (p, γ) , (α, γ) reactions from measuring ANC

- Low-energy (x, γ) reactions occur far from the nuclear surface
- $\sigma \propto |\psi(\text{large } r)|^2 \propto \text{ANC}^2$, ANC from a suitable peripheral transfer reaction into a bound state of B
- Issues: Require accurate OM Potentials



A.M. Mukhamedzhanov et al. (1997)



Early and recent Experiments

${}^7\text{Be}(p, \gamma){}^8\text{B}$ via ${}^{10}\text{B}({}^7\text{Be}, {}^8\text{B}){}^9\text{Be}$ and ${}^{14}\text{N}({}^7\text{Be}, {}^8\text{B}){}^{13}\text{C}$

${}^{13}\text{C}(\alpha, n){}^{16}\text{O}$ via the ${}^{13}\text{C}({}^6\text{Li}, d){}^{17}\text{O}$

${}^{15}\text{N}(p, \gamma){}^{16}\text{O}$ via the ${}^{15}\text{N}({}^3\text{He}, d){}^{16}\text{O}$ transfer reaction

${}^{26}\text{Si}(p, \gamma){}^{27}\text{P}$ via the ${}^{26}\text{Mg}(d, p){}^{27}\text{Mg}$ transfer reaction

A. Azhari et al, (2001)

S. Kubono et al, (2003),

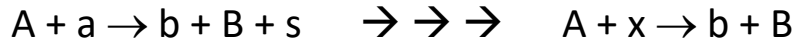
N. Keeley et al., Nucl. Phys. A (2003)

A.M. Mukhamedzhanov et al., J. Phys.: Conf. Ser. (2010)

G. D'Agata et al. (2020)

THM in short

Basic principle: relevant low-energy two-body σ from quasi-free contribution of an appropriate three-body reaction in quasi free kinematics



a: $x \oplus s$ clusters

Quasi free mechanism

- ✓ only $x - A$ interaction
- ✓ $s = \text{spectator}$ ($p_s \sim 0$)

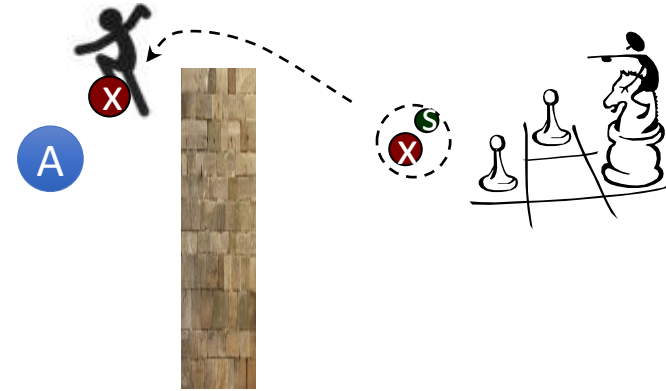
$$E_A > E_{\text{Coul}} \Rightarrow$$

NO Coulomb suppression

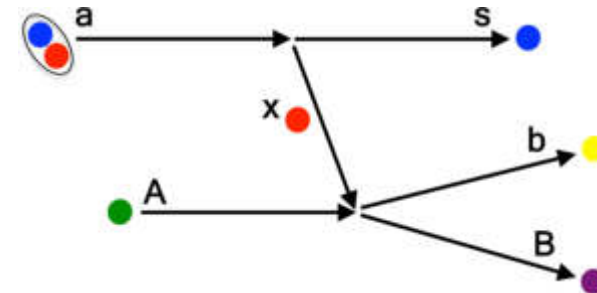
NO electron screening

$$\frac{\sigma}{\sigma_{\text{off}}} \propto \left| \Phi \right|^2$$

Issue: need to normalize the two-body σ to direct data



Repulsion wall



THM applied so far to more than 30 reactions, such as ${}^6\text{Li}(p,\alpha){}^3\text{He}$, ${}^7\text{Li}(p,\alpha)\alpha$, ${}^2\text{H}(d,p){}^3\text{H}$, ${}^2\text{H}(d,n){}^3\text{He}$, ${}^{10}\text{B}(p,\alpha){}^7\text{Be}$, ${}^{11}\text{B}(p,\alpha){}^8\text{Be}$, ${}^{17,18}\text{O}(p,\alpha){}^{14,15}\text{N}$, ${}^{13}\text{C}(\alpha,n){}^{16}\text{O}$, ${}^7\text{Be}(n,\alpha){}^4\text{He}$, ${}^{18}\text{F}(p,\alpha){}^{15}\text{O}$, ${}^{19}\text{F}(p,\alpha){}^{16}\text{O}$, ${}^{10}\text{B}(p,\alpha){}^7\text{Be}$, ${}^{11}\text{B}(p,\alpha){}^8\text{Be}$, ${}^{12}\text{C}({}^{12}\text{C},\alpha){}^{20}\text{Ne}$, ${}^{12}\text{C}({}^{12}\text{C},p){}^{23}\text{Na}$...

See for review:

R. Tribble et al., Rep. Prog. Phys. **77** (2014) 106901

C. Spitaleri et al. EpJA, **55**, (2019), 161

R.G. Pizzone et al EpJA, (2020)

Next:

a few cases of study:

- the cosmological Lithium problem;
- focus on helium and carbon burning;
- the neutron sources in the s process;
- r-process nucleosynthesis: challenges of study (n,γ) .

BBN and the cosmological Lithium problem

First proposed by Alpher, Bethe and Gamow in 1948, responsible for the nucleosynthesis of lighter elements.
BBN does not go beyond Li due to missing stable nuclei of mass number 5 or 8

1. $p(n,\gamma)d$
2. ${}^2\text{H}(p,\gamma){}^3\text{He}$
3. ${}^2\text{H}(d,n){}^3\text{He}$
4. ${}^2\text{H}(d,p){}^3\text{H}$
5. ${}^3\text{He}(n,p){}^3\text{H}$
6. ${}^3\text{H}(d,n){}^4\text{He}$
7. ${}^3\text{He}(d,p){}^4\text{He}$
8. ${}^3\text{He}(\alpha,\gamma){}^7\text{Be}$
9. ${}^3\text{H}(\alpha,\gamma){}^7\text{Li}$
10. ${}^7\text{Li}(p,\alpha){}^4\text{He}$
11. ${}^4\text{He}(d,\gamma){}^6\text{Li}$
12. ${}^6\text{Li}(p,\alpha){}^3\text{He}$

Using as inputs:

-12 key nuclear cross section

-the baryon-to-photon ratio $(6.19 \pm 0.15) \times 10^{-10}$
from WMAP)

-the neutron lifetime, (which is a puzzle itself)

we can predict the abundances of d, He, Li relative to H

To check if these numbers from BBN hold we compare
with abundance measurements in old parts of the
Universe (metal poor halo stars, globular clusters)

What do we get? $\rightarrow \rightarrow \rightarrow$

Green areas from observations

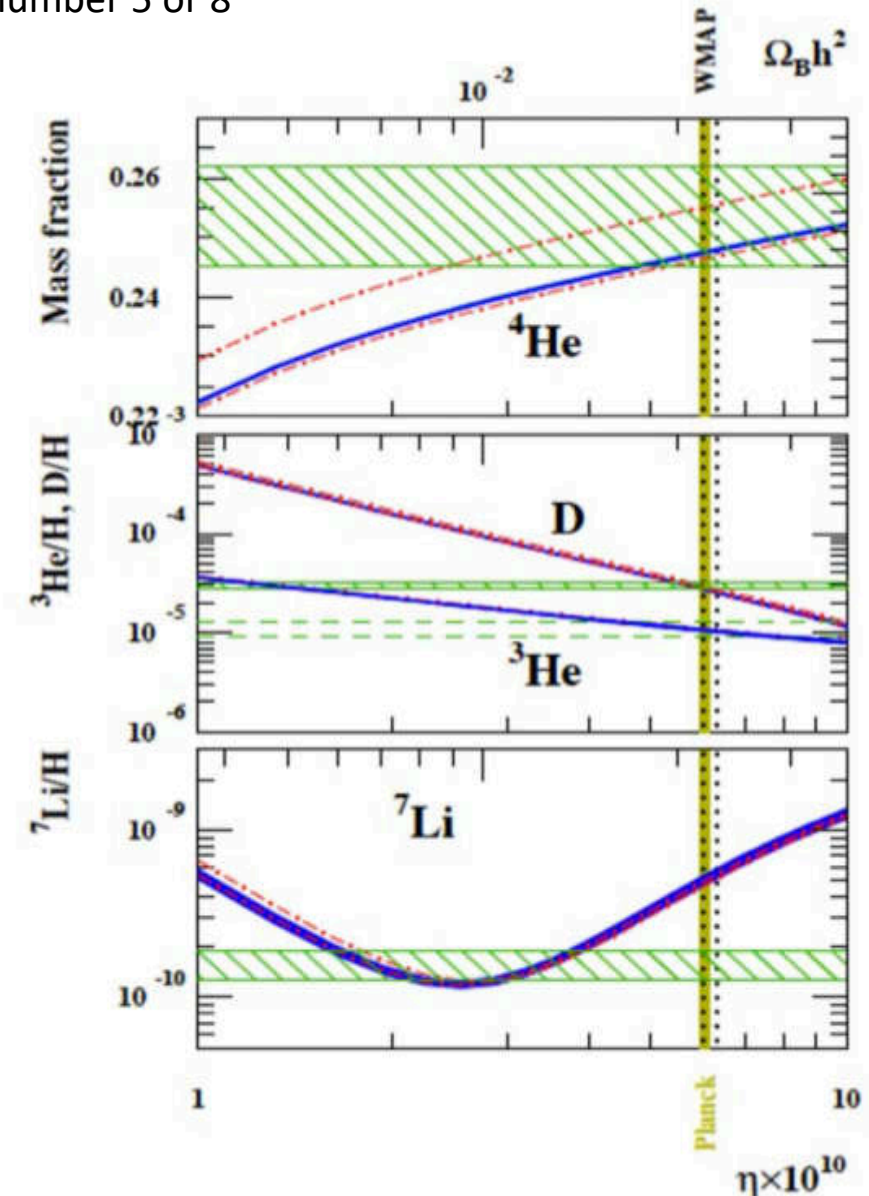
Blue and red lines from calculations

${}^3\text{He}$ is hard to measure since most stars
burn it

Remaining abundances agree within errors except for ${}^7\text{Li}$

...

cosmological Lithium problem!



cosmological Lithium problem ... what else could be wrong or missing?

- Improve cross sections of the network reactions
- Improve observations with unexplored areas

or/and introduce new Physics

- ${}^7\text{Li}$ also from primordial ${}^7\text{Be}$, but in this case need to measure processes that would get rid of ${}^7\text{Be}$

- Wimps decay as early speculation, but insufficient

- Decay of GeV scale SUSY particles might bring more neutrons through more complex paths.

- new statistics to describe the velocities of nucleons during the BBN era

13. ${}^7\text{Be}(n,p){}^7\text{Li}$

14. ${}^7\text{Be}(n,\alpha){}^4\text{He}$

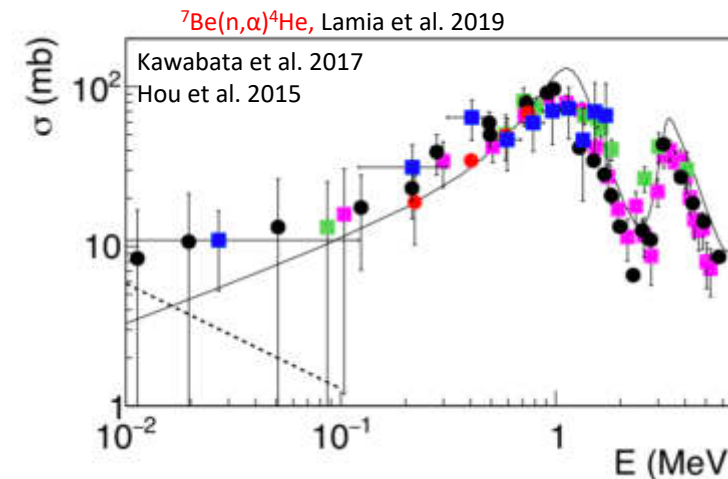
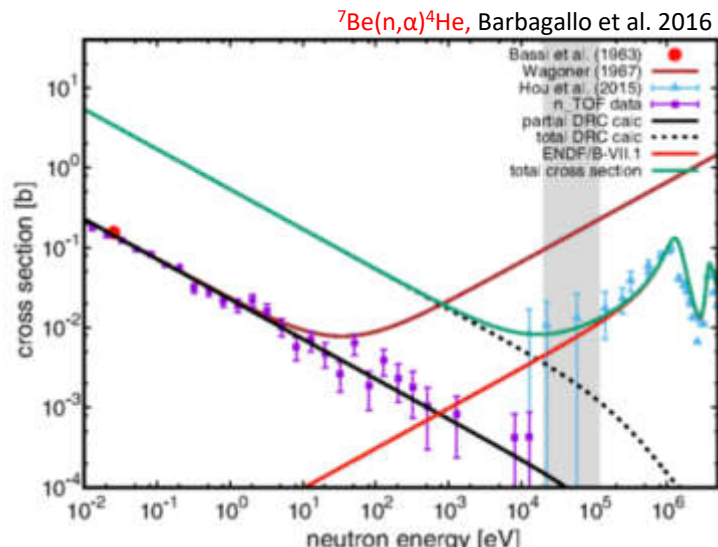
15. ${}^7\text{Be}(d,p){}^2{}^4\text{He}$

For review see:

B. D. Fields, *Ann. Rev. Nucl. Part. Sci.* **61**, 47 (2011)

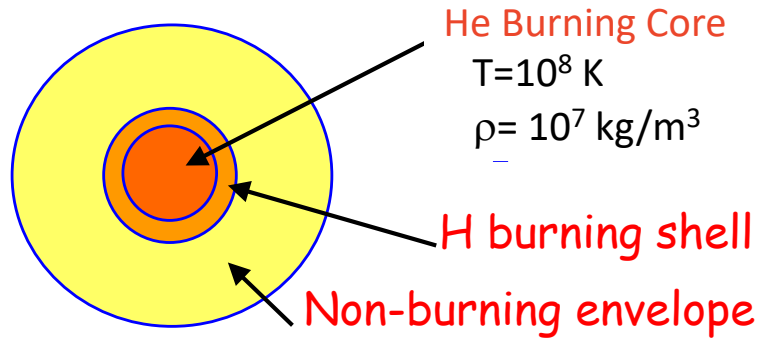
R. H. Cyburt *et al.*, *Rev. Mod. Phys.* **88**, 015004 (2016)

S.Q. Hu *et al*, *The Astrophysical Journal*. **834** (2): 165 (2017).



Quiescent life of a star: making heavy elements from light ones

Starts like the sun:

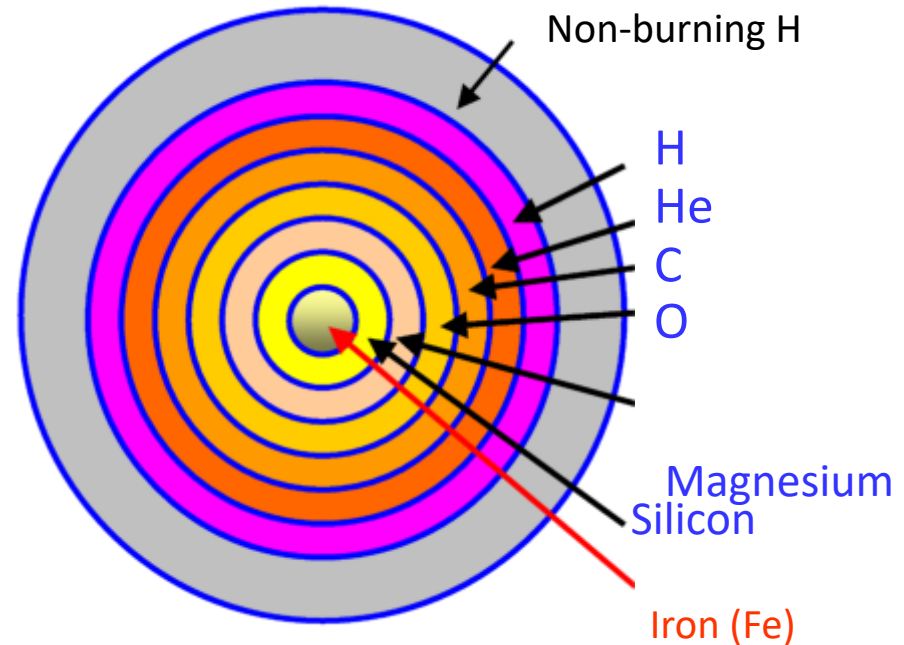


But now, when He is exhausted in the core and the core collapses, it does get hot enough to burn carbon and oxygen.

The successive stages in the core are
 $\text{H} \rightarrow \text{He}$, gravity, $\text{He} \rightarrow \text{C, O}$, gravity,
 $\rightarrow \text{C, O} \rightarrow \text{Mg, Si}$, gravity, $\text{Si} \rightarrow \text{Fe}$.

For massive stars

The Stellar Onion



Attention!!!



Massive Stars have complex interiors, where different reactions contribute

Nucleosynthesis in He burning

- 3 α : $\alpha + \alpha \rightleftharpoons {}^8\text{Be}^* + \alpha \rightarrow {}^{12}\text{C}^* \rightarrow {}^{12}\text{C} (\text{gs})$ Rate known to $\pm 10\%$
- ${}^{12}\text{C}(\alpha, \gamma){}^{16}\text{O}$ Poorly known (20-30%)



Gamow peak ~ 300 keV, where cross section enhancement is the result of interferences between resonances and nonresonant components, properties which are much more difficult to determine accurately.

The competition of these two reactions **determines the ${}^{12}\text{C}/{}^{16}\text{O}$ ratio in our universe**, and thus the late stellar evolution of massive stars and type Ia Supernovae.

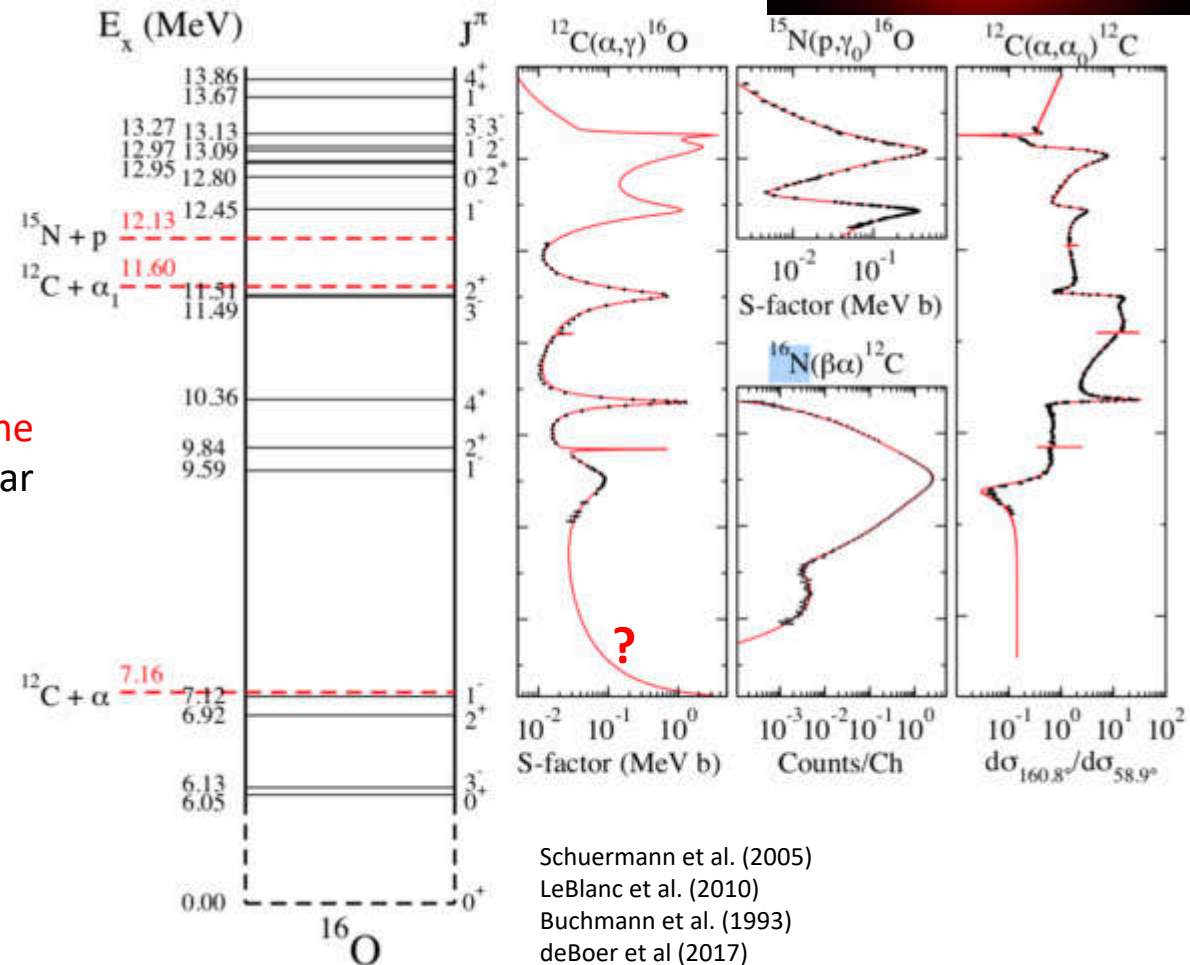
Forthcoming attempts:

${}^{16}\text{N}(\beta\alpha){}^{12}\text{C}$,

${}^{16}\text{O}(\gamma_0, \alpha){}^{12}\text{C}$: inverse photodisintegration

Coulomb dissociation ${}^{208}\text{P}({}^{16}\text{O}, {}^{16}\text{O}^*)$

Out of nuclear physics: to infer the ${}^{12}\text{C}/{}^{16}\text{O}$ ratio from white dwarf seismology



Schuermann et al. (2005)
 LeBlanc et al. (2010)
 Buchmann et al. (1993)
 deBoer et al (2017)

C-burning

Crucial phase in the nucleosynthesis of massive stars ($> 8 M_{\odot}$), determines M_{up} , ignition trigger for superbursts and Type Ia supernovae

astrophysical energy: 1 – 3 MeV

From direct measurement, minimum E:

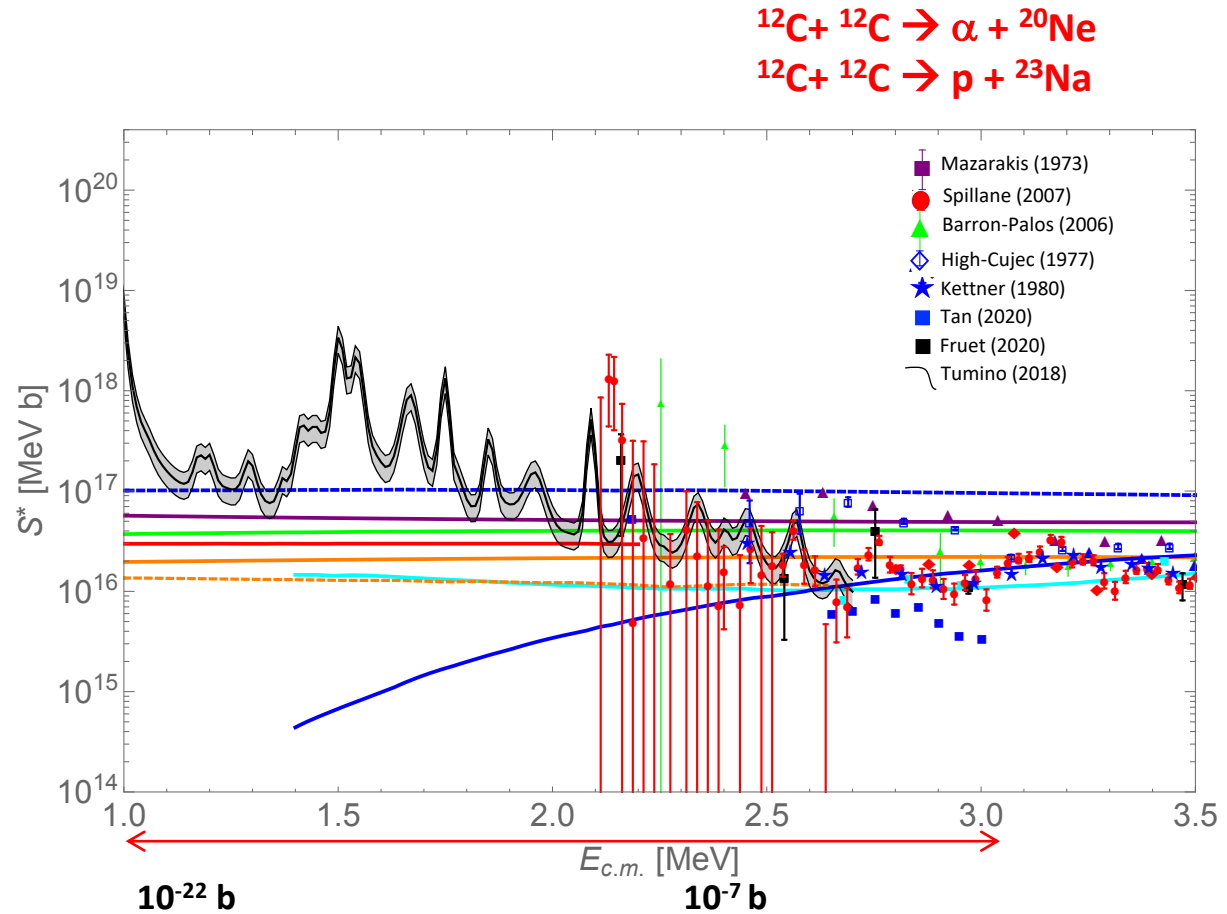
2.1 MeV

extrapolations differ by **3 orders of magnitude** without inclusion of resonances

Indirect measurement with THM down to 1 MeV: resonances dominate the astrophysical energy

Next step:

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



Synthesis of Heavy Elements: s-process neutron sources

Slow or s-process responsible for about 50% of the nuclei heavier than iron

Time scale $\sim 10^3$ - 10^4 years

Neutron sources in the s-process:

- $^{13}\text{C}(\alpha, n)$, in low-mass AGB stars:

main s-process - production of nuclides with $A > 90$

Knowledge of its cross section in the relevant energy window ($E \sim 190$ keV) is of crucial importance as input for astrophysical models of the s process.

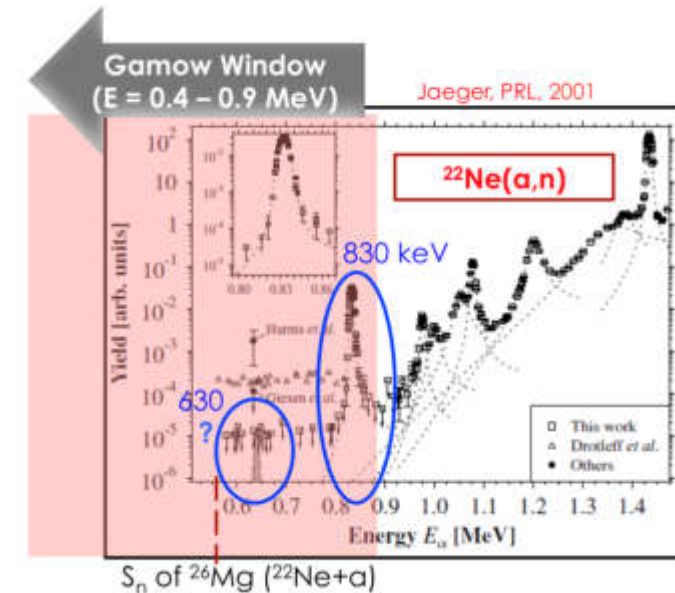
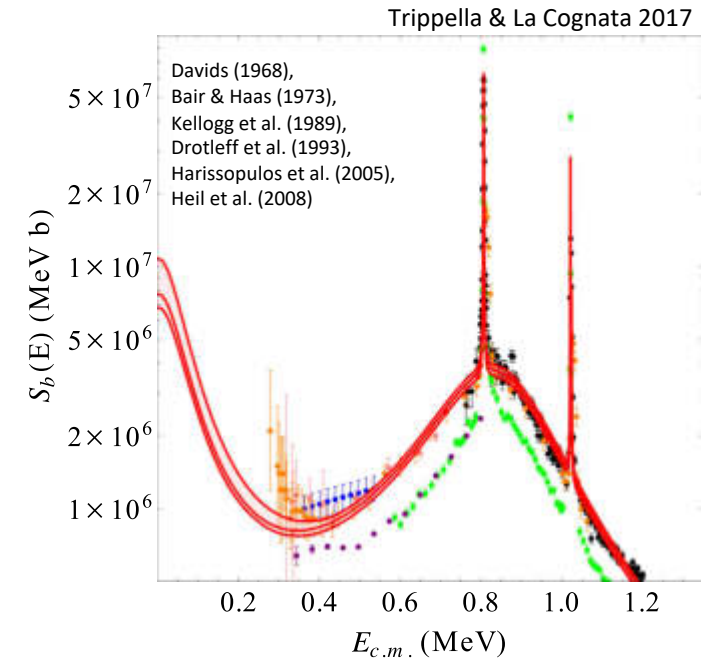
Only indirect measurements at the Gamow window.

- $^{22}\text{Ne}(\alpha, n)$, in intermediate mass and massive:

weak s-process - production of nuclides-- $A = 60$ - 90

still largely unknown. Several evaluations of the reaction rate exist, based on theoretical calculations. No direct measurements at the relevant energies, many spectroscopy studies of the levels involved.

Inputs for s-process nucleosynthesis models



Nuclear physics inputs to r-process

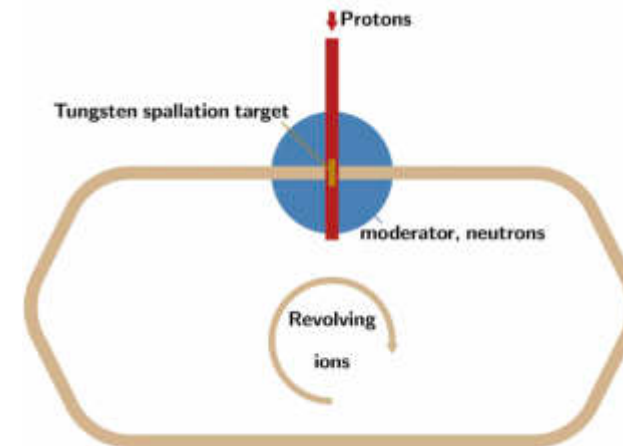
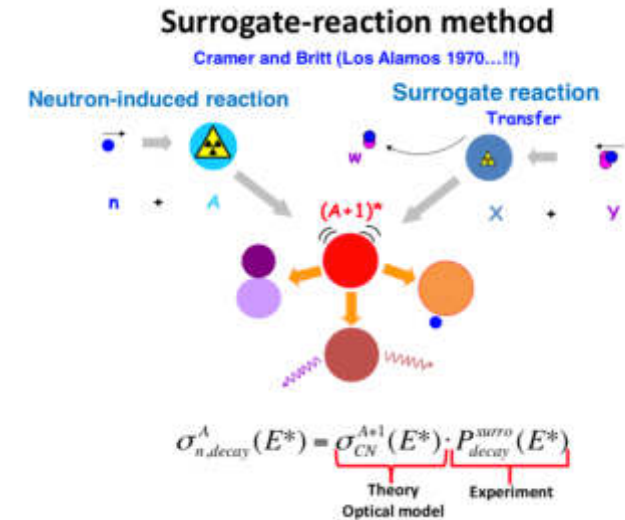
- neutron capture rates, β decay properties, fission barriers, mass measurements

Challenges of study (n, γ) in the Lab

Nuclei involved in r-process are very short-lived, how to proceed:

- To study (n, γ) on short-lived nuclei, we can create radioactive ion beams of these short lived nuclei and deliver them on a deuteron target \rightarrow surrogate reaction technique, or THM
- Recent idea to produce a neutron target from a spallation source of protons on tungsten, in a way to destroy nuclei and evaporate neutrons. Neutrons are finally thermalized and can be used as targets. (R. Reifarh 2020)

Very promising technique in conjunction with storage rings



Much remains to say...

this is just an introduction of topics that will be discussed in the next SNAQs



Thank you!