An introduction to nuclear astrophysics

Pierre Capel

ECOLE POLYTECHNIQUE DE BRUXELLES

24 January 2016

Introduction : a bit of history

Where do we come from ?

Where was produced the matter that surrounds us ?

Introduction : a bit of history

Where do we come from ?

Where was produced the matter that surrounds us ?

The answer came from astrophysics. . .

Introduction : a bit of history

Where do we come from ?
Where was produced the matter that surrounds us ?

The answer came from astrophysics. . .

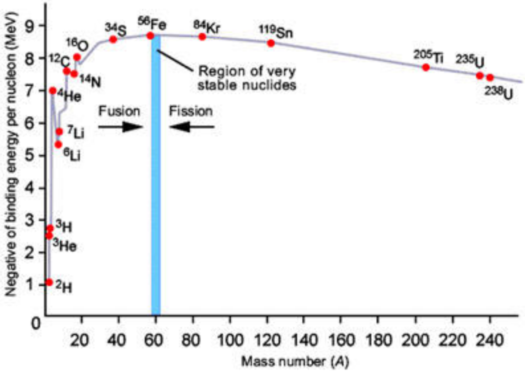
In 1920 A. Eddington : stars are nuclear powered
In 1929 R. Atkinson and F. Houtermans : fusion of light elements produces energy
e.g. fusion of 4 protons into ^{4}He

$$4\,p \rightarrow \ ^4\text{He} + 2e^+ + 2\nu_e + 26.73\ \text{MeV}$$

In 1938-39, H. Bethe and C. Critchfield : pp chain and CNO cycles (H. Bethe got NP in 1967)
In 1957, seminal paper of Burbidge, Burbidge, Fowler and Hoyle on nucleosynthesis in stars [Rev. Mod. Phys. **29**, 257]

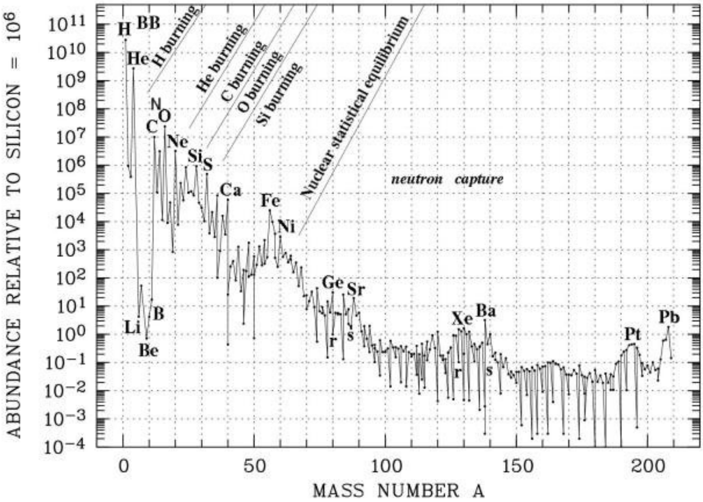
Introduction : nucleosynthesis in a nutshell

By fusion of light elements we can reach the Fe-Ni region because reactions are exoenergetic and Coulomb repulsion is small



Beyond, processes based on n or p capture lead to heavy nuclei : s, r, p, rp processes…

Abundances of elements



Abundance measured relative to Si fixed to 10^6.

pp chain $p + p \rightarrow {}^{2}_{1}\mathrm{H} + e^{+} + \nu_e$ or $p + e^{-} + p \rightarrow {}^{2}_{1}\mathrm{H} + \nu_e$

$${}^{2}_{1}\mathrm{H} + p \rightarrow {}^{3}_{2}\mathrm{He} + \gamma$$

(85%)

$${}^{3}_{2}\mathrm{He} + {}^{3}_{2}\mathrm{He} \rightarrow {}^{4}_{2}\mathrm{He} + 2p$$

ppI

(15%)

$${}^{3}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{7}_{4}\mathrm{Be} + \gamma$$

(15%)

$${}^{7}_{4}\mathrm{Be} + e^{-} \rightarrow {}^{7}_{3}\mathrm{Li} + \nu_e$$

$${}^{7}_{3}\mathrm{Li} + p \rightarrow {}^{4}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He}$$

ppII

(0.02%)

$${}^{7}_{4}\mathrm{Be} + p \rightarrow {}^{8}_{5}\mathrm{B} + \gamma$$

$${}^{8}_{5}\mathrm{B} \rightarrow {}^{8}_{4}\mathrm{Be} + e^{+} + \nu_e$$

$${}^{8}_{4}\mathrm{Be} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He}$$

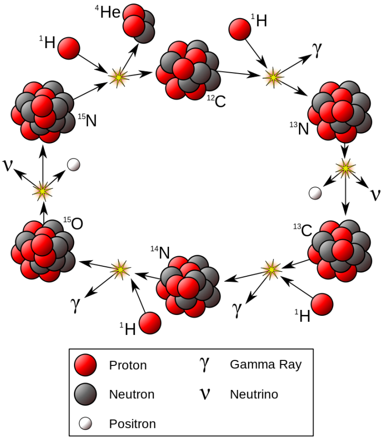
ppIII

Summary : $4p \rightarrow {}^{4}_{2}\mathrm{He} + 2e^{+} + 2\nu_e + 25\,\mathrm{MeV}$

CNO cycle(s)

If the star contains C, N or O they can be used as catalyst to synthesise ^{4}He from 4 p
e.g. CNO C cycle :

$$
\begin{aligned}
^{12}\mathrm{C} + \mathrm{p} &\rightarrow {}^{13}\mathrm{N} + \gamma \\
^{13}\mathrm{N} &\rightarrow {}^{13}\mathrm{C} + \mathrm{e}^{+} + \nu_{\mathrm{e}} \\
^{13}\mathrm{C} + \mathrm{p} &\rightarrow {}^{14}\mathrm{N} + \gamma \\
^{14}\mathrm{N} + \mathrm{p} &\rightarrow {}^{15}\mathrm{O} + \gamma \\
^{15}\mathrm{O} &\rightarrow {}^{15}\mathrm{N} + \mathrm{e}^{+} + \nu_{\mathrm{e}} \\
^{15}\mathrm{N} + \mathrm{p} &\rightarrow {}^{12}\mathrm{C} + \alpha
\end{aligned}
$$



CNO C cycle

Summary : $4\mathrm{p} \rightarrow {}^{4}_{2}\mathrm{He} + 2\mathrm{e}^{+} + 2\nu_{\mathrm{e}} + 25\mathrm{MeV}$

Other cycles

- CNO N cycle using ^{14}N as catalyst :

$$
\begin{aligned}
{}^{14}\mathrm{N} + \mathrm{p} &\rightarrow {}^{15}\mathrm{O} + \gamma \\
{}^{15}\mathrm{O} &\rightarrow {}^{15}\mathrm{N} + \mathrm{e}^{+} + \nu_{\mathrm{e}} \\
{}^{15}\mathrm{N} + \mathrm{p} &\rightarrow {}^{16}\mathrm{O} + \gamma \\
{}^{16}\mathrm{O} + \mathrm{p} &\rightarrow {}^{17}\mathrm{F} + \gamma \\
{}^{17}\mathrm{F} &\rightarrow {}^{17}\mathrm{O} + \mathrm{e}^{+} + \nu_{\mathrm{e}} \\
{}^{17}\mathrm{O} + \mathrm{p} &\rightarrow {}^{14}\mathrm{N} + \alpha
\end{aligned}
$$

- NeNaMg cycles
- ...

Reaction rate

We consider the radiative-capture reaction : $1 + 2 \rightarrow 3 + \gamma$

The reaction rate is the number of reactions occurring per unit time and volume

$$r = N_1 N_2 \, \sigma \, v$$

Reaction rate

We consider the radiative-capture reaction : $1 + 2 \rightarrow 3 + \gamma$

The reaction rate is the number of reactions occurring per unit time and volume

$$r = N_1 N_2 \, \sigma \, v$$

The velocity v is distributed according to Maxwell-Boltzmann

$$\phi(\boldsymbol{v}) \quad \propto \quad e^{-E/kT}$$

Reaction rate

We consider the radiative-capture reaction : $1 + 2 \rightarrow 3 + \gamma$

The reaction rate is the number of reactions occurring per unit time and volume

$$r = N_1 N_2 \, \sigma \, v$$

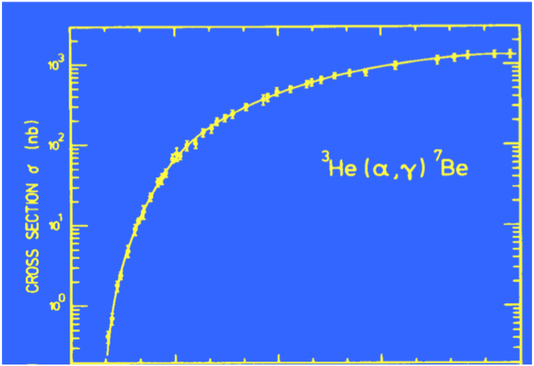
The velocity v is distributed according to Maxwell-Boltzmann

$$\begin{aligned} \phi(\boldsymbol{v}) &\propto e^{-E/kT} \\ \Rightarrow \langle \sigma \, v \rangle &= 4\pi \int \phi(\boldsymbol{v}) \, \sigma(v) \, v^3 \, dv \\ &\propto \int e^{-E/kT} \, \sigma(E) \, E \, dE \end{aligned}$$

$\sigma(E)$ at low energy

Due to Coulomb barrier σ plummets at low E
because reaction takes place only through tunneling

$^3\mathrm{He} + \alpha \rightarrow {}^7\mathrm{Be} + \gamma$ also noted $^3\mathrm{He}(\alpha, \gamma)\,{}^7\mathrm{Be}$



Astrophysical S factor

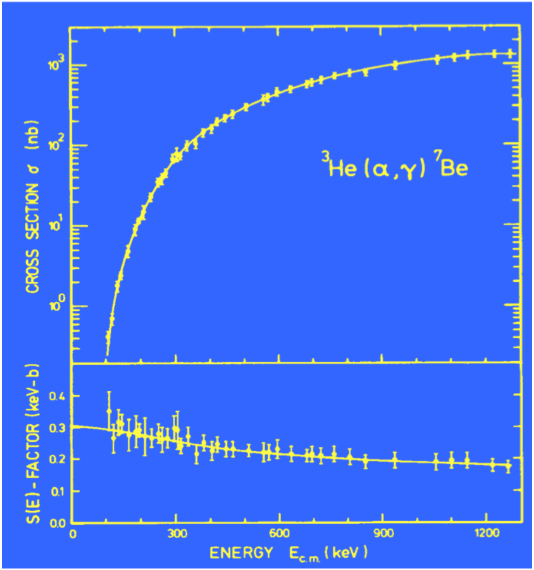
The rapid drop explained by the Gamow factor $e^{-2\pi\eta}$,

$$\eta = \frac{Z_1 Z_2 e^2}{4\pi\epsilon_0 \hbar v}$$

is Sommerfeld parameter

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

The astrophysical S factor varies smoothly with E

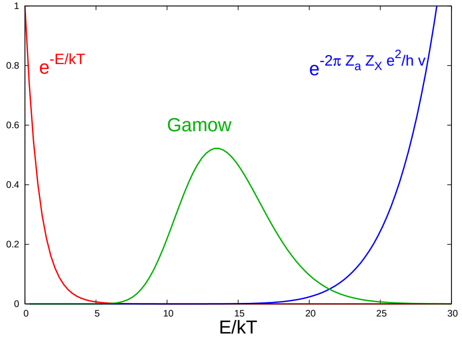


Gamow peak

$$\langle \sigma v \rangle \propto \int e^{-E/kT} \sigma(E)\, E\, dE$$
$$= \int e^{-E/kT} e^{-2\pi\eta} S(E)\, dE$$

$\Rightarrow S$ must be known
only in the Gamow peak

$$g(E) = e^{-E/kT} e^{-2\pi\eta}$$



Example

For the reaction $^3\mathrm{He}(\alpha,\gamma)\,^7\mathrm{Be}$ in the sun

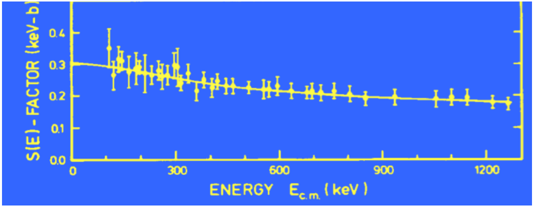
$Z_1 = 2, A_1 = 3$

$Z_2 = 2, A_2 = 4$

$T = 0.015\ T_9$

Gamow peak

at $E_0 \simeq 20$ keV



⇒ difficult to measure due to background

Example

For the reaction $^{3}\mathrm{He}(\alpha,\gamma)\,^{7}\mathrm{Be}$ in the sun

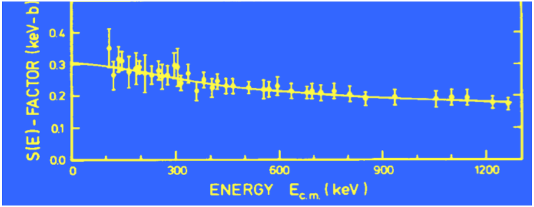
$Z_1 = 2, A_1 = 3$

$Z_2 = 2, A_2 = 4$

$T = 0.015\ T_9$

Gamow peak

at $E_0 \simeq 20$ keV



$\Rightarrow$ difficult to measure due to background

Solutions

- Rely on theory to extrapolate down to astrophysical energies

Example

For the reaction ${}^3\mathrm{He}(\alpha,\gamma)\,{}^7\mathrm{Be}$ in the sun

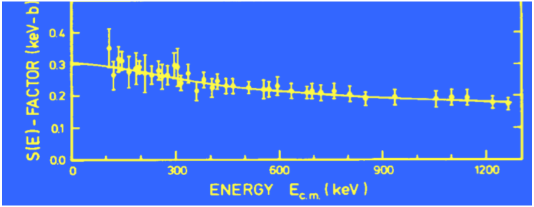
$Z_1 = 2, A_1 = 3$

$Z_2 = 2, A_2 = 4$

$T = 0.015\ T_9$

Gamow peak

at $E_0 \simeq 20$ keV



$\Rightarrow$ difficult to measure due to background

Solutions

- Rely on theory to extrapolate down to astrophysical energies
- Go to an underground laboratory to reduce background
  e.g. LUNA collaboration [see V. Mossa's poster on Monday]

Example

For the reaction $^3\mathrm{He}(\alpha,\gamma)\,^7\mathrm{Be}$ in the sun

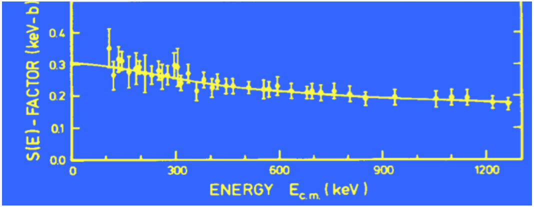
$Z_1 = 2, A_1 = 3$

$Z_2 = 2, A_2 = 4$

$T = 0.015\ T_9$

Gamow peak

at $E_0 \simeq 20$ keV



⇒ difficult to measure due to background

Solutions

- Rely on theory to extrapolate down to astrophysical energies
- Go to an underground laboratory to reduce background
  e.g. LUNA collaboration [see V. Mossa's poster on Monday]
- Use indirect techniques, e.g. Coulomb breakup

He and other fusions

When enough ^{4}He has built up,
if temperature and pressure are high enough,
He fusion starts

He and other fusions

When enough ^{4}He has built up,
if temperature and pressure are high enough,
He fusion starts

But ^{8}Be is unbound : $^8\mathrm{Be} \rightarrow\ ^4\mathrm{He} +\ ^4\mathrm{He}$

He and other fusions

When enough ^{4}He has built up,
if temperature and pressure are high enough,
He fusion starts

But ^{8}Be is unbound : $^8\mathrm{Be} \rightarrow\ ^4\mathrm{He} +\ ^4\mathrm{He}$
This $A = 8$ gap is bridged by the triple-α process

$$3\alpha \rightarrow\ ^8\mathrm{Be}^* + \alpha \rightarrow\ ^{12}\mathrm{C}^*$$

which occurs through the Hoyle state : $J^\pi = 0^+$ resonance in ^{12}C
predicted by F. Hoyle and observed by W. Fowler (NP in 1983)

He and other fusions

When enough ^{4}He has built up,
if temperature and pressure are high enough,
He fusion starts

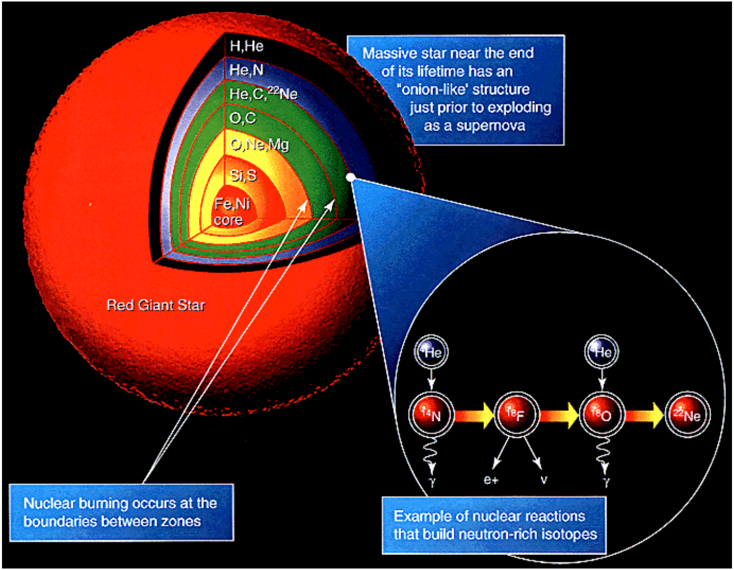
But ^{8}Be is unbound : $^{8}\mathrm{Be} \rightarrow {}^{4}\mathrm{He} + {}^{4}\mathrm{He}$
This $A = 8$ gap is bridged by the triple-α process

$$3\alpha \rightarrow {}^{8}\mathrm{Be}^{*} + \alpha \rightarrow {}^{12}\mathrm{C}^{*}$$

which occurs through the Hoyle state : $J^{\pi} = 0^{+}$ resonance in ^{12}C
predicted by F. Hoyle and observed by W. Fowler (NP in 1983)

At a later stage, C may capture α to form O
or fuse with itself to form Ne, Na or Mg
$\Rightarrow$ Onion structure of star…

The onion star



What happens next ?

Depending on the mass of the star :

- $M \lesssim 8M_\odot$:
  - ends with C-O core ($M \sim M_\odot$)
    or O-Ne-Mg core ($M \sim 8M_\odot$)
  - H outer layer is expelled → planetary nebula
  - core collapses gravitationally
    → white dwarf ($M \sim M_\odot$ and $R \sim R_\oplus$)

Planetary nebula : Cat's eye nebula

What happens next ?

- Massive star ($M > 8M_\odot$)
  - C burning → Fe-Ni core
  - Gravity strikes back : gravitational collapse of the core
    → neutron star ($M \sim M_\odot$ and $R \sim 10$ km ; $\rho \sim \rho_0$)
    or black hole…
  - outer layers expelled : supernova (type II)

Type II SN : Crab nebula

Equation of State

To understand the formation of neutron stars,
need to understand the nuclear matter
But no need for microscopic calculations
$\Rightarrow$ (nuclear) Equation of State (EoS)

Equation of State

To understand the formation of neutron stars,
need to understand the nuclear matter
But no need for microscopic calculations
⇒ (nuclear) Equation of State (EoS)
State of a perfect gas given by P, V, T, N : $PV = N\,k\,T$

For nuclear matter, the state variables are
Z : proton number
N : neutron number
or in infinite matter $\alpha = (N - Z)/A$, the n-p asymmetry
ρ the density

Equation of State

To understand the formation of neutron stars,
need to understand the nuclear matter
But no need for microscopic calculations
$\Rightarrow$ (nuclear) Equation of State (EoS)
State of a perfect gas given by P, V, T, N : $\quad PV = N\,k\,T$

For nuclear matter, the state variables are
Z : proton number
N : neutron number
or in infinite matter $\alpha = (N - Z)/A$, the n-p asymmetry
ρ the density

EoS obtained from the energy of the system per nucleon ϵ

see S. Gandolfi's talk on Tuesday

Nuclear EoS

Back to liquid-drop formula (Bethe Weizsäcker)

$$B(Z,N) = a_v A - a_s A^{2/3} - a_C \frac{Z(Z-1)}{A^{1/3}} - a_{\rm Sym} \frac{(A-2Z)^2}{A}$$

$$\epsilon \equiv -\frac{B(Z,N)}{A} \underset{V\to\infty}{\longrightarrow} -a_v + a_{\rm Sym}\,\alpha^2 \quad \text{with } \alpha = (N-Z)/A$$

Liquid drop assumes constant density $\rho = \rho_0 \simeq 0.16\ \mathrm{fm}^{-3}$

Nuclear EoS

Back to liquid-drop formula (Bethe Weizsäcker)

$$
\begin{aligned}
B(Z,N) &= a_v A - a_s A^{2/3} - a_C \frac{Z(Z-1)}{A^{1/3}} - a_{\mathrm{Sym}} \frac{(A-2Z)^2}{A} \\
\epsilon &\equiv -\frac{B(Z,N)}{A} \underset{V\to\infty}{\longrightarrow} -a_v + a_{\mathrm{Sym}}\,\alpha^2 \quad \text{with } \alpha = (N-Z)/A
\end{aligned}
$$

Liquid drop assumes constant density $\rho = \rho_0 \simeq 0.16\ \mathrm{fm}^{-3}$
We need density dependence

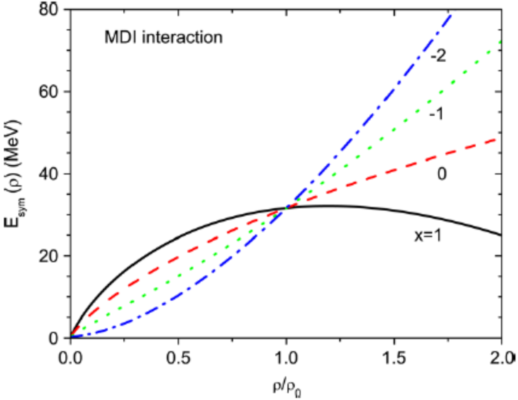
$$
\epsilon(\rho,\alpha) = \epsilon(\rho,\alpha=0) + S(\rho)\alpha^2 + \ldots
$$

where S is the symmetry energy

Symmetry energy

S characterises the increase in energy from $N = Z$
Taylor expanded around $\rho = \rho_0$:

$$S(\rho) = S_v + \frac{L}{3}\left(\frac{\rho - \rho_0}{\rho_0}\right) + \frac{1}{18}K_{\text{sym}}\left(\frac{\rho - \rho_0}{\rho_0}\right)^2 + \ldots$$



S is said

- stiff if $dS/d\rho > 0$
- soft if reaches saturation

Constraints

S can be constrained from nuclear experiments (laboratory) :

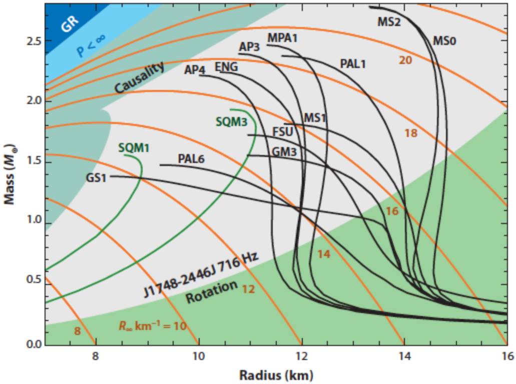
- neutron skin thickness (balance between surface tension and asymmetry term)
- Giant Monopole Resonance (breathing mode)
- Giant Dipole Resonance (n to p oscillations)
- heavy-ion collisions (n to p ratio in emitted fragments)

see W. Trautmann's talk on Friday

Constraints

from astrophysical observations

- Mass and radii of neutron stars (existing $2\,M_\odot$)

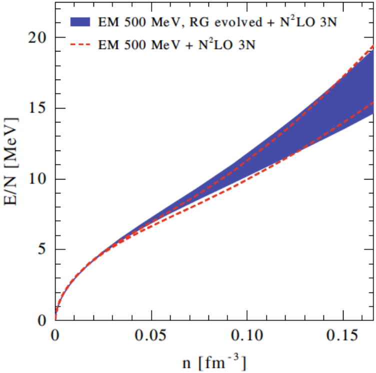


[J. Lattimer Ann. Rev. Nucl. Part. Sci. **62**, 485 (2012)]

Constraints

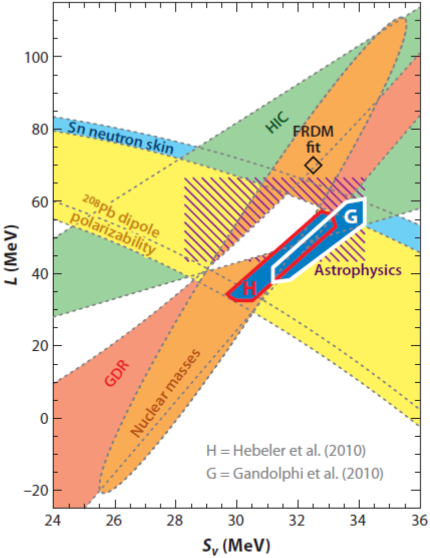
from nuclear-structure calculation

- EFT prediction of EoS
  [cf. S. Gandolfi's talk on Tuesday morning]



[K. Hebeler *et al.* Astrophys. J. **773**, 11 (2013)]

Constraints

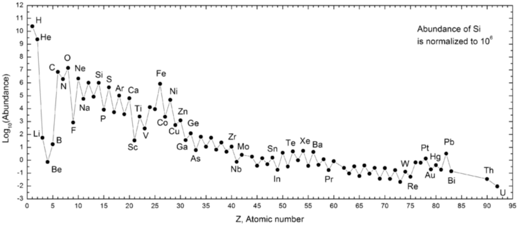


[J. Lattimer Ann. Rev. Nucl. Part. Sci. **62**, 485 (2012)]

How do we get heavier elements ?

Increasing Coulomb barrier suppress fusion

Once Fe synthesised no more fusion



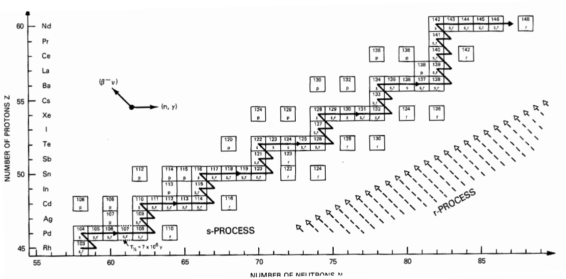
To explain formation of heavier elements

Burbidge, Burbidge, Fowler and Hoyle (B^2FH) suggest in 1957 successive captures of n by seed nuclei : s and r processes

s process

The s process is a *slow* process of n capture by stable nuclei
slow means slower than β decay, i.e. requires small n flux
e.g. He burning stage of AGB stars

$$^{13}C + \alpha \rightarrow {}^{16}O + n$$
$$^{22}Ne + \alpha \rightarrow {}^{25}Mg + n$$

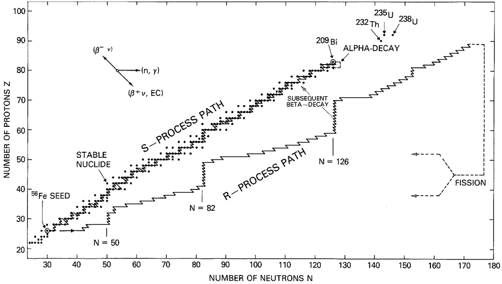


Synthesises elements close to stability ⇒ does not explain

- isotopes away from stability
- heavy elements (U, Th. . .)

r process

The r process is a *rapid* process of n capture by stable nuclei
rapid means faster than β decay, i.e. requires high n flux
e.g. core-collapse supernovæ see B. Messer's talk on Thursday



Synthesises elements far away from stability ⇒ requires

- masses of radioactive isotopes see D. Atanasov's talk on Wednesday
- location of nuclear shells

p and rp processes

s and r processes synthesise only n-rich nuclei
How to explain the presence of p-rich nuclei ?

p and rp processes are similar processes
with successive p captures

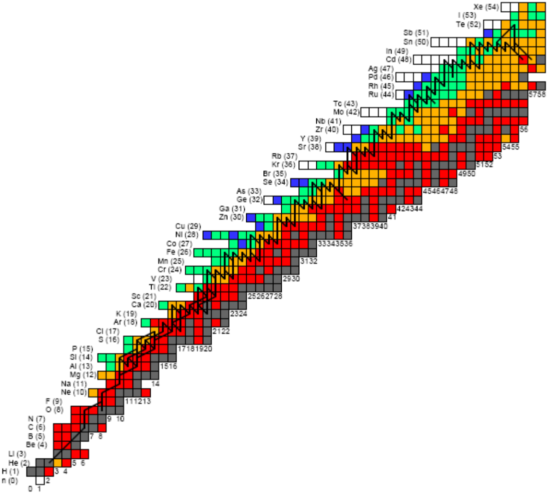
p process :
Slow capture of protons
Synthesises p-rich nuclei close to stability
Possible site : O-Ne layer in supernova

rp process

rapid p-capture reactions

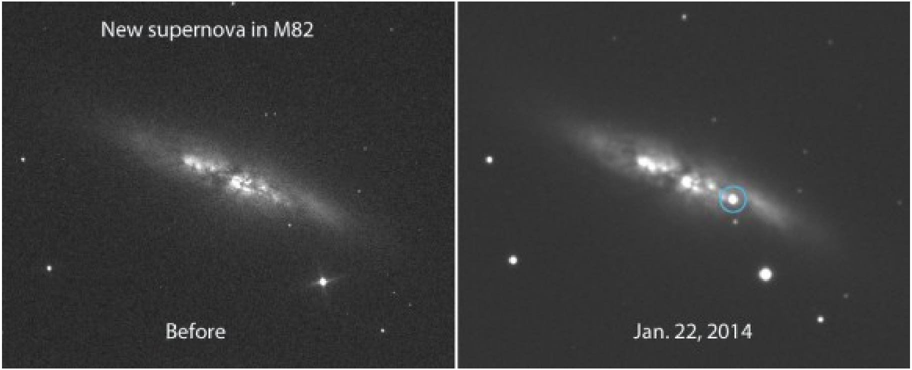
synthesises elements
away from stability
cf r process

Possible site : X-ray burst
accretion by neutron star
of H- and He-rich material
from companion star
⇒ type I supernova



[Schatz and Rehm NPA 777, 601 (2006)]

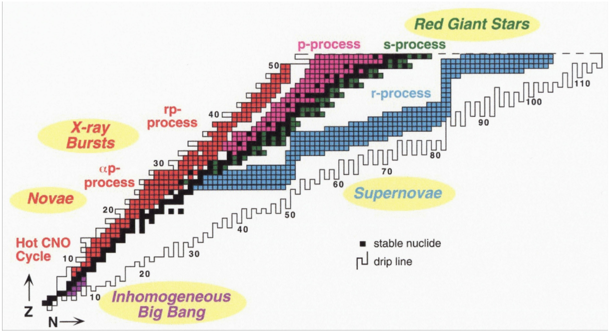
Type I SN : 21 January 2014



Summary

Nuclei are synthesised in stellar environments during various processes

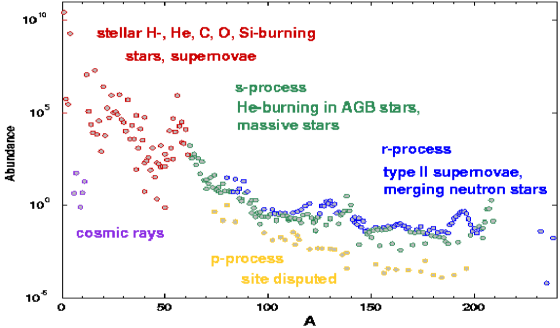
- pp chain, CNO cycles, He burning,...
- s and r processes (n capture)
- p and rp processes (p capture)



[Smith and Rehm Annu. Rev. Nucl. Part. Sci. 51, 91 (2001)]

Stardust

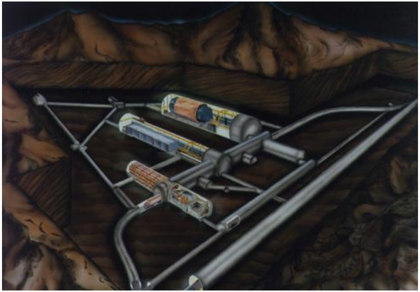
Abundances of elements and production mechanisms



We are all stardust. . .

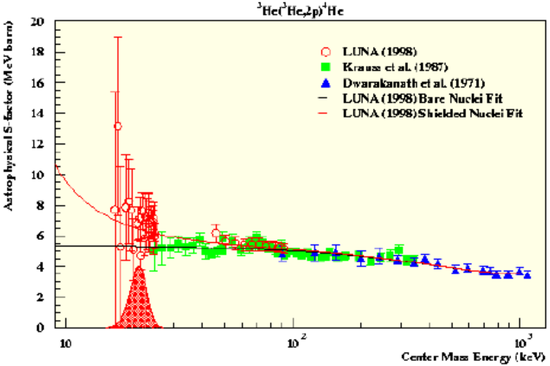
LUNA accelerator facility at the Gran Sasso Facility

Located below the Gran Sasso mountain in the Apennines



LUNA result for $^{3}\mathrm{He}(^{3}\mathrm{He}, 2p)^{4}\mathrm{He}$

LUNA can reach the Gamow peak in some cases



pp chain vs. CNO cycles

The type of cycle depends on temperature and pressure