Nuclear Physics and Astrophysics

PHY-302

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Lecture 22
Supernovae

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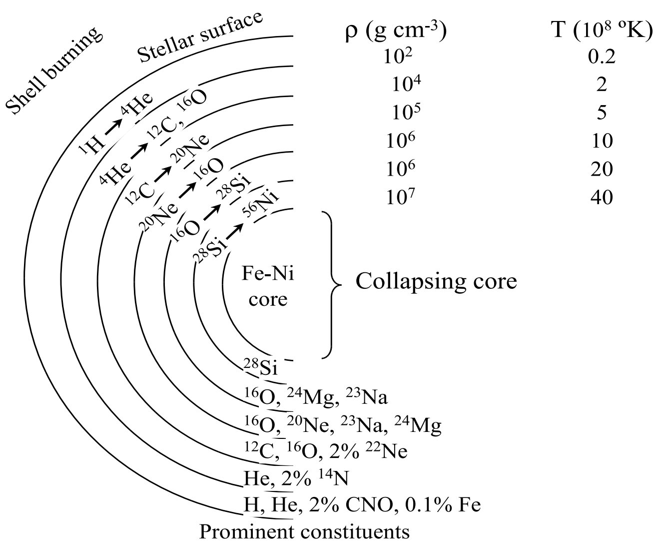
Shell Structure of Star



Why does stellar fusion not produce elements heavier than A~60 ?

Nucleosynthesis of Higher Mass Elements

Higher mass nuclei form via neutron capture chains:

$^{56}Fe \rightarrow {}^{57}Fe \rightarrow {}^{58}Fe \rightarrow {}^{59}Fe$

Produce isotopes of increasing neutron excess

Chains continue till isotope with lifetime shorter than mean time for neutron absorption

Depends on neutron flux within star and n absorption cross section

Nucleus undergoes β^- decay converts to element with Z+1

$$^{59}Fe \rightarrow {}^{59}Co + e^- + \bar{\nu}_e$$

New chain sequence with neutron capture of Co: unstable isotope undergoes β^- decay

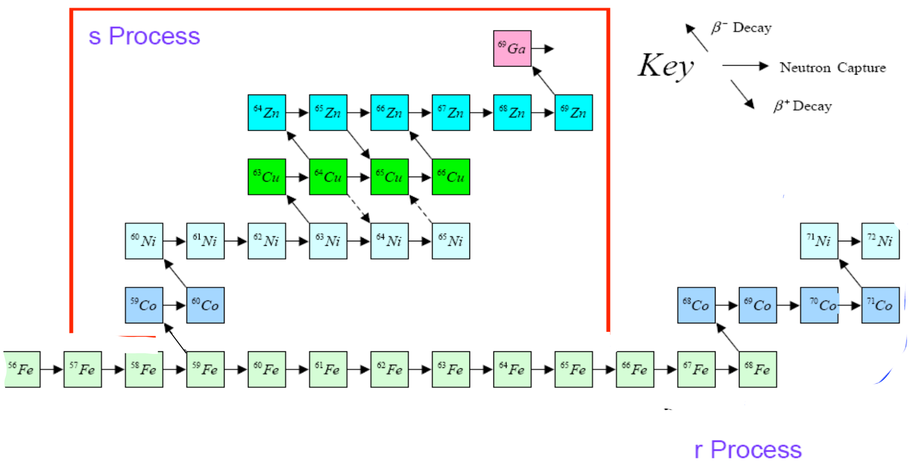
Process responsible for production of many nuclei A>60

S and R processes

Can be divided into 2 processes:

s process: neutron capture very slow - allowing β decays to occur

r process: neutron capture rapid - no time for β decays



Where do these neutrons come from?

Neutron Source?

where do neutrons come from?

After primordial nucleosynthesis all neutrons bound into ^{4}He...

Stellar interiors complex environments - look at neutron seperation energies

Most light nuclei require ~ 17 MeV for collision to knock out neutron (^{12}C, ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si)

Energy too high for stellar interior

More likely reactions are from neutron rich isotopes:

^{13}C (α,n) ^{16}O Q=2.2 MeV spallation process

^{22}Ne (α,n) ^{25}Mg Q=-0.48 MeV

These reactions can occur in helium burning phase of red giant stars

Can calculate reaction rate using techniques used previously

Determine velocity averaged cross section for thermalised neutron: rate ~ $n.\langle\sigma v\rangle$

Yields reaction rate of 1 per 20 years (per target nucleus) for typical red giant!

s-process occurs in core and shell of star (timescales ~ 10^4 years)

Supernovae & the r-process

r-process occurs when neutron flux is larger by ~ 10 orders magnitude:

supernova explosions

neutron stars

Supernova is catastrophic stellar collapse

Once Fe production is reached, no further energy release from burning

Star begin to collapse under gravity - iron core density increases

As core collapses electrons are 'squeezed' into higher energy quantum states

This electron degeneracy pressure can support core - due to Pauli Exclusion Principle

In some cases electron degeneracy pressure insufficient to support star

Density increases rapidly till electron capture cross section occurs:

$p + e \rightarrow n + \nu_e$ protons convert to neutrons

No more electrons to support core's gravitational collapse!

Collapse continues very rapidly - till core has density of atomic nucleus 10^{15} g/cm^3

Core radius drops from ~10^4 km to 10^2 km in ~1 s

Core consists of almost purely neutrons

supported by neutron degeneracy pressure (neutrons also obey exclusion principle!)

Core becomes solid

Outer layers no longer supported - fall inwards - infalling material bounces off stiff core

Heats outer stellar envelope very rapidly releasing huge amount energy

~ same as entire energy output of sun over complete lifetime 10^9 y!

In this brief supernova environment neutron flux is extremely high
Enough for r process to proceed

Tests of Heavy Element Production

Can we test our theory of heavy nucleosynthesis?

For s-process assume approximate equilibrium conditions reached for each species:

production rate = destruction rate

Consider species A, with abundance N_A

$$\frac{dN_A}{dt} \propto \sigma_{A-1} N_{A-1} - \sigma_A N_A$$

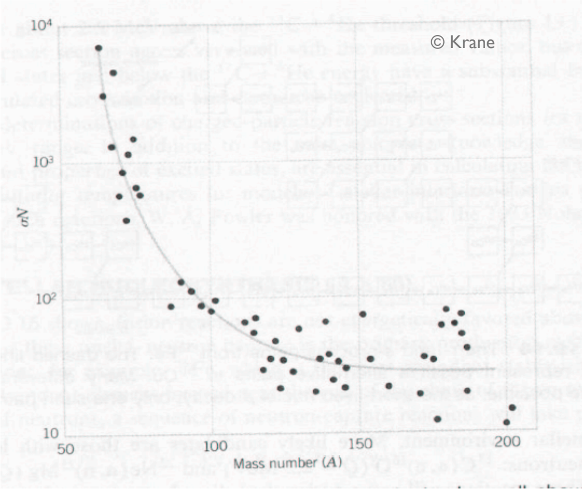
N_A produced by neutron capture of nucleus A-1, and destroyed by neutron capture of nucleus A

capture cross sections are σ

In equilibrium N_A is constant

$$\sigma_{A-1} N_{A-1} = \sigma_A N_A$$

neutron capture cross section x abundance



For Fe constant rate is invalid

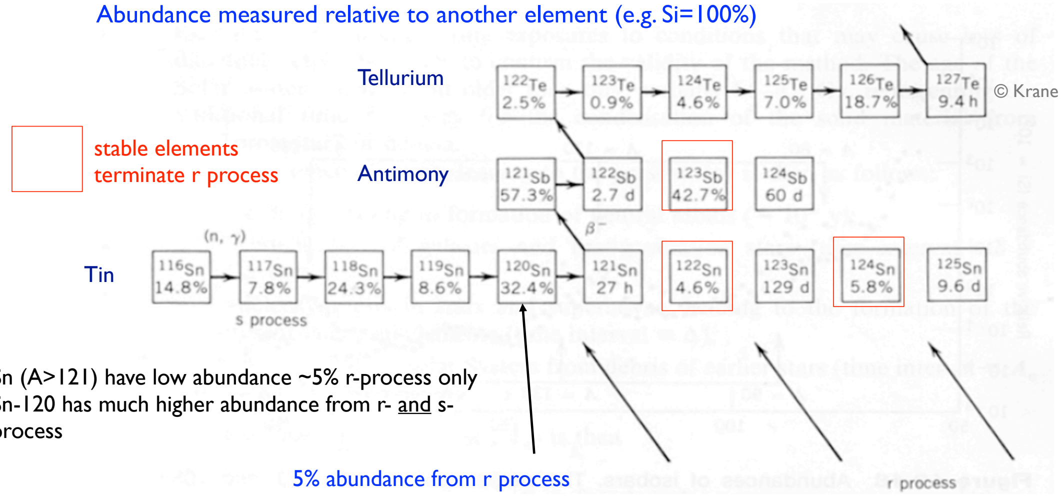
Because Fe not produced via s-process

Fe production via fusion & r-process

Equilibrium value reached for A~100

Implies assumptions of s-process valid

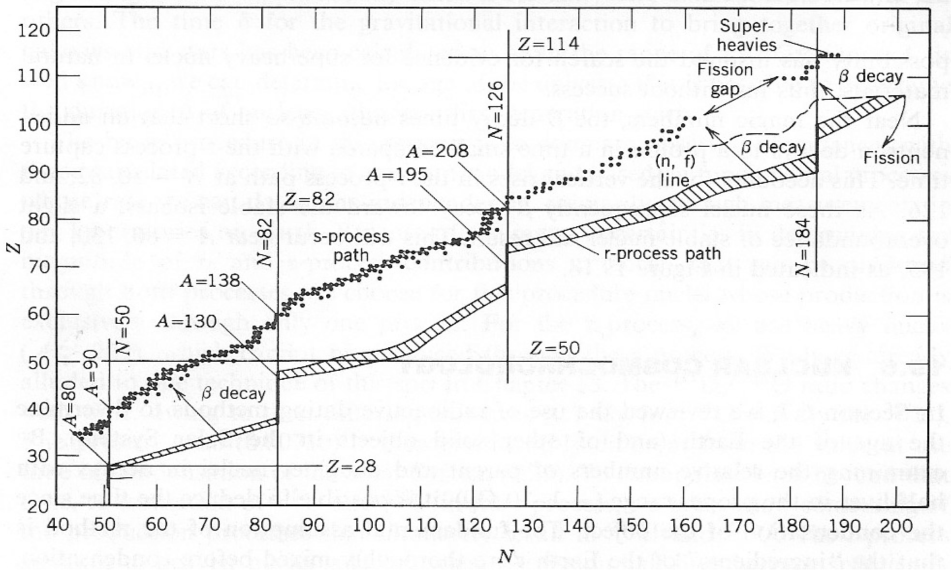
Abundance measured relative to another element (e.g. Si=100%)



Sn (A>121) have low abundance ~5% r-process only
Sn-120 has much higher abundance from r- and s-process

5% abundance from r process
rest from s process

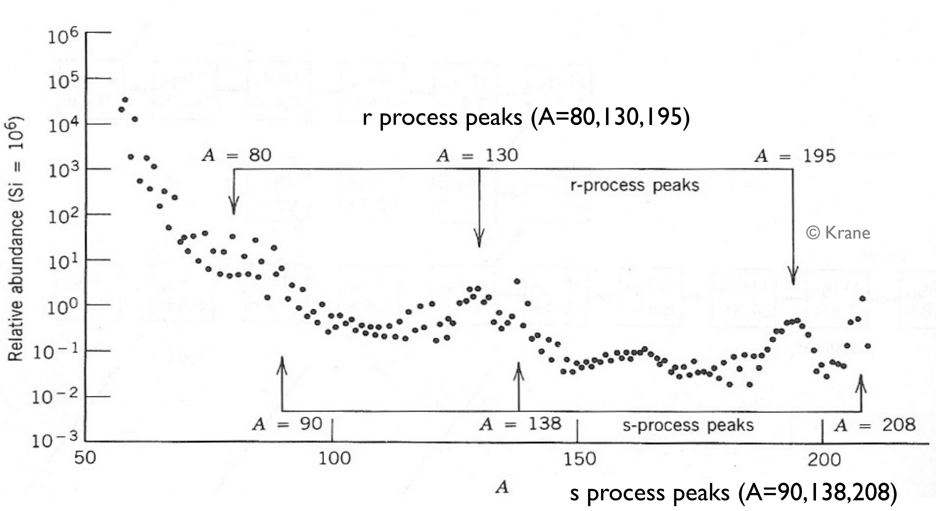
^{122,123,124}Te only produced via s-process (r process terminate ^{123}Sb, ^{122}Sn, ^{124}Sn)
i.e. Te is shielded from the r-process
Can make predictions of relative abundances



s-process terminates at A=209: no more stable isotopes

r-process has vertical lines at N=magic numbers - Why ?

r-process produces heavy elements up till point when fission half-life ~ n-absorption time



Peaks at A=80,130,195 from beta decays of r-process parents with N=50,82,126

Peaks at A=90,138,208 from s-process stable nuclei with N=50,82,126

Note the odd-A, even-A structure in the relative abundances

Summary of Nucleosynthesis