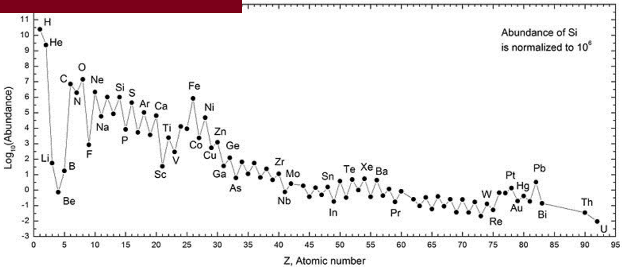
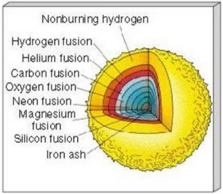
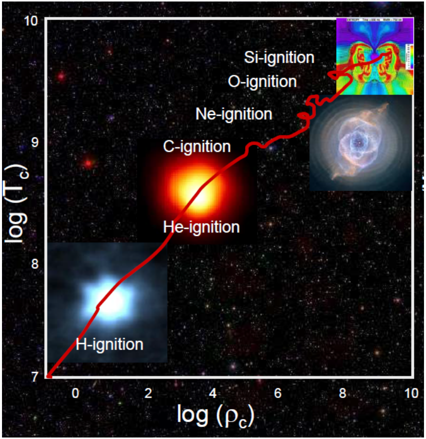




Night Sky from SARF

Jung Keun Ahn (Korea University)

Nuclear Burning and Stellar Evolution

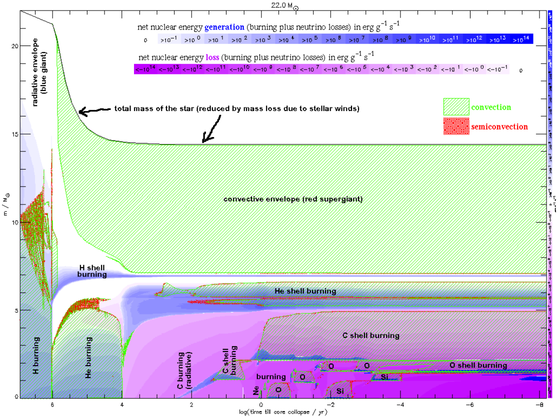


- A slowly contracting star behaves like a classical ideal gas:

$$T_c \propto M^{2/3} \rho_c^{1/3}$$

- Hydrogen burning phase is characterized in terms of CNO proton capture reactions.
- Helium burning phase corresponds to alpha capture reactions.
- Carbon burning phase is related to C/O fusion and capture reactions.

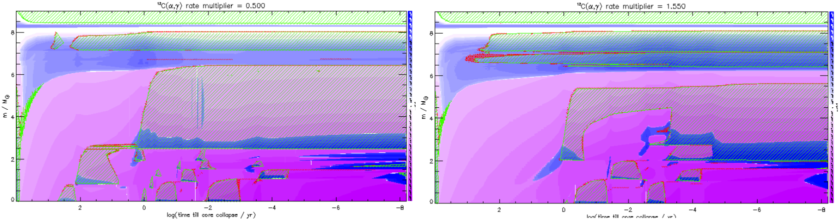
Time Evolution of Nuclear Burning Phases [1]



- Kippenhahn diagrams, i.e., stellar structure as a function of t.

[1] Boyes, Heger and Woosley, `2sn.org/stellarevolution/`

Time Evolution of Nuclear Burning Phases [2]

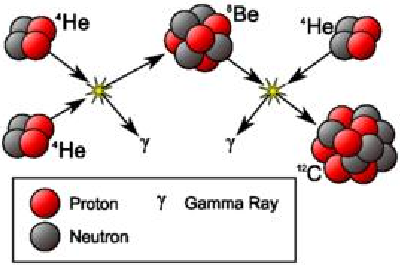


- Stellar structure in terms of $^{12}\mathrm{C}(\alpha,\gamma)$ rate for a $25M_{\odot}$ star.

Stage reached	Time scale	$T_{\mathrm{core}}(10^9 K)$	Density(g/cm^3)
H burning	7×10^6y	0.06	5
He burning	5×10^5y	0.23	7×10^2
C/O burning	600y/6 months	0.93-2.3	$2 \times 10^5 - 1 \times 10^7$
Si melting	1d	4.1	3×10^7
Explosive burning	0.1-1s	1.2-7	varies

[2] Boyes, Heger and Woosley, `2sn.org/stellarevolution/`

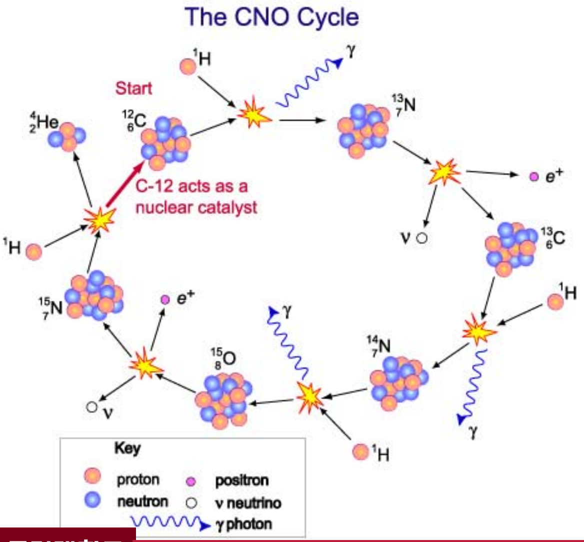
Triple-Alpha Process



$$3^4\text{He} \rightarrow {}^{12}\text{C} \quad 0.6\text{MeV/u}$$

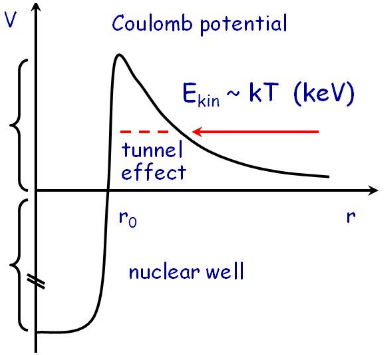
- Competing with $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction (poorly known with 20-30% uncertainty.
- Ratio affects $^{12}\mathrm{C}/^{16}\mathrm{O}$ after He burning.

CNO Cycle (Energy Production in Stars)



- The ^{12}C nucleus used in the first reaction is re-generated in the last reaction.

Reactions between Charged Particles



- Reactions occur through TUNNEL EFFECT during quiescent burnings: ($kT \ll E_C \sim Z_1 Z_2$(MeV))
- Astrphysical $S(E)$ factor:

$$\sigma(E) = \underbrace{\frac{1}{E}\exp(-2\pi\eta)}_{\text{non-nuclear origin}} \quad \underbrace{S(E)}_{\text{nuclear origin}} \;,$$

for s-wave only.

- Energy available from thermal motion ($kT \sim 8.6 \times 10^{-8}$T(K) keV)

  $T \sim 1.5 \times 10^7$K (e.g. our Sun) $kT \sim 1$ keV
  $T \sim 10^{10}$K (Big Bang) $kT \sim 2$ MeV

Maximum Reaction Rate

$$< \sigma v >_{12} = \left(\frac{8}{\pi\mu_{12}}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty S(E) \underbrace{\exp\left[-\frac{E}{kT} - \frac{b}{E^{1/2}}\right]}_{f(E)} dE,$$

where $b = \sqrt{2\mu}\pi Z_1 Z_e^2/\hbar$. $f(E)$ governs energy dependence.

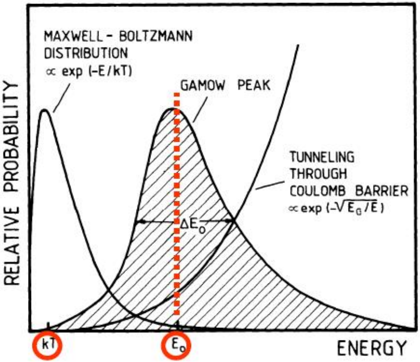
$$\frac{df(E)}{dE} = 0 \underbrace{\longrightarrow}_{\Delta E_0 < E_0} E_0 = \left(\frac{bkT}{2}\right)^{2/3}$$

Only small energy range contributes to the reaction rate.
$S(E) \sim S(E_0) =$ constant.

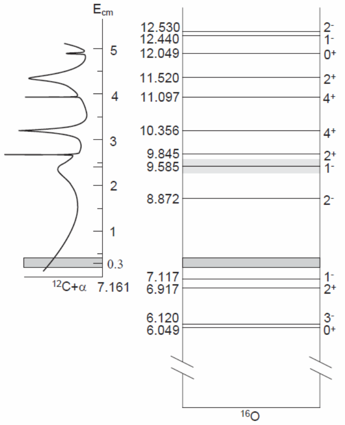
Gamow Peak

For $T \sim 1.5 \times 10^7$K

Reaction	Coulomb barrier (MeV)	E_0(keV)	$\exp(-3E_0/kT)\Delta E_0$
$p+p$	0.55	5.9	7.0×10^{-6}
$\alpha+^{12}$C	3.43	56	5.9×10^{-56}
^{16}O+^{16}O	14.07	237	2.5×10^{-237}



$^{12}C(\alpha,\gamma)^{16}O$ Reaction

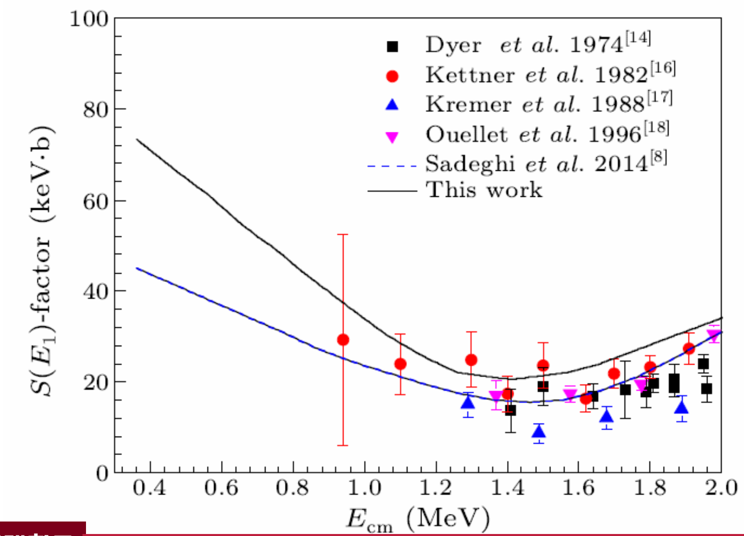


- $^{12}C/^{16}O$ ratio after helium burning process affects evolution of heavy starts - supernova or white dwarf.

$I_{^{12}C} = 100\ p\mu A$

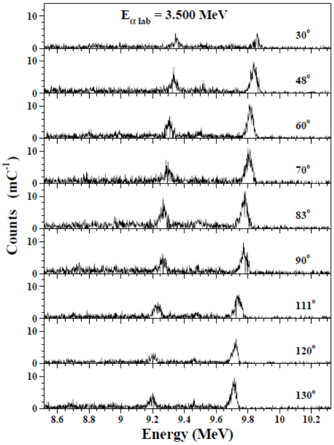
E_{cm}(MeV)	σ(pb)	Rate (fusions/d)
2.0	7500	4×10^5
1.0	36	2000
0.5	0.03	2
0.3	0.0001	0.4

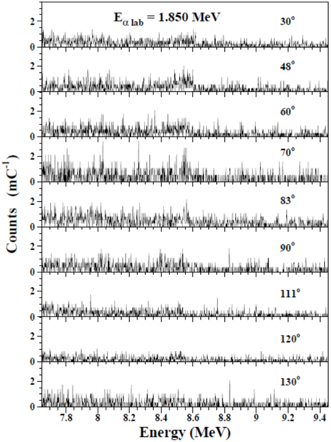
^{12}C$(\alpha,\gamma)^{16}$O Reaction



Measurement of Capture Gamma-Rays

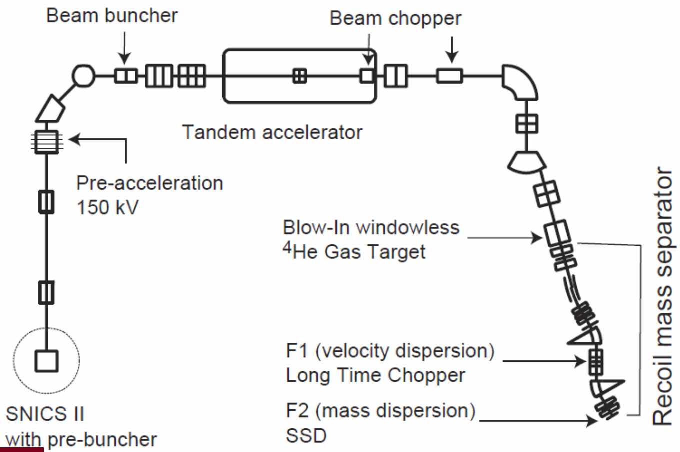
- Results from LUNA.



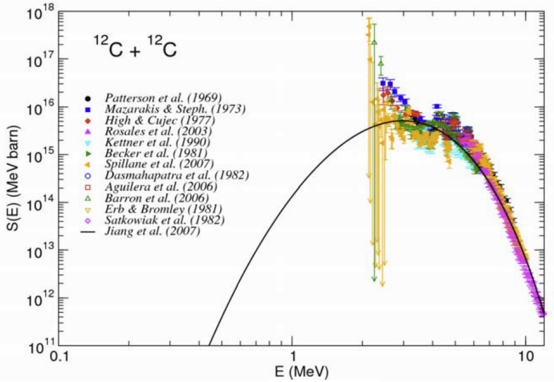


Measurement of Recoil Nucleus

- Tandem accelerator with a recoil spectrometer at Kyushu University.



^{12}C+^{12}C

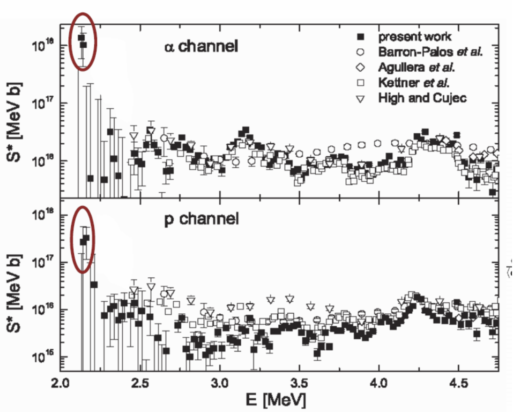


- Time scale for stellar C and O burning phases:

$$^{12}\mathrm{C} + ^{12}\mathrm{C} \rightarrow ^{20}\mathrm{Ne} + \alpha, \quad ^{23}\mathrm{Na} + p, \quad ^{23}\mathrm{Mg} + n$$

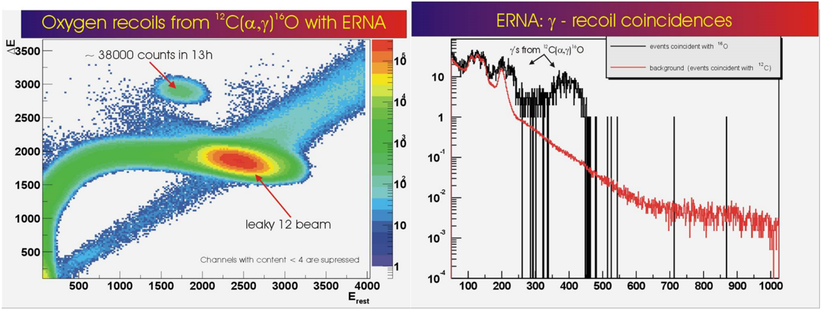
- Different potential models lead to different extrapolations.

$^{12}C+^{12}C$



- Recent data suggest strong but narrow resonance structure in the $^{12}C+^{12}C$ reaction system, which may enhance the reaction rate substantially.

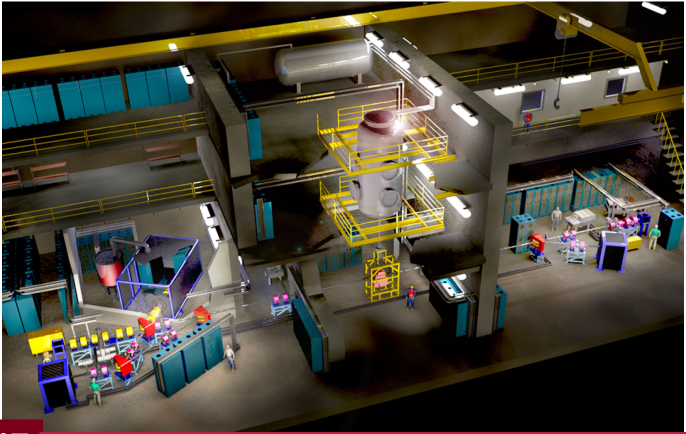
Recoil Separator vs Gamma Ball



- Recoil separator provides a clear ^{16}O tagging above $E_{\rm cm} > 1.4$ MeV
- Below $E_{\rm cm} = 1.4$ MeV, $\Delta E - E$ identification is not possible, a larger acceptance is needed, and beam suppression becomes more difficult.

DIANA at the Homestake Sanford Lab

- The DIANA (Dual Ion Accelerator for Nuclear Astrophysics) collaboration is awaiting a federal budget approval for final design and construction of the experiment.

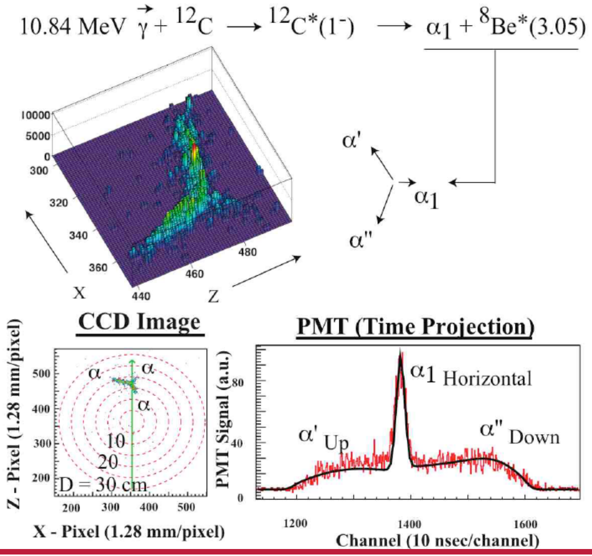


Competing with DIANA?

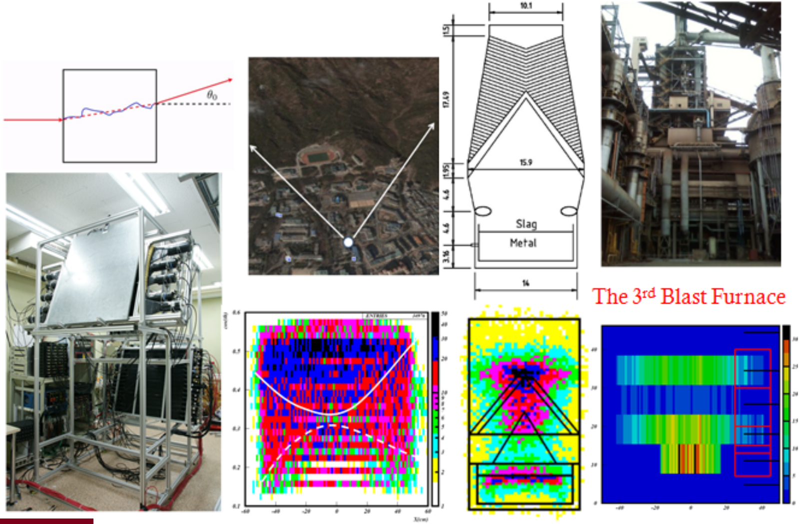
Facility	Ion Source	Accelerator	Beam Currents (mA)
DIANA	2.45 GHz ECR	Dynamitron	100 mA for p at 50 keV 50 mA for ^{4}He$^+$ at 50 keV 0.6 mA for ^{4}He$^+$ at 400 keV

- High-intensity heavy ion beam and a He gas-jet target / a ^{12}C target.
- ^{4}He$(^{12}$C$,\gamma)^{16}$O vs ^{12}C$(^4$He$,\gamma)^{16}$O
- Beam induced background and robustness of solid targets.

Optical Readout TPC



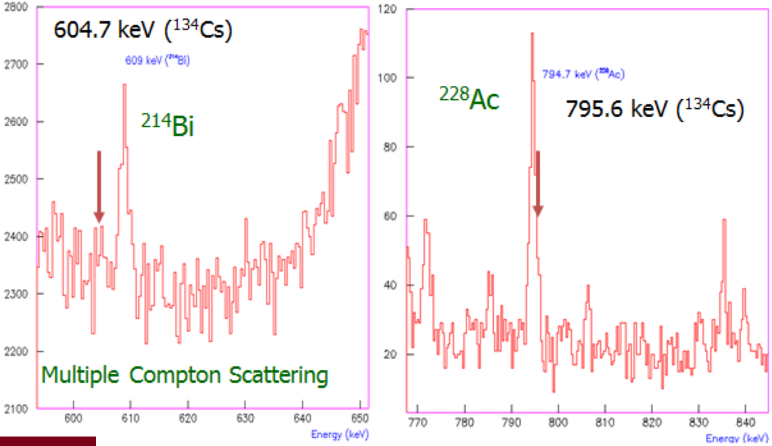
Cosmic-ray Muon Radiography



The 3rd Blast Furnace

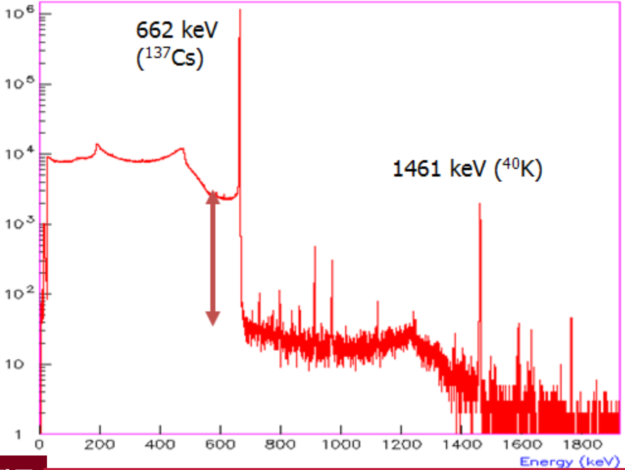
^{134}Cs and ^{137}Cs

- ^{137}Cs from nuclear fission and ^{134} from $^{133}Cs(n,\gamma)^{134}Cs$.
- ^{134}Cs concentration in soil samples.



^{134}Cs and ^{137}Cs

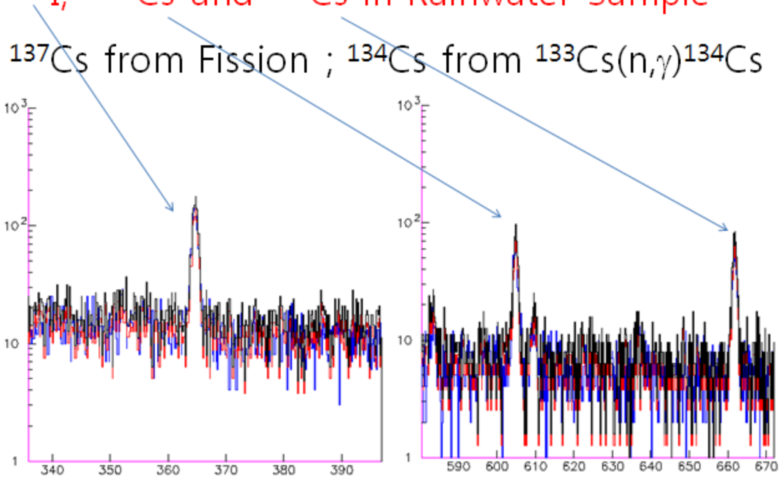
땅 깊숙이 가더라도? (양양 양수발전소 터널 안)



^{134}Cs in Rainwater Samples

^{131}I, ^{134}Cs and ^{137}Cs in Rainwater Sample

^{137}Cs from Fission ; ^{134}Cs from ^{133}Cs(n,γ)^{134}Cs



Summary

- Heavy-ion accelerator facility with a 18-GHz ECR ion source!
- Cosmic-ray muon radiography!