Review on the LUNA experiment

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Overview

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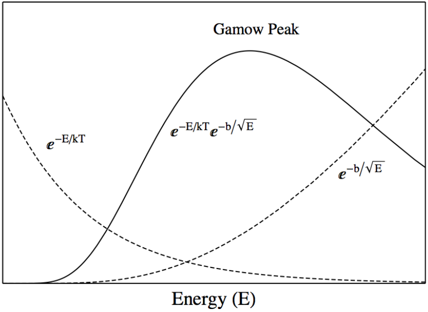
Reaction rate and S-factor

- Reaction rate $<\sigma v>= \int_0^\infty \sigma(v) v \phi(v) dv$
- Nuclei follow Maxell-Boltzmann distribution
  $<\sigma v>= \sqrt{\frac{8}{\pi\mu}}(k_b T)^{-\frac{3}{2}} \int_0^\infty \sigma(E) E exp[-\frac{E}{k_b T}] dE$
- Expressed in term of the astrophysical S-factor
  $\sigma(E) = \frac{S(E)}{E} exp[-2\pi \frac{Z_1 Z_2 e^2}{\hbar}\sqrt{\frac{\mu}{2E}}]$
- When using the S-factor the known exponential dependence on the energy is removed

Gamow Peak

Typical stellar energies below coulomb barrier $\rightarrow$ competition between exponentially decaying cross section at low energies and exponentially decaying density of nuclei at high energies gives a peak called **Gamow peak**



Resonances

Cross section can be enhanced by resonances at specific energies, for the usual **Breit–Wigner** resonance shape the reaction rate is given by

$$< \sigma v >= (\frac{2\pi}{\mu k_b T})^{\frac{3}{2}} \hbar^2 exp[-\frac{E_{res}}{k_b T}]\omega\gamma$$

where

$$\omega\gamma = \frac{2J+1}{(2j_p+1)(2j_t+1)\frac{\Gamma_{in}\Gamma_{ex}}{\Gamma}}$$

Reactions

Reactions of astrophysical interest:

- Hydrostatic Burning:
  - p-p chain
  - CNO Cycle
- Exposive burning $\rightarrow$ Big Bang Nucleosynthesis
- C burning and successive cycles
- Origin of n for r-,s- processes

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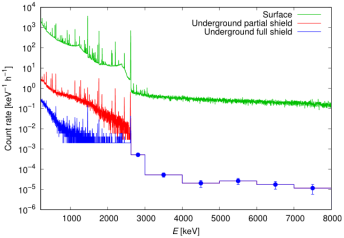
Objectives

The objectives of the LUNA experiment include the study of the reactions relevant to :

- Hydrogen burning in the Sun
- Big Bang Nucleosynthesis
- Stellar reactions at higher energies (Cycles, He burning, C Burning...)

Environmental Background

- Underground laboratory → reduction of the background due to cosmic rays (muon flux by 6 orders of magnitude)



- Radioactive isotopes (^{238}U, ^{232}Th, ^{40}K) in the experiment setup → Passive Shielding and material selection
- Neutron flux from ^{238}U and (α, n) reactions → Shields used in the search or rare events

Ion-beam background

Contaminants can react with the beam releasing γ's.

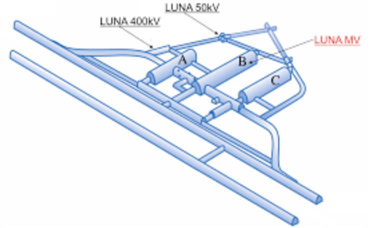
- Proton beam background : $^2H, 7^Li,^{11}B,^{13}C,^{18}O,^{23}Na$
- Alpha beam background: indirect process on ^2H
- In general B,C,O,F can be deposited on the setup while C,^2H,O can be residual gasses

Accelerators

Both the active accelerators are electrostatic accelerator with the potential difference given by Cockroft-Walton generators that can deal with H and He beams

- LUNA 50k : Hot cathode plasma source with axial magnetic field
- LUNA 400k: Radio-Frequency ion source

An additional accelerator is under construction called LUNA MV



Targets

Two types of targets have been used:

- **Gas target**:
  - Single element
  - Accurate density profile needed
  - Correct for gas heating
  - Unable to measure beam current $\rightarrow$ Calorimeter
- **Solid target**:
  - Point-like source
  - Closer Geometry
  - Cold trap to freeze impurities
  - Characteristics must be measured

Detectors

Two types of detectors are typically used:

- **HPGe**: Higher angular and energy resolution , useful when extrapolations are still needed
- **BGO** : Higher efficiency , useful when working directly at Gamow energies, when only the total cross section is needed

In some special cases also Silicon detectors and the activation method have been used.

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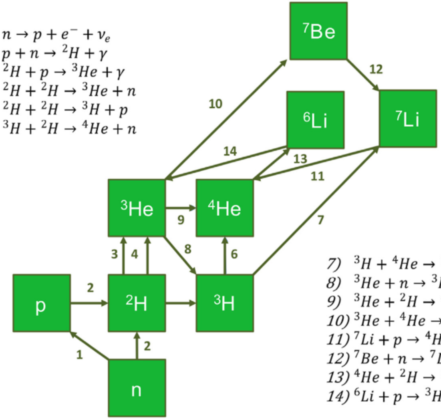
Big Bang Nucleosynthesis

- $^2H(p,\gamma)^3He$
- $^3He(,\gamma)^7Be$
- $^2H(\alpha,\gamma)^6Li$

1) $n \rightarrow p + e^- + \nu_e$
2) $p + n \rightarrow {}^2H + \gamma$
3) $^2H + p \rightarrow {}^3He + \gamma$
4) $^2H + {}^2H \rightarrow {}^3He + n$
5) $^2H + {}^2H \rightarrow {}^3H + p$
6) $^3H + {}^2H \rightarrow {}^4He + n$



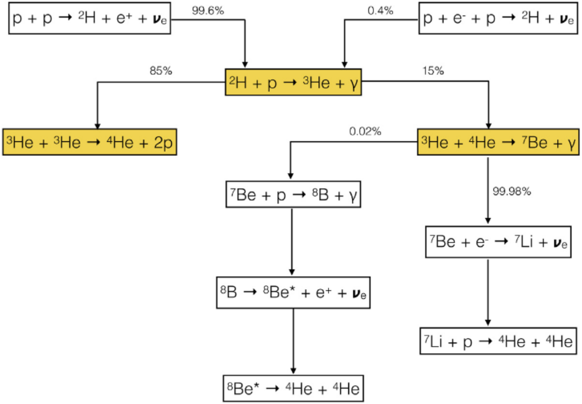
7) $^3H + {}^4He \rightarrow {}^7Li + \gamma$
8) $^3He + n \rightarrow {}^3H + p$
9) $^3He + {}^2H \rightarrow {}^4He + p$
10) $^3He + {}^4He \rightarrow {}^7Be + \gamma$
11) $^7Li + p \rightarrow {}^4He + {}^4He$
12) $^7Be + n \rightarrow {}^7Li + p$
13) $^4He + {}^2H \rightarrow {}^6Li + \gamma$
14) $^6Li + p \rightarrow {}^3He + {}^4He$

Big Bang Nucleosynthesis

- $^2H(p,\gamma)^3He$: A precise measurement of the cross section allows a precise determination of the abundance of deuterium [D/H], to be compared to the value given by the ΛCDM model. Experiment currently underway with LUNA 400kV.
- $^3He(,\gamma)^7Be$: Be decays to ^7Li. The study of the reaction disproved the presence of resonances near the Gamow energy, leaving the Lithium problem open. (Amount of Lithium 2-4 smaller than predicted)
- $^2H(\alpha,\gamma)^6Li$: Exluded a nuclear solution to the discrepancy of the ratio $\frac{^6Li}{^7Li}$ between prediction and observation (3 orders of magnitude larger than predicted).

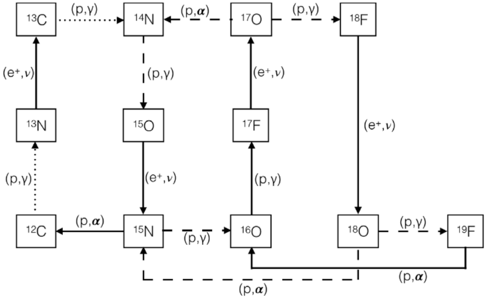
Solar Phase

- $^3He(^3He,2p)^4He$: Reaction in the p-p chain, experiment ruled out resonance at Gamow energy $\rightarrow$ neutrino problem unsolved. (Only two events per month!)



Solar Phase

- $14N(p,\gamma)^{15}O$: Slowest reaction in the CNO cycle, cross section 2 times smaller than previous value obtained with extrapolation $\rightarrow$ lower solar neutrino flux. New value increased lower limit on age of the universe by $\sim$ 1 billion years.



Higher Energy reactions

- $^{15}O(p,\gamma)^{16}O$: Ratio between this and $^{15}N(p,\alpha)^{12}C$ determines leak to 2nd CNO cycle. Measurement at nova energies lead to a value 2 times smaller than previous value $\rightarrow$ 30% less ^{16}O produced in novas
- $^{17}O(p,\gamma)^{18}F$: Ratio between this reactio and $^{17}O(p,\alpha)^{14}N$ gives leak to 3rd CNO cycle. Studied two resonances important for the reaction at 64.5 keV and 183 keV. Lead to factor two times higher than previous value $\rightarrow$ correct identification of production site of a star grain population.

Higher Energy reactions

- $^{22}Ne(p,\gamma)^{23}Na$: Part of the Ne-Na cycle. Had very high uncertainty due to unmeasured resonances $\rightarrow$ 3 resonances measured by LUNA and stricter limits on other 3. Analysis still ongoing on latest experiment.
- $^{25}Mg(p,\gamma)^{26}Al$: Part of the MgAl cycle, can proceed to ground state or isomeric state. Resonances studied by LUNA $\rightarrow$ reaction rate 2 times higher and isomeric state 5 times more present than previously estimated

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Accelerator

A new accelerator will soon be operational, called LUNA MV, that will operate at energies up to 3.5 MV. It will be able to deliver beams of H, He, C and it will mark the start of a new research phase focused on the study of carbon burning.

Neutron production

Production of neutrons important for r- and s- processes

- Low T (90 MK) : $^{13}C(\alpha, n)^{16}O$: Rate gives number of n, half of elements heavier than Fe depend on it. Unknown influence by sub-threshold resonances. Currently never measured at correct energies due to high background and uncertainty.
- High T (300 MK) : $^{22}Na(\alpha, n)^{25}Mg$: Present in the He burning stage but also influences production in stars with lower initial masses. Main source of neutron for s-processes in hydrostatic burning of massive stars, responsable for production of elements between Fe and Sr. Currently uncertainty is too high and the influence of possible sub-barrier resonances is unknown.

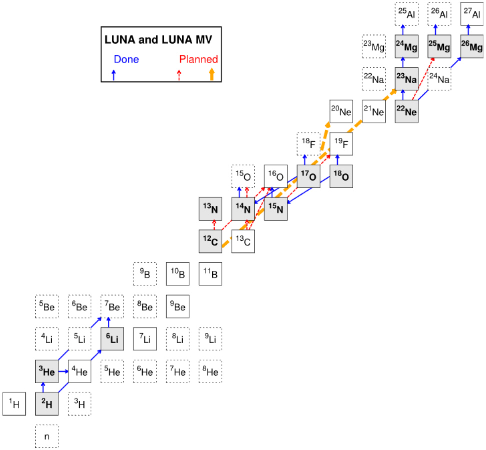
C Burning

C burning triggered by $^{12}C +^{12} C$ reaction.

- Reaction rate influences temperature of C burning and duration.
- Releases protons and α used in reactions that give n $\rightarrow$ s-process.
- Cross sections influenced by many resonances of width 10 keV spaced by 300-500 keV
- Background due to target impurities (beam very pure), main problems due to H and ^2H that bond strongly with C.

Reactions

Summary of reactions studied and planned at LUNA



The End