Nuclei in the Cosmos

• When and where were all the known nuclei existing naturally on Earth produced?
• What kind of nuclear reactions are involved?
• What kind of stellar or galactic or Big Bang environments provide these reactions?
• How can we learn more about this with experiments on Earth?
The Structure of Matter

- What nuclei is the Universe made off?
- What nuclei where there in the beginning (right after the big bang)?
- When and how did nuclei important for life form?
- Where do heavy nuclei come from?
All the nuclei in the universe

**Challenge:** Most nuclear reactions in the Universe are at low energies or involve the weak interaction (tiny cross sections) => Experiments and Theory are HARD! (subtle effects play big role!)
Where does $^4$He come from?

First “3” minutes:
- quarks fuse to p, n
  (everything else decays)
- $p+n = d, d+p = ^3$He, $^3$He+n = $^4$He
- Competes with n decay (15 min) => observed abundance = test of Big Bang models
- Smattering of Li,…

“Ordinary” nucleosynthesis in stars (like the sun):
- $p+p = d + e^+ + \nu \rightarrow ^4$He, …
C, N, O: Elements for Life

• How do you form C?
  – Core runs out of H fuel, compacts and heats up
  – “Helium burning”: \( \alpha + \alpha + \alpha = ^{12}\text{C} \)
  – \( \alpha + \alpha = ^{8}\text{Be} \)? Unbound! => Crucial importance of Hoyle state (3-dim structure recently discovered)

• From C to oxygen

• Other elements
C, N, O: Elements for Life

- Carbon/Oxygen ratio in our universe?
- What reaction do we need to study?
- What is the problem?
- What do we need to study it?
Heavier elements – the r process

- What is the r-process?
- What kind of nuclei do we need to study to understand it?
- What are possible sites for it?
- How can LIGO help?
Neutron Stars and Nuclear Pasta

n stars = End states of star collapse for stars > several solar masses (supernovae)
Gigantic nuclei: $A = 10^{57}$ (but superdense core due to gravity >> nuclear force!)

![Image of Nuclear Pasta (crust of n star)]

Measuring the n radius of lead to predict the radius of a n star
Summary

• Much already known about nuclear processes in the universe
• Still more information needed: cross sections of very rare processes, properties for very exotic nuclei, equation of state of nuclear matter, r-process sites,…
• Tools: low energy accelerators (future: underground!), rare isotope facilities (FRIB!), parity violating electron scattering (JLab), LIGO