Field Manual of Fine-Tuning

Chapter Notes: Nucleosynthesis

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Physics Covered
Big Bang Nucleosynthesis, Stellar Nucleosynthesis

Previous Chapter:
Unknown, likely particle/weak physics, and/or background cosmology

Following Chapter:
Unknown, likely star formation

Types of Fine-Tuning:
$\frac{\Delta X}{X}$ small, for fundamental constants X such that process still happens. Two ranges: Inner range of observed value with error bars, Outer range allowable area in local parameter space leading to process. Vital limitation: Only explore connected regions in certain directions, could be other disconnected 'islands' which lead to a similar result: See nucleosynthesis without weak interactions.

Directly explored Fine-Tuned Parameters:

- B_E: The binding energy of nuclear isotopes (particularly Deuterium)
- τ_n: The lifetime of the neutron
- Q: The mass difference between protons and neutrons
- σ_{AB}: Cross sections for nuclear interactions
- η: The ratio of baryons to photons at nucleosynthesis, equivalently Ω_b

Indirectly explored Fine-Tuned Parameters:

- α_{em}: The electromagnetic fine-structure constant
- α_G: The gravitational fine-structure constant
- V_H: The Higgs vacuum expectation value

Assumed Background:

- Friedmann Equation (temperature form)
- Weak interactions ($n \leftrightarrow p$)
- Basic chemistry (Table of elements, protons neutrons electrons, shells)

Outline of Chapter:

Introduction:

- Background material beginning with the table of the elements and basic chemistry.
- Statement of the goal of nucleosynthesis is to populate this table with the right abundances, starting from protons, neutrons, electrons, positrons and cosmic rays.
- Most interactions are two body, so looking at fusion, fission as $2 \to 1$, $2 \to 2$ or $1 \to 2$ processes.
- Description of binding energy (plot of binding energies by isotope / nucleon number?). Atom is unstable if there exists components with higher binding energies and the lifetime of such particles.
- Standard prefactors for abundances: Density, time

Physical Process: BBN

- Universe well described by Friedmann equation in radiation era: $H^2 \sim T^4$
- Start at high temperature (100MeV), universe populated by $n, p, e^{\pm}, \gamma$
- $n/p \sim e^{-Q/T} \approx 1$ due to high temperature. $\eta \approx 10^{10}$ - initial condition.
- $T > B_D$ so cannot form deuterium. Bottleneck until $T < B_D$.
- $B_{4He} >> B_D$ so any formed deuterium quickly turns into Helium.
- As T drops below Q, neutron decay starts, Z_n important. Few free neutrons, most bound up in He.
- Next should be $A = 5$ or $A = 8$ but mass gap stops process
- Lithium, and the problem with missing $Li7$
- Observational evidence of abundances, constraints from Planck / WMAP

Modelling Nucleosynthesis

- Choosing a network of interactions
- Parameters that determine rates
- Unknown/unknowable cross sections, log normal distributions
- Modelling interactions: Coulomb and nucleon-nucleon potentials
- Numerical solutions of the Schrödinger equation

Physical Process: Stellar Nucleosynthesis

- Initial conditions: Hot dense stars of Hydrogen/Helium. Low metallicity.
- Differences with BBN: Longer time, higher densities
- Instability of Beryllium
- The triple α process
- Other pathways to CNO
- Heavier elements: Beyond Iron

Fine-Tuning Issues

- The idealized situation: Dependence of observation on fundamental parameters $\frac{dLog[O]}{dLog[\alpha_i]}$
- Requires a lot of uknown theoretical input. Complete solutions to QCD/QED in unsolved contexts
- The practical parameters C_i for interactions
- Dependence of interactions upon practical parameters
- Overabundance of practical parameters: Should be constrained by theory but currently aren't. Too many dimensions to cover practically, so assumptions of interrelatedness.
- Recovering dependence of observation on fundamental parameters through novel means: $\frac{\Delta B_D}{B_D} \sim \frac{\Delta \Lambda}{\Lambda}, \frac{\Delta v}{v}$ etc
- Effects of chaging parameters: Opening channels, new routes. Can't hold network fixed.
- Joint issues: Opening new pathways in BBN changes stellar pathways.
- "Non-perturbative solutions": Pathways to elements without any weak forces (Universe Without Weak Interactions - Harnik, Kribs and Perez)