Big Bang Nucleosynthesis - Characterizing Abundances of Light Abundances

Niranjan Bhatia\(^1\) and Evan Grohs\(^2\)

\(^1\)Department of Physics - University of California, Berkeley
\(^2\)Department of Physics – North Carolina State University

\section*{MOTIVATION}

- Evaluator of Big Bang Cosmological Model
  - 75\% H, 25\% \(^4\)He, 10\(^{-5}\) \(^3\)H, 10\(^{-10}\) \(^7\)Li, etc.
  - Model uncertainties; parameter uncertainties; physical processes
- Good place to look at because of how early it is and how high the temperatures were. Standard Model BBN theory is well defined.
- Allows us to test theories beyond the Standard Model
- Some problems in standard BBN already
  - Cosmological Lithium Problem: Observed amount is 3 times lower than calculated amount.
  - Extra neutrino species? Dark matter density?

\section*{WAGONER KAWANO BBN Code}

- BBN Code made in 1992 (3) based on an older code from late 60s. (1,2)
- Fortran 77 code used to calculate primordial abundances of light elements such as D, He, Li.
- Reaction Rate coefficients approximated as polynomial in temperature expansions using old nuclear reaction data.
- Doesn’t give uncertainties in light abundance calculations in current form of code.
- Allowed to vary parameters at run time to study different physics as well as computational inputs.

\section*{Methods and Data}

- Calculate uncertainties.
  - Use more recent cross section data. Ex. From Luna Paper (4)
  - Use MINUIT, minimization software from ROOT, to incorporate cross section data from multiple papers. (5)
  - Compute a covariance matrix and equation for S factor.

\begin{equation}
\Delta R_i(T) = \int_0^\infty dE' K(E', T) \int_0^\infty dE K(E, T) \sum_{i,j} \left( \frac{\partial S_{ij}(E', a)}{\partial a_i} \right) \left( \frac{\partial S_{ij}(E, a)}{\partial a_j} \right) \text{cov}(a_i, a_j).
\end{equation}

- Use Gauss Laguerre quadrature to estimate squared rate error double integral.

\begin{equation}
\sigma_{ij}^2 = \frac{1}{4} \sum_k [(X_i(G_k') - X_i(G_k)][(X_j(G_k') - X_j(G_k))]
\end{equation}

\begin{equation}
\sigma_i = \sqrt{\sigma_{ii}}
\end{equation}

\section*{Results}

- Currently experimenting with d(p, \(\gamma\))\(^3\)He reaction as it’s the best measured reaction.
- Have calculated abundances uncertainties for abundances of deuterium with reaction.
- Doesn’t match well with predicted values. Error rate abundances look legitimate at lower temperature but ultimately become the same magnitude or even higher than the abundance values at higher temperatures.
- Possibility of error in double integral calculation.
  - Unit conversion error
  - Lack of double precision.

- Used Minuit to calculate S-factors and their respective covariance matrices.
- Wrote own program to calculate average cross sections using the integrated s factors along with their errors.
- Currently debugging the error in cross section calculations to get more accurate abundance values.
- Will incorporate data from more papers to get improved error margins.

\section*{Conclusion}

\section*{References}

6. O. Pisanti et al. JCAP04(2021)020