# Nuclear Physics Measurements to Understand Big Bang Nucleosynthesis

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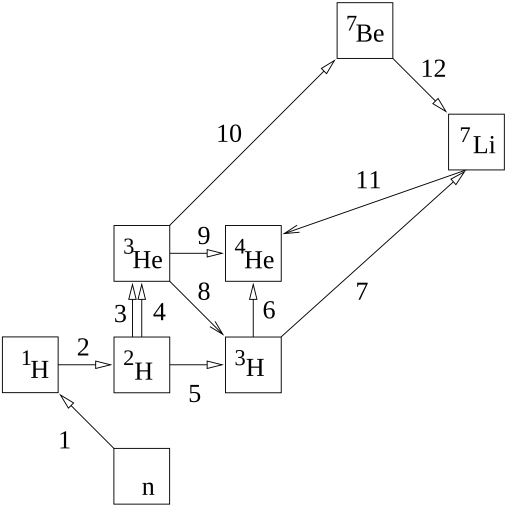
# BBN: simplified reaction network




1. $p \longleftrightarrow n$
2. $p(n,\gamma)d$
3. $d(p,\gamma)^3\mathrm{He}$
4. $d(d,n)^3\mathrm{He}$
5. $d(d,p)t$
6. $t(d,n)^4\mathrm{He}$
7. $t(\alpha,\gamma)^7\mathrm{Li}$
8. $^3\mathrm{He}(n,p)t$
9. $^3\mathrm{He}(d,p)^4\mathrm{He}$
10. $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$
11. $^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$
12. $^7\mathrm{Be}(n,p)^7\mathrm{Li}$

figure: Ken Nollett

# BBN: evolution of light elements

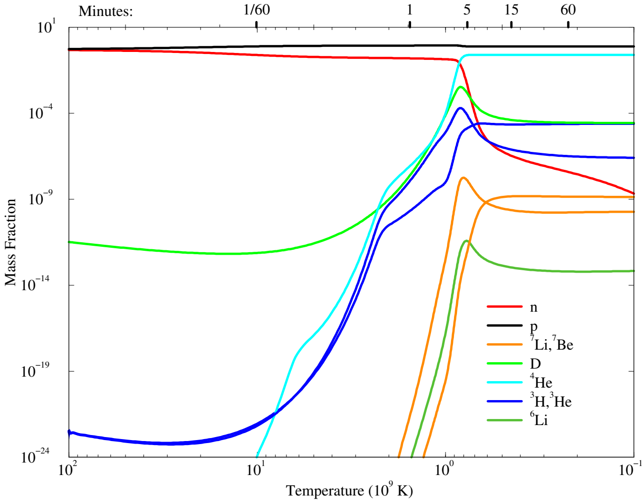



figure: Ken Nollett

# BBN: light elements H, D, $^4$He, Li

- The main game is comparing BBN predictions to observations.
- The observations are:

  $D/H = 2.55(3) \times 10^{-5}$ Yeh *et al.* JCAP 03 (2021) 046.

  $Y_p = 0.2453(34)$ Aver *et al.* JCAP 07 (2015) 011, arXiv:2010.04180.

  $Li/H = 1.6(3) \times 10^{-10}$ Cyburt *et al.* RMP 88 015004 (2015).

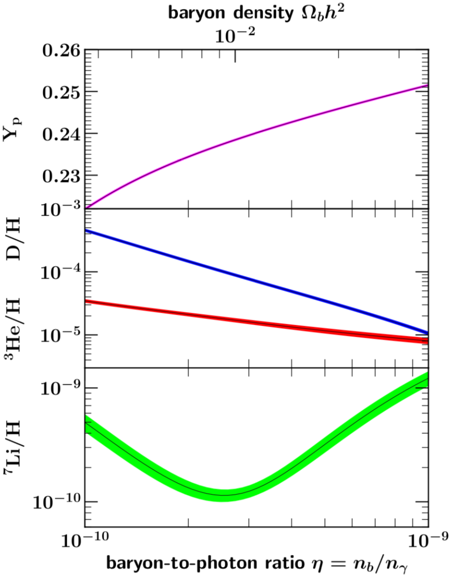
- Why do we care?

  Determine the baryon-photon ratio $\eta$, compare to value deduce from CMB.

  Search for new physics (neutrinos, new particles, ...).

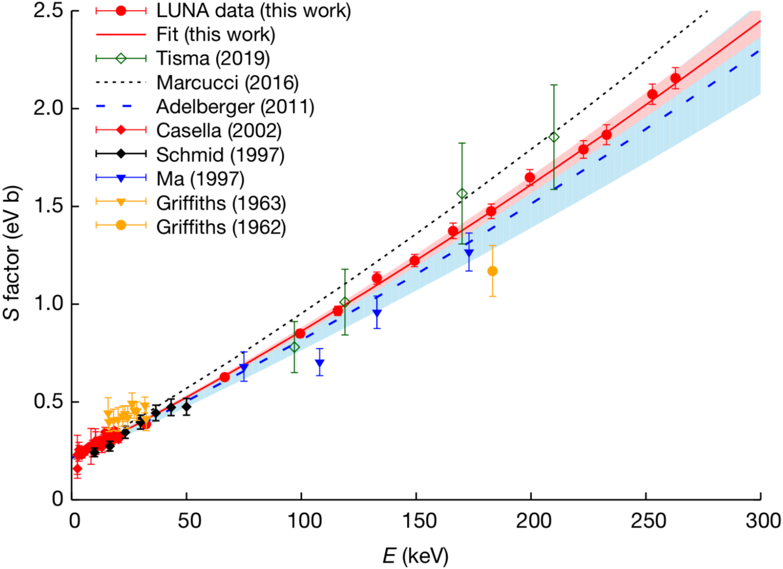
  Set initial conditions for chemical evolution of the universe.

# How the game is played




Yeh *et al.* JCAP 03 (2021) 046.

# Important new result: $D(p,\gamma)^3He$




Mossa *et al.* (LUNA), Nature 587, 210 (2020).

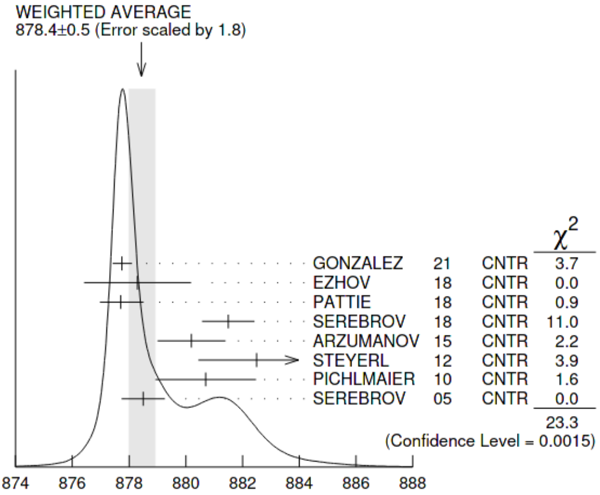
# Why is this a big deal?

- The absolute uncertainty is 3%, a factor of 3 improvement over previous measurements.
- The BBN deuterium abundance calculations agree with predictions based on the CMB at the 3% level.
- Further progress on the nuclear physics side is called for – recall that the observation uncertainty is 1%.
- The nuclear physics uncertainty is now dominated by the $\mathrm{D}(d,n)$ and $\mathrm{D}(d,p)$ rates.

# Turning now to $^4$He

- The observational uncertainty for $^4$He is also about 1%. The systematic uncertainties are probably more challenging in this case.
- The neutron half life is the only nuclear physics input that significantly effects the BBN prediction for $^4$He.
- There is, however, great sensitivity to new physics in this case.
- A nice new measurement of the neutron lifetime, using ultracold neutrons at LANL, has recently been published: F. M. Gonzalez *et al.* (UCN $\tau$ Collaboration), Phys. Rev. Lett. 127, 162501 (2021).

# Current status of the neutron lifetime



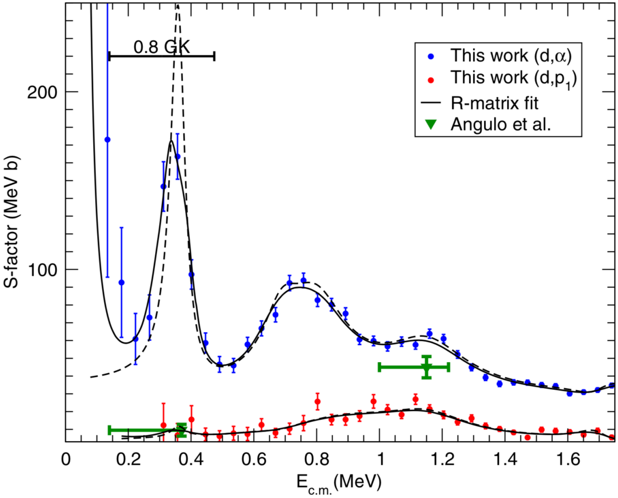

The uncertainty coming in the BBN $^4$He calculation coming from this source is negligible (assuming this uncertainty is reasonable).

Figure: Particle Data Group.

# Now for lithium

- The observed lithium abundance (presumed to be $^7$Li) is over predicted by a factor of 3 to 4 – far outside the estimated uncertainties.
- Many possible explanations have been considered: depletion subsequent to BBN, new particle physics, observational issues, nuclear physics issues,...
- Many workers is the field believe that depletion is the explanation, although a detailed explanation is lacking.
- On the nuclear physics side, the reaction $^7\mathrm{Be} + d \to 2\alpha + n$ has received considerable attention.
- BBN predicts $^6\mathrm{Li} \ll {}^7\mathrm{Li}$, but the observational separation of the isotopes remains a challenge.

# New measurement of $^7\mathrm{Be} + d \to 2\alpha + n$




Rijal *et al.* PRL 122, 182701 (2019).

# More on $^7\mathrm{Be} + d \to 2\alpha + n$

- The cross section would need to be a factor of $\times \sim 10$ larger than presently estimated.
- The reaction mechanism very complicated, making it very difficult for nuclear theory to make predictions.
- Improved measurements in the Gamow window for BBN are called for. Intense $^7$Be beams ($\sim 10^9$/sec) are now available at TRIUMF, making these measurements possible.

# Beyond lithium

- BBN produces very little material heavier than lithium. It is not clear that observations of such isotopes can ever be linked to BBN.
- However, they remain interesting for several reasons, including constraining non-standard physics and determining the initial conditions for the further chemical evolution of the universe.
- Additional nucleosynthesis mechanisms to consider for Be, B, and CNO include cosmic-ray spallation, neutrino spallation and other reactions immediately following core-collapse supernovae (CCSN), and stellar processes.
- Understanding the origin of Be and B may also provide insight into possible issues with determination of the primordial abundances of H, D, He, and Li.

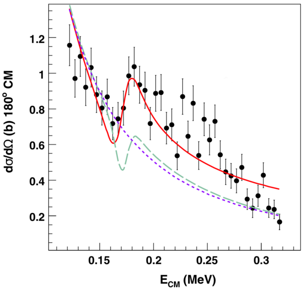
# The possibility of CNO from BBN

- Standard BBN predicts that CNO/H is about $10^{-14}$ [Coc, Uzan, and Vangioni, JCAP 10 (2014) 050].
  But it is uncertain by about two orders of magnitude!
- CNO/H $\gtrsim 10^{-13}$ leads to significant effects on the evolution of the first generation of stars.
- There are a large number of reactions, many involving radioactive species ($t$, $^{7}$Be, $^{10}$Be,...), and many are unmeasured.
- From a nuclear physics perspective, many of the reactions that are important for BBN are also important in the other scenarios (CCSN, stellar nucleosynthesis).

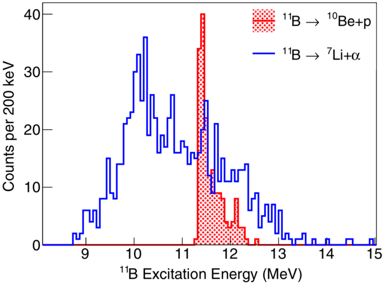
# Reactions on $^{10}$Be

- My group at Ohio University is focused on reactions involving the isotope $^{10}$Be ($t_{1/2} = 1.4$ MY): $^{10}\mathrm{Be}(\alpha, n)^{13}\mathrm{C}$, $^{10}\mathrm{Be}(p, n)^{11}\mathrm{B}$, and $^{10}\mathrm{Be}(p, \alpha)^{7}\mathrm{Li}$.
- We are fortunate to possess highly-enriched $^{10}$Be targets.
- Measurements of the above reactions, and the proton-transfer reaction $^{10}\mathrm{Be}(d, n)^{11}\mathrm{B}^*$, are underway at Ohio University.

# Recent experiments indicate a new $\ell_p = 0$ low-energy resonance in $^{10}$Be + $p$!

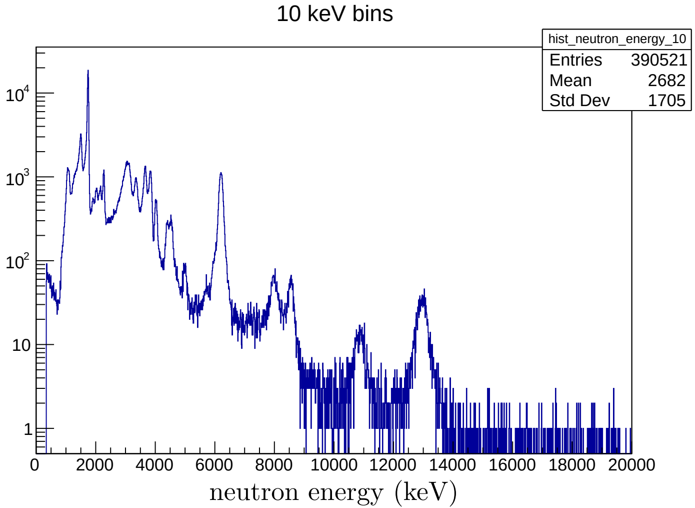



180° differential cross section, $^{10}\text{Be}(d,n)^{11}\text{B}^*$, neutron undetected, E. Lopez-Saavedra *et al.*, PRL 129, 12502 (2022), NSCL, Ayyad *et al.*, PRL 129, 012501 (2022).




$^{10}\text{Be}(d,n)^{11}\text{B}^*$, neutron undetected, FSU, E. Lopez-Saavedra *et al.*, PRL 129, 12502 (2022).

# Ohio University: $^{10}$Be$(d,n)$, neutron time of flight
# $E_d = 4.0$ MeV, $\theta_n = 0°$




This measurement will provide a conclusive determination of $\ell_p = 0$ states with significant proton width.

# Conclusions

- BBN remains a very successful model connecting cosmology to the light elements.
- It has become a high-precision endeavor.
- The lithium problem is still with us.
- There are many interesting nuclear physics question regarding the reactions that affect the Be, Be, and CNO elements.
- Uncertainty quantification and Bayesian methods have become essential tools in this research area.

Thank you for your attention.

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