PRIMORDIAL NUCLEOSYNTHESIS

- Theoretical predictions
  for standard Big Bang
- Observational tests
- Non-standard big bangs

EARLY HISTORY

- Gamow and friends : neutron ball
- Hayashi : n $\rightleftharpoons$ p equilibrium
- B^2FH : ignored for lack of a
  cosmological model

  : stellar n/s ≈ adequate
  "except possibly in case of
  deuterium and helium"

: may be necessary "to assume some helium in the original matter of the Galaxy"

- Cameron (1957) : "it may be that one should expect primordial abundances of deuterium, He^3 and He^4 to be formed in the early stages of an exploding universe".

- Hoyle and Tayler (1964)

  : stars fail by ~10 times to synthesize present abundance of Galactic He

  : "the Universe has had at least one high-temperature high-density phase or massive objects must play (or have played) a larger part in astrophysical evolution than has hitherto been supposed"

- Penzias & Wilson (1965)
  : Cosmic Microwave Background
  → Hot Big Bang
- Peebles (1966): nucleosynthesis in BB of He ÷ "primordial helium abundance should be in the range 26-28 per cent by mass"
- Wagoner, Fowler & Hoyle (1967)
  : Big bang | supermassive objects
  - nucleosynthesis
- REST IS "DETAILS" but "the devil is in the details"

STANDARD MODEL OF ELEMENTARY PARTICLES
+ STANDARD MODEL OF COSMOLOGY

STANDARD MODEL OF ELEMENTARY PARTICLES

FERMIONS ($s=1/2$)			BOSON ($s=1$)		
1st	2nd	3nd	Boson force carriers		
generations			weak force	em (QED)	strong color force (QCD)
u	c	t			
d	s	b			g^0
e	μ	τ	Z^0	γ	
ν_e	ν_μ	ν_τ	$W^\pm$		

and anti-particles

proton $\equiv$ uud

neutron $\equiv$ udd

COSMOLOGICAL ASSUMPTIONS

- The Cosmological Principle
  - universe is homogeneous & isotropic on a large scale
    : CBR is best evidence (1 in 10^5)
- Einstein's theory of general relativity
- Principle of Equivalence: laws of physics found locally apply at all times throughout the Universe
- Baryon asymmetry is very small

$$\frac{N_B - N_{\bar{B}}}{S} \ll 1 \qquad (\sim 10^{-8} \text{ to } 10^{-11} \text{; Pagel})$$

- Lepton asymmetry is very small:

$$L_e, L_\mu, L_\tau \ll B$$

$$L_e \equiv (N_{e^-} - N_{e^+} + N_{\nu_e} - N_{\bar{\nu}_e})$$

$$L_{\mu,\tau} = (N_{\nu_{\mu,\tau}} - N_{\bar{\nu}_{\mu,\tau}})$$

General relativity gives $R(t)$, the scale factor, by a field equation

$$8\pi G \rho R^2 = 3kc^2 + 3\dot{R}^2 - \Lambda R^2$$

ρc^2 = total energy density

Λ = cosmological constant $\cong 0$ at early times

Then,

$$H = \frac{\dot{R}}{R} \quad \text{or} \quad H^2 = \left(\frac{\dot{R}}{R}\right)^2$$

$$= \frac{8\pi G\rho}{3} - \frac{kc^2}{R^2}$$

k = curvature $\cong 0$ (flat universe)

Then $$\frac{\dot{R}}{R} = \frac{1}{3}(24\pi G\rho)^{1/2}$$

For relativistic particles (ie. photons/

$\rho \propto R^4$ or $R \propto \rho^{-1/4}$

Substitute in above eqn and integrate

$$\rho = \frac{3}{32\pi G}\,\frac{1}{t^2}$$

If just photons $\rho_\gamma = \frac{aT^4}{c^2}$

$$T = \left(\frac{3c^2}{16\pi G a}\right)^{1/4}\frac{1}{\sqrt{t}}$$

For 'all' relativistic particles

$$T = \left(\frac{3c^2}{16\pi G a g^*}\right)^{1/4}\frac{1}{\sqrt{t}}$$

(see Pagel)

$$\text{where } g^* = \left[\underbrace{1}_{\text{Photons}} + \underbrace{\frac{7}{4}}_{\substack{\text{electrons}\\ \text{positrons}}} + \frac{7}{8}\underbrace{N_\nu}_{\substack{\text{neutrinos}\\ (N_\nu = \#\text{ families})}}\left(\frac{T_\nu}{T_\gamma}\right)^4\right]$$

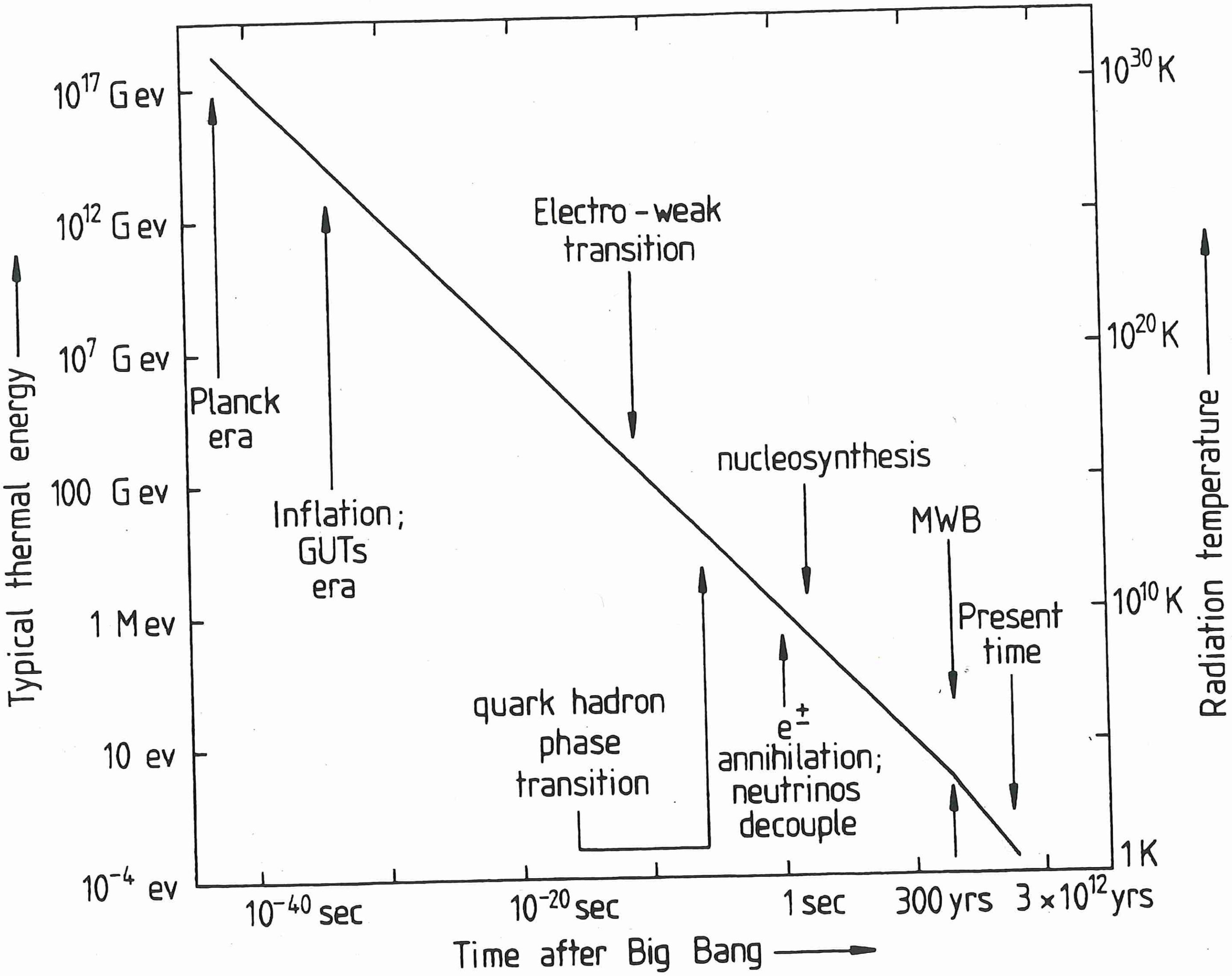


Fig. 4.1. Schematic thermal history of the Universe showing some of the major episodes envisaged in the standard model. GUTs is short for grand unification theories and MWB is short for (the last scattering of) the microwave background radiation. The Universe is dominated by radiation and relativistic particles up to a time a little before that of MWB and by matter (including non-baryonic matter) thereafter, with dark energy eventually taking over.

Table 4.1. *Brief thermal history of the Universe*

	Time	kT_γ	T_γ	g_*	
Uncertain physics	10^{-42} s	10^{19} GeV			Planck era; quantum grav.
	10^{-35} s	10^{15} GeV			GUTs, Infl., Primord. fluct.
	10^{-9} s	100 GeV		~ 100	Electroweak trans.
	10^{-4} s	150 MeV		20	Q-H trans.; meson decay
Physics fairly well known	1 s	1 MeV	10^{10} K	43/4	Weak interaction decoupl.; $e^{\pm}$ annihilation; $T_\nu < T_\gamma$
	100 s	0.1 MeV	10^{9} K	3.36	BBNS (D, ^{3}He, ^{4}He, ^{7}Li)
Uncertain details					Matter domination
	4×10^{5} yr	0.2 eV	3000 K		(Re)comb.; MWB last scat.
	10^{8} yr	4×10^{-3} eV	50 K		Re-ionization; Structure formation
	10^{10} yr	2×10^{-4} eV	3 K		Present

$T \sim 10^{12}$ K

$e^{\pm}$, ν and $\bar{\nu}$ from e, μ, τ

n, p

with (e, ν) equilibrium via

$e^- + e^+ \rightleftharpoons \nu_i + \bar{\nu}_i \qquad i = e, \mu, \tau$

NEUTRAL WEAK CURRENT INTERACTIONS

plus

$e^{\pm} + \nu_i \rightleftharpoons e^{\pm} + \nu_i$

$e^{\pm} + \bar{\nu}_i \rightleftharpoons e^{\pm} + \bar{\nu}_i$

NEUTRAL WEAK CURRENT ELASTIC SCATTERING

→ energy distr'ns at equilibrium values

also $p + e^- \rightleftharpoons n + \nu_e$

but lack of muons & tauons mean no equiv. processes of mu & tau neutrinos

But ν's decouple from $e^\pm$ at
$T \sim 3 \times 10^{10}$ K or ~0.1s
and expand independently of the
$e^\pm$, n, p.

AFTER THIS event of neutrino decoupling
N(n)/N(p) is set at ≅ equilibrium value and subsequently decays

- $p + e^- \rightarrow n + \nu_e$ [ENDOTHERMIC]
$n + e^+ \rightarrow p + \bar{\nu}_e$ [EXOTHERMIC]
$n \longrightarrow p + e^- + \bar{\nu}_e$

$$\frac{n_n}{n_p} = \exp\left[-\frac{(m_n - m_p)c^2}{kT}\right]$$

$$= \exp\left[-\frac{1.29\,[\mathrm{MeV}]}{kT}\right]$$

$T \sim 3\times10^{10}\,\mathrm{K} \simeq 3\,\mathrm{MeV}$

$\left(\frac{n_n}{n_p}\right)_0 \sim 0.7$

Full freeze out at $T \sim 0.1$ MeV

$\left(\frac{n_n}{n_p}\right)_0 \sim 0.15$

THIS AND TIME TO ONSET OF N'SYNTHESIS SETS N'SYNTHESIS PRODUCTS

ν DECOUPLING IS OVERLAPPED BY

(e^-, e^+) annihilation and lack of new production of $e^\pm$ pairs

[T_γ increased by factor of $\left(\frac{11}{4}\right)^{1/3}$] (see Pagel

$$T = \frac{1.34 \times 10^{10}}{t^{1/2}} \qquad [°K] \qquad t \text{ in } [s]$$

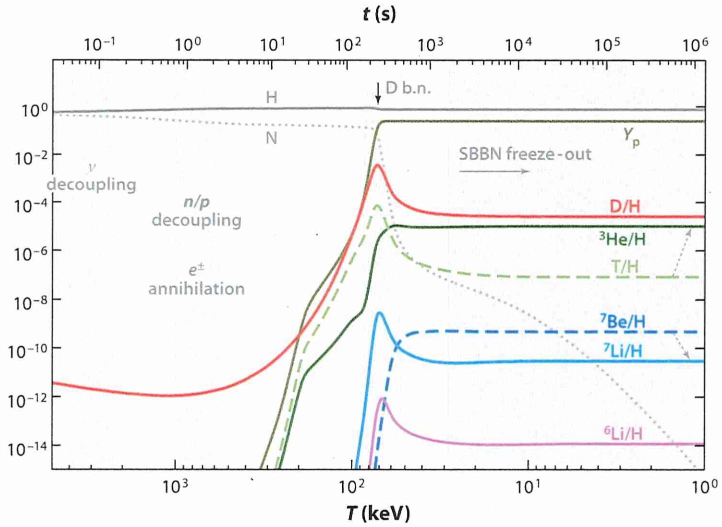
EPISODE OF NUCLEOSYNTHESIS (10 s to 1000 s)

Two bottlenecks :

i) low BE of the deuteron sets (late) onset of n'synthesis

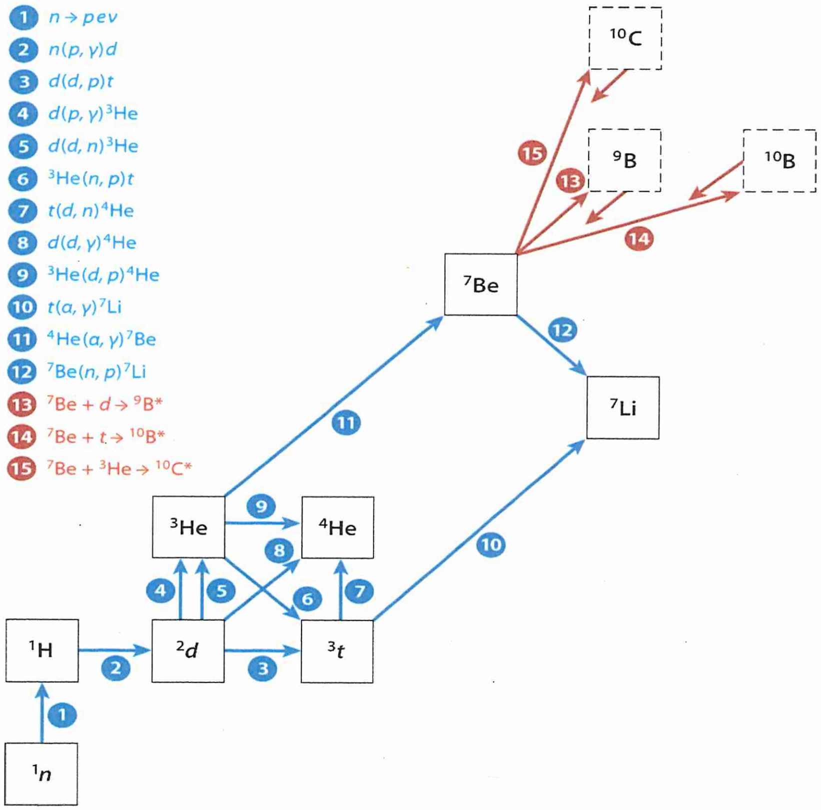
ii) $A = 5$ and 8 are all highly unstable
$\therefore$ $p + {}^4He$, ${}^4He + {}^4He$ do not advance the n'synthesis

- d/p kept in equilibrium by $p + n \rightleftharpoons d + \gamma$
- d and t kept in equilibrium by $d(d,p)t$
- at a certain t abundance : $d(t,n){}^4He$
- detours around $A = 5$ and 8 are slow because of the Coulomb barrier
  $t({}^4He,\gamma){}^7Li$ ${}^3He({}^4He,\gamma){}^7Be$
- Small reaction network with well determined reaction rates : expt'l rates at Gamow peak.



Pospelov M, Pradler J. 2010.
Annu. Rev. Nucl. Part. Sci. 60:539–68

Annual Reviews



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Annual Reviews

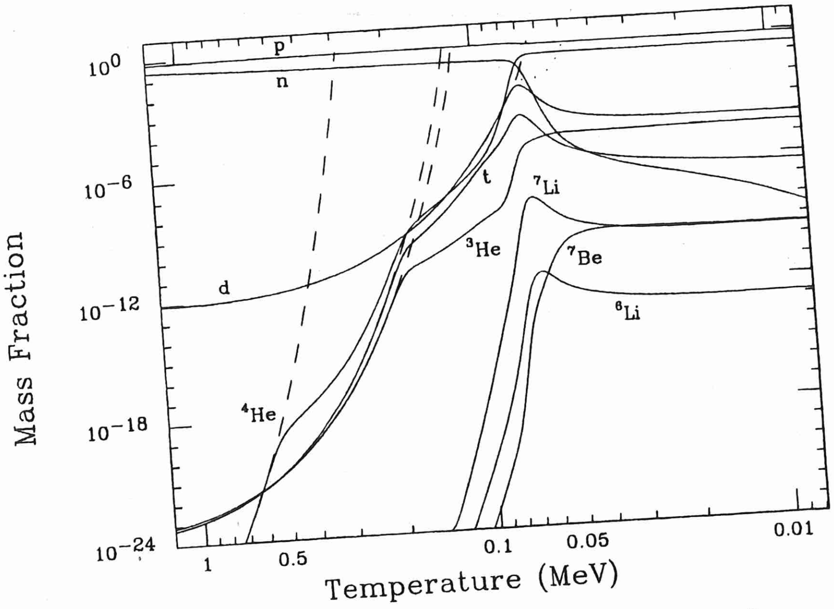


Fig. 4.2. Evolution of light-element abundances with temperature, for $\eta_{10} = 3.16$. The dashed curves give the nuclear statistical equilibrium abundances for ^{4}He, ^{3}He, ^{3}H(t) and ^{2}D(d) respectively; the dotted curve for ^{2}D allows for the diminishing number of free neutrons. After Smith, Kawano and Malaney (1993). Courtesy Michael Smith.

MASS FRACTION OF ^{4}He

- Essentially all $n \to {}^4$He from onset of n'synthesis

$$\therefore \quad n_4 \simeq \frac{n^{\overset{\text{onset}}{0}}_n}{2}$$

$$n_p = n_p^0 - 2n_4 = n_p^0 - n_n^0$$

$$\frac{He}{H} = \frac{n^0_n/2}{n_p^0 - n_n^0} = \frac{\frac{1}{2}\left(\frac{n}{p}\right)^0}{1 - \left(\frac{n}{p}\right)^0}$$

$$Y = \frac{2\left(\frac{n}{p}\right)^0}{1 + \left(\frac{n}{p}\right)^0}$$

$(n/p)^0$ set by T at freezeout and time delay between freezeout and onset of n'synthesis: $Y \to 0.25$ or so.

^2H, ^3He ↓ as η ↑ [more baryons in an expansion dominated by photons]

^7Li (also ^7Be)

low η : $^4He + ^3H \Rightarrow ^7Li + \gamma$
$^7Li + p \Rightarrow 2\,^4He$

higher η : $^3He + ^4He \Rightarrow ^7Be + \nu_e$
$^7Be \Rightarrow ^7Li$ later

PREDICTED ABUNDANCES ARE A FUNCTION OF ONE COSMOLOGICAL PARAMETER η $\left(\equiv \frac{n_B}{n_\gamma}\right)$

- PAST : choose η from fit of inferred primordial abundances to predictions
- NOW : η chosen by CBR anisotropies (esp. WMAP, PLANCK)

PREDICTIONS depend on SMs of particle physics and cosmology.

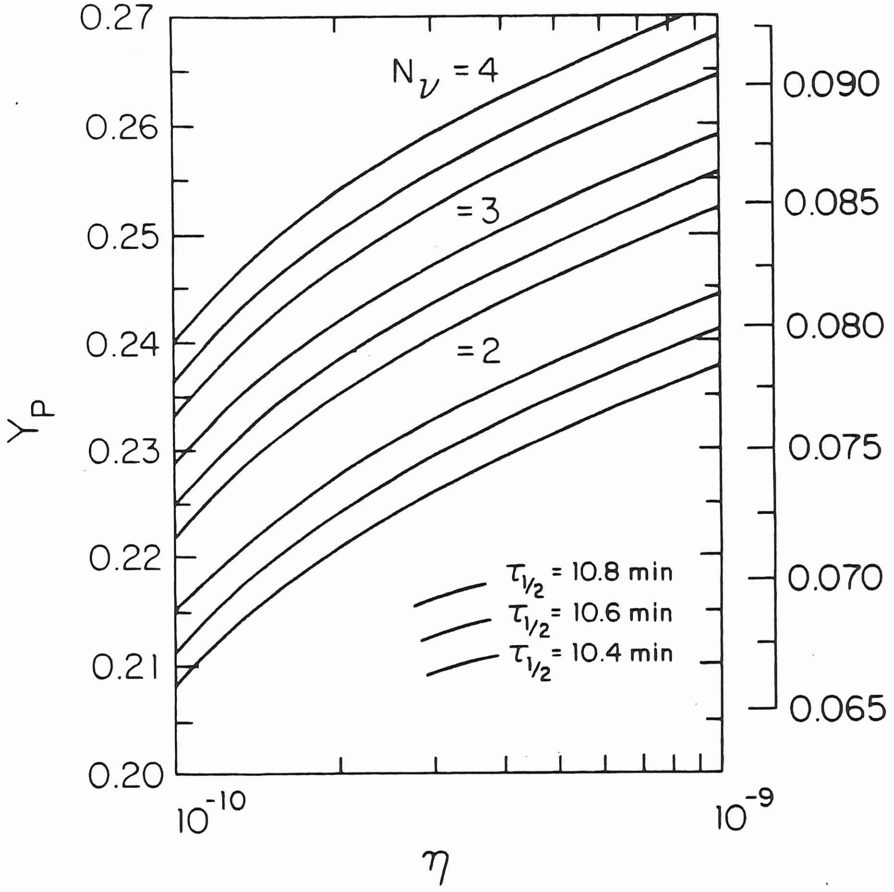


Fig. 4.6: Predicted ^{4}He abundance.

$\tau_{1/2}$	τ
648 s	935
636	918
624	900

too high.

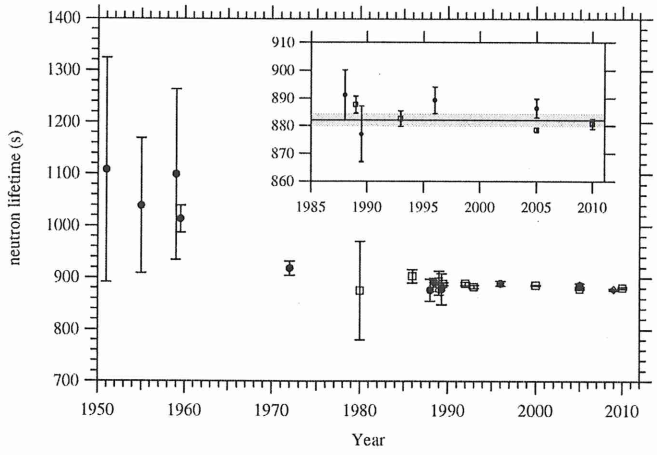


FIG. 11. A summary of neutron lifetime measurements. Solid circles are beam experiments, open squares are bottle experiments, and diamonds are magnetic trap experiments. The inset shows the eight experiments included in our global averages. See Table I for references.

TABLE I. A summary of neutron lifetime measurements. When applicable, statistical and systematic errors have been added in quadrature. Asterisks indicate the 8 experiments included in our global averages.

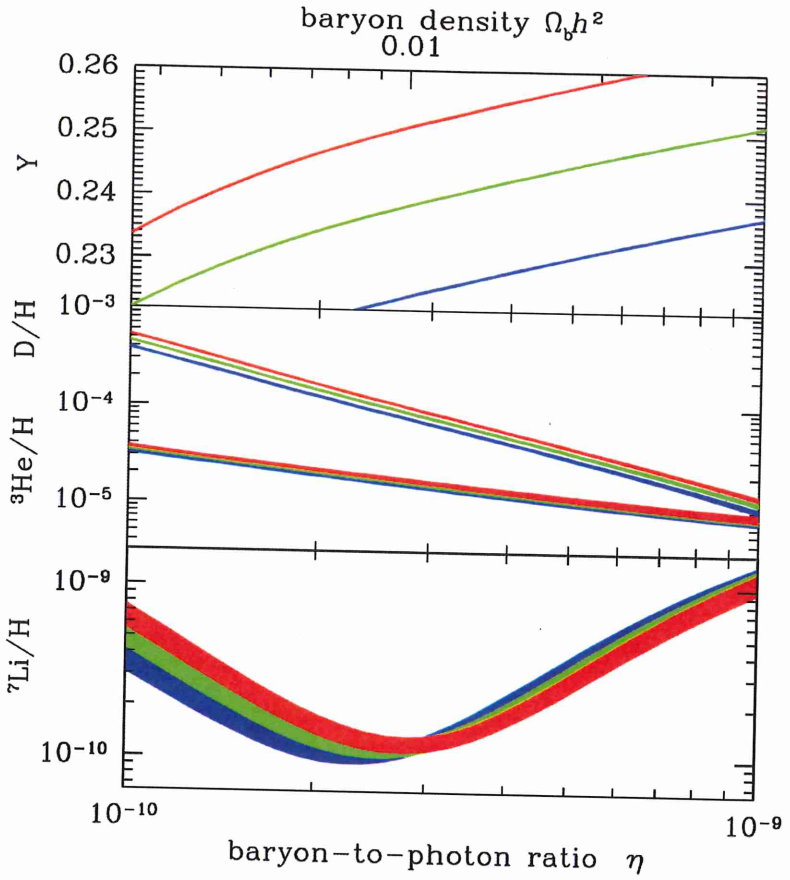
Reference	Neutron lifetime (s)	Uncertainty (s)
	Beam Experiments	
Robson, 1951	1110	220
Spivak *et al.*, 1956	1040	130
D'Angelo, 1959	1100	160
Sosnovsky *et al.*, 1959	1013	26
Christensen *et al.*, 1972	918	14
Last *et al.*, 1988	876	21
Spivak, 1988*	891	9
Kossakowski *et al.*, 1989	878	30
Byrne *et al.*, 1996*	889.2	4.8
Nico *et al.*, 2005*	886.3	3.4 ← 887.7 ± 2.1
	Bottle Experiments	
Kosvintsev *et al.*, 1980	875	95
Kosvintsev, Morozov, and Terekhov, 1986	903	13
Morozov, 1989	893	20
Mampe *et al.*, 1989*	887.6	3.0
Alfimenkov *et al.*, 1992	888.4	3.3
Mampe *et al.*, 1993*	882.6	2.7
Arzumanov *et al.*, 2000	885.4	0.98
Serebrov *et al.*, 2005*	878.5	0.76
Pichlmaier *et al.*, 2010*	880.7	1.8
	Magnetic Trap Experiments	
Paul *et al.*, 1989*	877	10
Ezhov *et al.*, 2009	878.2	1.9

method, span a range of 881–937 s and are in poor agreement relative to their quoted uncertainties. They comprise the first "neutron lifetime problem." This troubling disagreement motivated concerted programs at neutron sources around the world to produce more measurements using novel techniques such as the bottle method and magnetic traps. The fruit of this substantial effort can be seen in Fig. 11 as the cluster of 10 precision results in the period of 1986–1993. These are all in good agreement and they confirmed the lowest of the three disagreeing numbers (Bondarenko *et al.*, 1978). Thus, the problem seemed to be solved. Subsequent experiments through 2004 gave additional confirmation. The 2004 Review of Particle Properties (Eidelman *et al.*, 2004) used a weighted mean of the seven most recent measurements to date with quoted errors less than 10 s to obtain a recommended world average for the neutron lifetime of $\tau_n = 885.7 \pm 0.8$ s, with a chi squared of 3.5 for 6 degrees of freedom, a very comfortable agreement.

In 2004, Serebrov and collaborators from PNPI announced the result of the Gravitrap II experiment: $\tau_n = 878.5 \pm 0.76$ s, in serious conflict with the existing world average. Not unexpectedly, this result was treated with some skepticism at first, but since then it has been widely discussed and is now taken seriously by scientists in this field. The PNPI group is very experienced and the experiment was done carefully. Because the new cryogenic oil coating gave a much smaller probability for inelastic scattering at the wall, the measured neutron storage times were much longer, and the extrapolation time to the neutron lifetime much shorter than previous bottle experiments. It is often claimed, as a general argument, that experiments with smaller extrapolations from their measurements to the physics result tend to be more reliable. As a guiding principle that is no doubt true, but of course it does not prove the validity of a particular experiment. We are now faced with a second neutron lifetime problem. The new result from the magnetic bottle experiment (Ezhov, 2009) adds support to the lower number. The Particle Data Group chose not to include these new results in their most recent evaluated average, nor to expand the uncertainty in the usual prescription. Instead, they maintained their 2004 recommended value, noting (Nakamura, 2010) the following:

> The most recent result, that of Serebrov *et al.* (2005, 2008), is so far from other results that it makes no sense to include it in the average. It is up to workers in this field to resolve this issue. Until this major disagreement is understood, our present average of 885.7 ± 0.8 s must be suspect.

In a recent and significant development, Arzumanov *et al.* stated that they reanalyzed the experiment and found two important new corrections: (1) a previous correction for the geometry dependence of the thermal neutron detector efficiencies had the wrong sign, and (2) an ultracold neutron heating effect that had not been previously accounted for. The combination of these is expected to lower their neutron lifetime result significantly (Bondarenko, 2011), bringing it much closer to the Gravitrap II number. We note, however, that this will not completely solve the problem. If we take the set of experiments used for the Particle Data Group 2004 average and omit the Arzumanov *et al.* (2000) number, the average becomes 886.4 ± 1.4 s, still 5 standard deviations above the Gravitrap II result. The consensus in the field is that



N_ν
4
3
2

$N_\nu \leq 4$ from Y_{obs} before
$N_\nu = 3$ from high-energy physics concepts

FIG. 7. The sensitivity of the light element predictions to the number of neutrino species, similar to Figure 1. Here, abundances shown by blue, green, and red bands correspond to calculated abundances assuming $N_\nu = 2, 3$ and 4 respectively.

purely from matching the BBN calculations with the observed abundances of helium and deuterium. In this case, the fact that the peak of the likelihood function is at $N_\nu = 2.85$ can be traced directly to the fact that the central helium abundance is $Y_p = 0.2449$. Given the sensitivity of Y_p to N_ν found in Eq. 13, the drop in N_ν from the Standard Model value of 3.0, compensates for a helium abundance below the Standard Model prediction closer to 0.247. Nevertheless, the uncertainty again places the Standard Model within 1 σ of the distribution peak. The remaining cases displayed (in green) correspond to combining the CMB data with BBN. There are 4 green curves in the left panel and these have been isolated in the right panel for better clarity. As one can see, once one combines the BBN relation between helium and the baryon density, the actual abundance determinations have only a