Gamow took a bold new tack—non-equilibrium physics in the expanding universe. If the universe began in a hot, dense state comprising pure neutrons, the periodic table could be built up by successive neutron captures. Because neutron capture cross sections roughly followed the observed abundances, the idea had the right smell. Gamow’s young collaborators, Alpher and Robert Herman, carried out the calculations and broke new ground in cosmology. As it turns out, the basic idea of nucleosynthesis by neutron capture was wrong, and most of the calculations were irrelevant. The lack of stable nuclei of mass 5 and mass 8 and the rapid incorporation of free neutrons into helium-4 prevent the scheme from working. Interestingly enough, αβγ did anticipate the so-called r-process, today’s paradigm for the production of the heaviest nuclei by rapid neutron capture in stellar explosions. Sometimes a wrong paper can be very influential and important (Physical Review Letters referees take note!). That certainly was the case with αβγ.

Although only the lightest nuclei were made in the Big Bang and not by neutron capture, Big Bang nucleosynthesis (BBN) is a cornerstone of modern cosmology. It led to the prediction of a relic thermal radiation—the cosmic microwave background or CMB—which has turned out to be a cosmic Rosetta stone. Paradoxically, Gamow’s Big Bang model spurred Fred Hoyle to think more creatively about the stellar nucleosynthesis to keep his steady-state model competitive and in 1957, with Geoffrey Burbidge, Margaret Burbidge, and William Fowler, he worked out the correct theory of how the bulk of the elements were made in stars.

So what was wrong with αβγ? Although nonequilibrium nuclear processes are an essential ingredient, equilibrium processes are just as important. At very early times, when densities and temperatures in the universe were high, nuclear reaction rates were rapid—so rapid that thermal equilib-
The various predictions made by Alpher and Herman were based on the neutron capture model. To produce the observed pattern of abundances, they required that the density of nucleons times the age of the universe \((= f_a)\) be about \(10^{18} \text{s/cm}^3\) when the temperature of the universe \((= T_u)\) was around \(10^{10} \text{K}\). That requirement leads to a different formula, \(T = \frac{(\rho_a m_n a)}{(\rho_m m_p) a^{1/3}}\). For the Goldilocks range, the prediction is \(T = 1\) to 10 K, consistent with the value of 2.725 K ± 0.001 K measured by NASA's Cosmic Background Explorer (COBE) satellite.

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The spectrum of anisotropy depends not only on two or three inflationary parameters but also on cosmological ones—curvature of space, total matter density, baryon density, Hubble constant, and age of the universe. In particular, the angular power spectrum takes the form of a series of harmonic or acoustic peaks whose strengths and positions (as a function of angle) encode information about cosmological parameters: The position of the first peak indicates the curvature; the strength of the first peak, the matter density; the ratio of the strengths of the odd to even peaks, the baryon density; and so on (see my article with Charles Bennett and Martin White, PHYSICS TODAY, November 1997, page 32).

The COBE discovery triggered a race to measure the wiggles in the CMB angular power spectrum. And a series of ground-based and balloon-borne CMB experiments, mostly in Antarctica, and NASA's Wilkinson Microwave Anisotropy Probe have now determined the CMB power spectrum from about 0.1 to 90 degrees. That spectrum, together with maps of the large-scale structure in the universe today, have determined a host of cosmological parameters to percent-level precision. The Hubble constant is now known to be 70 ± 1.3 km/s/Mpc; the age of the universe is fixed at 13.73 ± 0.12 Gyr, its curvature is within 0.6% of the “flat” critical density model, and the values of the various components of mass and energy have been determined with error bars of less than 2% (see below). Finally, measurements of nearby and distant supernovae have directly pinned down the expansion rate today and long ago, revealing that the expansion rate is speeding up and not slowing down.

Today's wealth of cosmological data also permits croschecks and has paved the way for precision cosmology. The poster child is the baryon density. From measurements of the primordial deuterium abundance, the baryon density is fixed at \(4.0 ± 0.2 \times 10^{-5} \text{g/cm}^3\), while CMB anisotropy measurements give \(4.2 ± 0.1 \times 10^{-31} \text{g/cm}^3\)—an agreement and precision of about 5% (see my Reference Frame in PHYSICS TODAY, December 2001, page 10).

For all its success and precision, cosmology is not yet solved (thank goodness!). Particle dark matter accounts for 23.3% ± 1.3% of the universe, but which particle? The bulk of the universe (about 72% ± 1.5%) is made of a mysterious dark energy whose gravity is repulsive and is causing the expansion of the universe to speed up. The crazy combination of atoms, particle dark matter, and dark energy that is our universe is without explanation. What happened before the Big Bang and the destiny of the universe still elude us. And last but not least, the full extent of the universe is unknown—is it WYSIWYG or a multiverse of disconnected pieces? All of that is why cosmology is so exciting—big questions that seem to be within reach of our powerful instruments and ideas.

The road to precision cosmology started on April Fool's Day 60 years ago with a game-changing idea—that just after the Big Bang the universe was a nuclear reactor. Though Alpher, Bethe, and Gamow didn't get the physics right, they were right about the importance of nuclear physics (and physics in general) in the early universe and the existence of the CMB (though not its temperature), and they broke new ground in cosmology by studying the early radiation-dominated phase that is the focus of much of theoretical cosmology today. Although that groundbreaking paper received little attention when the CMB was discovered in 1965, with hindsight today we can trace the beginning of today's revolution in cosmology to it.