The Early Universe

With the discovery of the cosmic background radiation, the pendulum of cosmological opinion swung abruptly from the Steady State model to the Big Bang model. The Big Bang theory had predicted the existence of the background radiation, and the Steady State theory not only did not predict it but could not even explain it. To contemporary scientists, it appears as if the universe must have had a beginning – a moment in the past beyond which it is impossible to trace any chain of cause and effect. Recent calculations indicate that this beginning occurred about 13.7 billion years ago.

The Formation Structure in the Early Universe

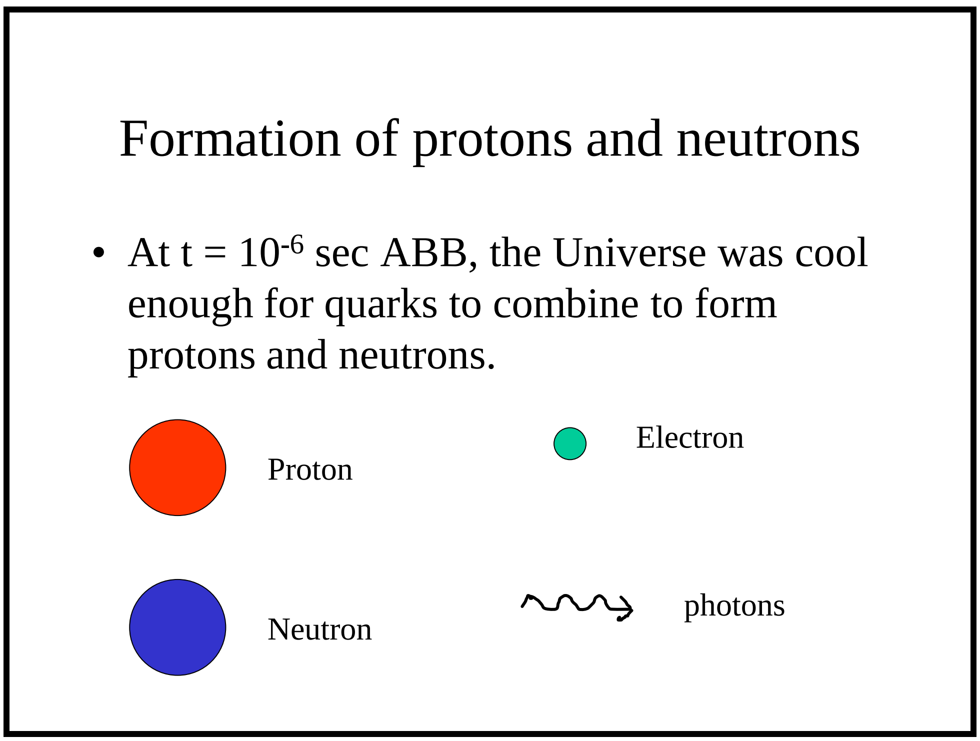
To return in your mind to the Big Bang, you would have to travel in time but not in space. The Big Bang occurred here, in our very location – just far back in time. Our planet, our solar system, and our galaxy are at the center of the universe. This claim is, however, equally true for every other location in the universe. As with the balloon model, all places in the universe are equivalent. The Big Bang did not occur at a point in space; that is, the expansion is not an expansion of matter into what was previously unoccupied space. All of the space of the universe has been occupied, more or less uniformly, by matter and radiation from the beginning of time. The expansion we refer to is an expansion of space itself. Most matter stays essentially at rest in the space it occupies. Where we are now, physically, is where the material particles that would eventually form our bodies were located (give or take a tiny fraction of the size of the visible universe) when the universe began.

At the initial instant, the universe was in a state of such high density and temperature that our current physical theories cannot be applied to it. Some highly speculative theories can be used to discuss the universe 10^{-42} seconds after its beginnings. The physics used to describe the universe10^{-35} seconds after the Big Bang, though still unconfirmed in the laboratory, is on somewhat firmer ground. This is the era of “Inflation,” a time of extremely rapid expansion. Inflation explains several otherwise unexplainable facts about the universe. Also, at the time the theory of inflation was proposed in the early 1980s, it made a prediction about the geometry of the universe that everyone believed was false, but which by the twenty-first century has been shown to be true.

One millionth of a second after the beginning of the universe, expansion had reduced the temperature and density of the universe to well within the range covered by laboratory-tested physical theories. To be on the conservative side, we will begin our discussion of the evolving universe with this time period, when the temperature of the universe was about 10^{12} K. The ordinary matter of the universe, the matter that would eventually form atoms, stars, and us, was at this time in the form of elementary particles — i.e., quarks and leptons.

(Aside: The ancient Greek philosopher Aristotle objected to the concept of elementary particles on the basis that, if they had extension in three-dimensional space, they were, at least in principle, divisible and could not be elementary. It appears as if quarks and leptons do not, in fact, have extension in three-dimensional space. After more than 2,000 years, and long after scientists accepted the idea of elementary particles, Aristotle's legitimate scientific objection has been addressed and answered.)

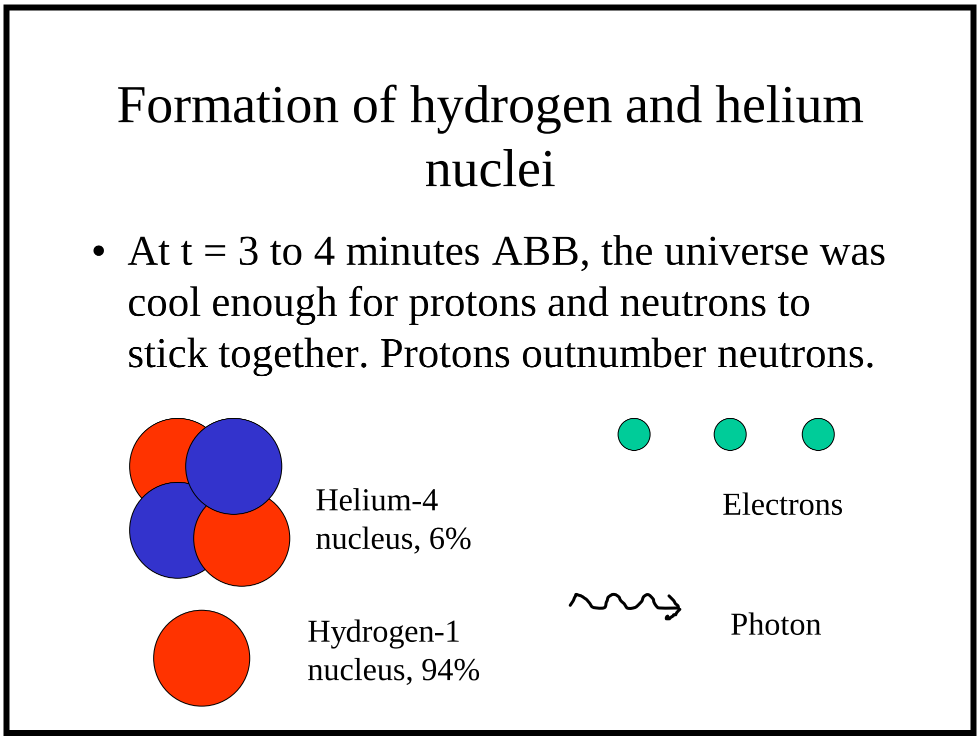
There are forces in nature that are capable of holding quarks and leptons together, but they are not infinitely strong. If the temperature is too high, the particles will collide so violently that any structure that has existed temporarily will be knocked apart by the impact. However, as the universe expands and cools, levels of structure appear depending on the strength of the force responsible for the structure. The structure that is formed by the very strongest of these forces appears first. That force is the force that quarks exert on one another. At a few millionths of a second after the beginning, when the temperature was about 10^{12} K, groups of three quarks came together to from nucleons, particles that will eventually form atomic nuclei. Depending on the type of quarks involved, the nucleon will either have a positive charge (a proton) or no charge (a neutron). This era in the history of the universe is known as the period of "quark confinement."



The second level of structure formed about three to four minutes following the beginning of the universe, when the temperature was reduced to 10^{9} K. At the time of quark confinement, there are an equal number of protons and neutrons. Because of their slightly greater mass, nuclear reactions favor the transformation of neutrons to protons over the transformation of protons to neutrons, so by this time protons outnumber neutrons about seven to one. It is now cool enough for the strong nuclear force to bind the protons and neutrons together to form atomic nuclei.

The strong nuclear force is actually a residual force resulting from the interactions between the quarks that form the protons and neutrons. This residual force is less strong than the force that binds quarks and therefore a lower temperature is required in order for it to exert an effect. Its nature also restricts it to very short ranges, unlike gravity or the electromagnetic force. The protons and neutrons must literally come in contact with one another for the force to have an effect.

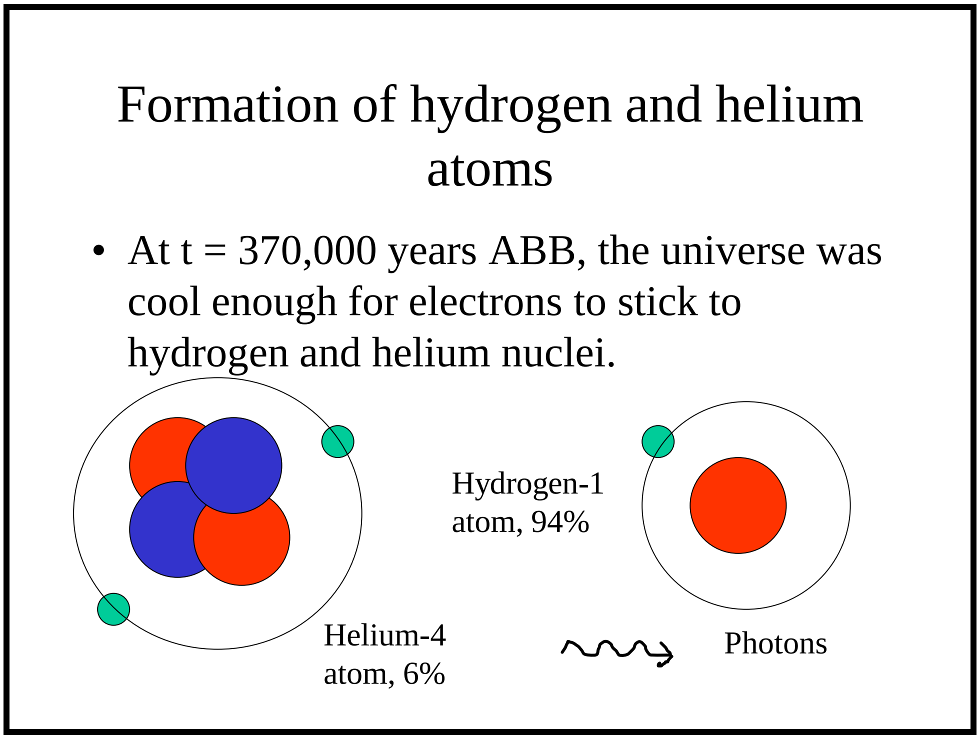
Most of the neutrons are quickly bound with protons to form a helium nucleus consisting of two neutrons and two protons. A small fraction of the neutrons are bound into nuclei consisting of one proton and one neutron (hydrogen, sometimes called deuterium in this form), or two protons and one neutron (helium). Even rarer, nuclei consisting of three protons and four neutrons (lithium) can form. When all of the neutrons are bound into nuclei, left-over protons (hydrogen nuclei) constitute about 94% of the nuclei and almost all of the rest are helium nuclei consisting of two protons and two neutrons. The other types of nuclei constitute only a tiny fraction of a percent of the nuclear matter.



The third level of structure did not form until about 370,000 years after the Big Bang. This level consists of neutral atoms formed when electrons combine with nuclei due to the electromagnetic force of attraction between the negatively charged electrons and the positively charged nuclei. The electromagnetic force is very much weaker than the force that binds protons and neutrons to form nuclei, so much lower temperatures must be reached before atoms can form, something on the order of 3,000 K.

In this discussion of the early universe, we have focused on the development of structure in the universe. The particles involved are the quarks and leptons and the structures are, first of all, protons and neutrons, then nuclei, and finally, atoms. This matter, as we will learn later, makes up only a small fraction of the matter in the universe. The other matter, sometimes called exotic matter or dark matter, does not form structures and exists in the universe only in the form of elementary particles.

Because our goal is to trace the cosmological history of human beings, and because we are composed of ordinary matter, our focus will be on the evolution of ordinary matter.



The Formation of the Cosmic Background Radiation

Prior to the formation of neutral atoms, photons interacted very strongly with matter. This interaction was caused by the fact that the individual particles of matter (hydrogen nuclei, helium nuclei, and electrons) are electrically charged. Photons (electromagnetic radiation, after all) interact very strongly with charged matter, traveling only short distances before they are destroyed and new photons are created. Constantly interacting in this way, matter and electromagnetic radiation evolved together, both at a common temperature.

However, with the formation of neutral atoms, the probability of interaction between matter and photons is reduced to nearly zero. The average distance a photon travels between interactions with matter suddenly becomes so large that virtually all of the photons present in the universe at the time have not interacted with matter since, and thus must still be in the universe. Matter and radiation began to evolve independently, each occupying the same universe more or less uniformly, but without interacting. This phenomenon is referred to as decoupling. Matter has since gone on to form stars, planets, people, and so on, while the continuing expansion of space has caused the temperature of the electromagnetic radiation to drop. At the time of decoupling, the temperature of the universe was about 3,000 K. Today it is 2.73 K.

The scenario just described is the same reasoning that both Gamow and Dicke went through in analyzing their assumption that the universe began a finite time ago in an extremely hot and dense state. That reasoning convinced them that the early universe was essentially pure hydrogen and helium. It also resulted in their independently predicting the existence of the cosmic background radiation, the discovery of which is the single most significant evidence in favor of the Big Bang theory.

The Evolving Universe

- **The Planck era.** Time = 10^{-43} sec, temp = 10^{32} Kelvin. Current theories are inadequate. We can't get any closer to the Big Bang at t=0 and say anything with confidence (or even with informed speculation).
- **Inflation.** Time = 10^{-35} sec, temp = 10^{28} Kelvin. A temporary period of exponential expansion. A speculative theory, but one that has so far been consistent with observations.
- **Quark confinement.** Time = 10^{-6} sec, temp = 10^{12} Kelvin. Quarks become bound into the protons and neutrons we see today.
- **Primordial nucleosynthesis.** Time = 10 sec, temp = 10^{9} Kelvin. The universe cools to a point where protons and neutrons can combine to form light atomic nuclei, primarily helium, deuterium, and lithium.
- **Decoupling.** Time = 3.7×10^{5} yrs, temp = 3×10^{3} Kelvin. The universe cools to a point where electrons can combine with nuclei to form atoms, and matter becomes transparent. The cosmic background radiation is released.