The creation of matter in the early Universe: A quantum perspective

Frikkie de Bruyn
168 Cleland Road, Hayfields 3201, Pietermaritzburg
debruyn1@telkomsa.net

Abstract. The creation of matter in the early universe is inextricably linked to the origin of the universe and the extreme conditions of temperatures and densities prevalent at the time. The Standard Model is used to describe the creation of matter in the early universe. Due to the extreme conditions in the early universe, specifically in the very early universe, before one hundredth of a second, we have to apply quantum theory to explain the creation of matter. The role of the uncertainty principle in the creation of matter is investigated and highlighted.

Introduction

The question we have to find an answer to is, "How could a single 'genesis event' create billions of galaxies, black holes, stars and planets?" What were the conditions under which matter was created in the early Universe, and what laws were applicable then?

When I talk about the creation of matter, I don't mean atoms or molecules, but the very building blocks of matter – quarks – and of course protons and neutrons consisting of quarks, leptons, and their antiparticles. We have to understand that only certain kinds of matter existed in the early Universe – some of the more exotic forms of matter, as we shall see, are not to be found in the present epoch of the Universe.

However, the basic building blocks of matter – quarks, protons, neutrons, leptons, and their antiparticles – were forged in the furnace of the early Universe. At about 10^{-5} seconds after the big bang, quarks formed protons and neutrons and, when the temperature of the Universe cooled enough for protons and neutrons to form atomic nuclei and electrons to join them, atoms were formed. Hydrogen, helium He4 and very small amounts of deuterium and lithium were formed through nucleosynthesis. The rest of the matter we see around us, and of which our bodies are made, were created in stars.

There was a time when the Universe was so small that quantum effects became dominant. Any study of the creation of matter in the early Universe has to account for the role of the uncertainty principle, $\Delta E\ \Delta t > \hbar$. This means that it is impossible to calculate the energy transferred from one particle to another in a certain time in the process of matter creation.

Methodology

Cosmology attempts to describe the behaviour of the entire Universe by using the fundamental laws that govern the Universe. In applying these laws to the Universe one immediately encounters a problem. What is the initial state that the laws should be applied to?

Reproduced by Sabinet Gateway under licence granted by the Publisher (dated 2013.)

In practice, cosmologists tend to work backwards by using the observed properties of the present Universe to understand what it was like at earlier times. This approach has proved very successful and has been used to determine the conditions in the early Universe relevant to the creation of matter. These conditions (i.e., threshold temperatures of the various particles and the temperature of the Universe at earlier times), are used to describe the creation of matter at various times in the history of the Universe, at least from a hundredth of a second after the big bang, with due consideration to the uncertainty principle.

Due to the extreme conditions in the very early Universe before one hundredth of a second we will have to apply quantum theory to explain the creation of matter. When we refer to the early Universe, more particularly the very early Universe, we refer to the origin of the Universe.

I have made use of Steven Weinberg's exposition of the Standard Model for the purpose of this talk. The Standard Model is the same as the 'Big Bang' theory, but supplemented with a much more specific recipe for the contents of the Universe. The Standard Model does not make provision for the most basic tenet of quantum mechanics (the uncertainty principle) to account for the creation of matter. The creation of matter took place at the quantum level and without the uncertainty principle the creation of matter simply cannot be adequately described. The description of quantum effects is my own work. I would therefore argue that the Standard Model be rejected as inadequate to account for the creation of matter, or it must be amended to make provision for the uncertainty principle.

To find out what conditions were like in the early Universe, we have to imagine winding the clock back so that the resulting model of the Universe contracts. The result of contraction is to increase the density of matter and radiation in the model Universe. The increase in radiation density shows up as a blue shift, and can also be expressed in terms of temperature starting out from the present-day 3 kelvin (K), and getting hotter the farther back in time we go. Eventually, as we go back further and further, the temperature of the radiation increases to the extent that matter is created out of pure energy. Einstein's well-known equation $E = mc^2$ and a fundamental constant of statistical mechanics, Boltzmann's constant, are used to determine the rest mass of particles.

Conditions required to create matter

Einstein's equation $E = mc^2$ tells us that each particle has a certain rest energy, mc^2. In order for two photons to create an electron-positron pair in a head-on collision, the photons must have at least the energy mc^2. The process would still take place if the photons had more energy than the rest mass, the excess energy going into the momentum of the electron-positron pair.

In order for two photons to produce an electron and positron pair in a head-on collision, the energy of each photon must exceed the rest energy in an electron or positron mass. This energy is 5.11003×10^5 electron volts (eV). To find the threshold temperature, we divide the energy by Boltzmann's constant (8.617×10^{-5} $eV{\cdot}K^{-1}$) and find a threshold temperature of six thousand million kelvin (6×10^9 K). At any higher temperature electrons and positrons would have been freely created in collisions of photons with each other, and would therefore be present in large numbers.

Reproduced by Sabinet Gateway under licence granted by the Publisher (dated 2013.)

Incidentally, the threshold temperature of 6×10^9 **K** for the creation of electrons and positrons out of radiation is much higher than any temperature we normally encounter in the present Universe; even the centre of the Sun is only at a temperature of about 1.5×10^7 K

Similar remarks apply for every other type of particle. It is a fundamental rule of modern physics that there is a corresponding 'antiparticle', with precisely the same mass and spin, but with opposite electric charge. The only exception is for certain purely neutral particles, like the photon itself, which can be thought of as being its own antiparticle. Given enough energy, it is always possible to create any kind of particle pair in collisions of pairs of photons.

The next lightest particle types after the electron and the positron are the muon (μ^-), a kind of heavy unstable electron, and its antiparticle (μ^+). Just as for electrons and positrons, the μ^- and μ^+ have opposite electrical charge, but equal mass and can be created in collisions of photons with each other. The μ^- and μ^+ each have a rest energy mc^2 equal to 1.057×10^8 eV, and dividing by Boltzmann's constant, the corresponding threshold temperature is 1.2×10^{12} K.

It must be emphasized, however, that the transfer of energy from one particle to another takes place within the limit of the uncertainty principle. The inherent uncertainty in the transfer of energy in a sub-atomic process makes it impossible to determine how much energy the particle has, at least for a certain amount of time.

From Table 1 we can tell which particles could have been present in large numbers at various times in the history of the Universe: they are just the particles whose threshold temperatures were below the temperature of the Universe at that time.

We must consider the question, "How many of these material particles actually were present at temperatures above the threshold temperature?" Under conditions of high temperature and density that prevailed in the early Universe, the number of particles was governed by the basic conditions of thermal equilibrium: the number of particles must have been just high enough so that precisely as many particles and antiparticles that were annihilated each second, were created. Since two photons collide to create a particle-antiparticle pair and annihilate into two photons, the number of particles of each type, whose threshold temperature is below the actual temperature, should be about equal to the number of photons.

At temperatures above the threshold temperature, a material particle behaves much like a photon. Its average energy is much larger than the energy in the particle's mass, and the mass can be neglected. Under such conditions the pressure and energy density contributed by energy particles of a given type are simply proportional to the fourth power of the temperature, just as for photons. We can therefore think of the Universe, under such high temperatures as being composed of a variety of types of radiation, one type for each species of particle whose threshold temperature was below the cosmic temperature at that time.

If the Universe in the first few minutes was really composed of precisely equal numbers of particles and antiparticles, they would all have annihilated as the temperature dropped below 10^9 K, and nothing would be left but radiation. There must have been some excess of particles over antiparticles in order that there would have been something

Reproduced by Sabinet Gateway under licence granted by the Publisher (dated 2013.)

Table 1. Properties of some elementary particles.

	Particle	Symbol	Rest energy (10^6 eV)	Threshold temperature (10^{12} K)
Leptons	Photons	γ	0	0
	Neutrinos	υ	0	0
	Electrons	e	0.51	0.0059
	Muon	μ	105.66	1.2262
Hadrons	Pi mesons	π^0	134.96	1.5662
		π^-	139.57	1.6197
	Proton	p	938.26	10.89
	Neutron	n	939.55	10.903

left over after the annihilation of particles and antiparticles to furnish the matter of the present Universe.

I don't want to deal with this matter in too much detail, but because of the importance of the apparent inconsistencies pointed out above, I will deal very briefly with them. The decay of specifically one type of kaon, called K^0_L, a neutral particle that, like the photon, is its own antiparticle, showed the first chink in the symmetry laws of physics at this level. It shows that as kaons decay they produce more positrons than electrons and therefore cause a slight disproportion of positrons in the Universe by a tiny amount.

To solve the problem of matter over antimatter, the Russian physicist Andrei Sakharov set out (in 1967) the underlying principles that must apply to any process that could produce matter particles preferentially in the early Universe. Sakharov said three conditions must be satisfied:

- there must be processes that produce baryons out of non-baryons;
- these baryon interactions must violate both the C (charge) and the CP (charge-parity) conservation; and
- the Universe must evolve from a state of thermal equilibrium into a state of disequilibrium.

Sakharov was far ahead of his time: only in 1978 did it became clear that the single most solid prediction of all the Grand Unification Theories (GUTs; attempts to unify the electromagnetic, strong and weak forces) is that there are X bosons, very massive particles that could produce an excess of baryons over antibaryons at the end of the GUT era, 10^{-35} seconds after the moment of creation. The decay of X bosons is a complicated process, just as the decay of the kaon, and it can unfortunately not be explained in detail here, suffice to say that the decay of X bosons explains the excess of matter over antimatter. Sakharov's conditions were duly met.

Recipe for the contents of the Universe. It should be noted that there are literally hundreds of so-called elementary particles, but fortunately for our purposes, it is not neces-

Reproduced by Sabinet Gateway under licence granted by the Publisher (dated 2013.)

sary to list all of them in order to arrive at our recipe for the contents of the Universe. It is important to remember that the Universe passed through a state of thermal equilibrium – in fact, this is what allows us to speak with such confidence about the contents of the Universe at any given time. When collisions or other processes bring a physical system to a state of thermal equilibrium there are always quantities whose values do not change. One of these conserved quantities is the total energy. Energy may be transferred from one particle to another, subject to the uncertainty principle, but the total energy never changes.

However, 'conserved quantities' can have a shifting meaning. At the temperatures of several thousand million degrees, as found in the early Universe, even atomic nuclei dissociate readily into their constituents (protons and neutrons). Reactions occur so rapidly that matter and antimatter can easily be created out of pure energy, or annihilated again. Under these conditions the conserved quantities are not the numbers of particles of any specific kind. Instead the relevant conservation laws are reduced to just that small number which (as far as we know) are respected under all possible conditions. It is believed that there are just three conserved quantities whose densities must be specified in our recipe for the early Universe.

We can create or destroy pairs of particles with equal and opposite electric charge, but the net electric charge never changes.

The term 'baryon' includes the nuclear particles, protons and neutrons, together with somewhat heavier unstable particles known as hyperons. Baryons and antibaryons can be created or destroyed in pairs; and baryons can decay into other baryons, as in the 'beta decay' of a radioactive nucleus in which a neutron changes into a proton, or vice versa. However, the total number of baryons minus the number of antibaryons (antiprotons, antineutrons, antihyperons) never changes.

Leptons are light-weight negatively charged particles: electrons, muons, electrically-neutral zero-mass neutrinos, and their antiparticles (the positron, antimuon, and antineutrino). The lepton number, that is, the total number of leptons minus the total number of antileptons, never changes. Of course, it should be remembered that there are at least two types of neutrino, an 'electron type' and a 'muon type', and there are therefore two types of lepton number: electron lepton number is the total number of electrons plus the electron-type neutrinos, minus the number of their antiparticles, while the muon lepton number is the total number of muons plus muon-type neutrinos, minus the number of their antiparticles. Both seemed to be absolutely conserved, but this is not known with great certainty.

To complete our recipe for the contents of the Universe at any given time we must specify the charge, baryon number, and lepton number per unit volume as well as the temperature at that time. We know that the Universe is expanding, and the conservation laws tell us that in any volume that expands with the Universe the values of these quantities remain fixed. Therefore, the charge, baryon number, and lepton number per unit volume simply vary with the inverse cube of the size of the Universe. But the number of photons also varies with the inverse cube of the size of the Universe, and we know that the number of photons per unit volume is proportional to the cube of the temperature, and the temperature varies with the in-

Reproduced by Sabinet Gateway under licence granted by the Publisher (dated 2013.)

verse size of the Universe. Therefore, the charge, baryon number and lepton number per photon remain fixed.

Armed with our recipe for the contents of the Universe, we are now ready to follow the course of matter creation in the early Universe. Since events move much faster initially, it is not practical to discuss events at equal time intervals. I will rather divide the events according to the decrease in the temperature of the Universe, as it expands, by a factor of about three.

When the temperature of the Universe was above a threshold of 1.5×10^{12} K, there were large numbers of strongly interacting particles present, which makes the calculation of the behaviour of matter extremely difficult, and I shall deal with this period of matter creation separately.

Stage 1: Universe at 10^{11} K

The Universe is filled with an undifferentiated soup of matter and radiation, each particle of which collides very rapidly with other particles. Despite its rapid expansion, the Universe is in a state of nearly perfect thermal equilibrium. At 10^{11} K, the conserved quantities are very small. Particles whose threshold temperatures are below 10^{11} K, are created freely out of pure energy. These are the electron and its antiparticle, the positron, and of course the massless particles, the photons, neutrinos and antineutrinos. At such a high temperature, the nuclear particles (protons and neutrons) are not yet bound into nuclei, since complex nuclei are destroyed as fast as they are formed. Only a small number of nuclear particles exist at this time. The collisions of neutrons or protons with the much more numerous electrons, positrons and so on, will produce rapid transitions of protons to neutrons and vice versa. The most important reactions are:

- Antineutrino plus proton yields positron plus neutron (and vice versa)
- Neutrino plus neutron yields electron plus proton (and vice versa)

The circumference of the Universe is now about four light years.

Stage 2: Universe at 3×10^{10} K

0.11 seconds have elapsed since the previous temperature of 10^{11} K. Nothing has changed qualitatively – the contents of the Universe is still dominated by electrons, positrons, neutrinos, antineutrinos and photons, all in thermal equilibrium, and all high above their threshold temperatures. The small number of nuclear particles are still not bound into nuclei, but with the falling temperature it is now much easier for the heavier neutrons (a mass difference between the neutron and the proton is equivalent to an energy of 1.293×10^{6} eV) to turn into lighter protons than vice versa. The nuclear particle balance is 38 per cent neutrons and 62 per cent protons.

Stage 3: Universe at 10^{10} K

1.09 seconds have elapsed since the temperature of 10^{11} K. The decreasing density and temperature have increased the mean free time of neutrinos and antineutrinos so much that they are behaving like free particles, no longer in thermal equilibrium with the electrons positrons or photons. Since the neutrinos are now moving freely, the neutrino wavelength increases (redshifts) in direct proportion to the size of the Universe. The temperature is now twice the threshold temperature of electrons and positrons, so they are beginning to annihilate more rapidly than they can be created out of radiation. It is still

Reproduced by Sabinet Gateway under licence granted by the Publisher (dated 2013.)

too hot for protons and neutrons to be bound into atomic nuclei. Due to the decreasing temperature the proton-neutron balance has now shifted to 24 per cent neutrons and 76 per cent protons.

Stage 4: Universe at 3×10^9 K

It is now 13.82 seconds since the temperature of 10^{11} K. The temperature is now below the threshold temperature for electrons and positrons, so they are beginning to disappear rapidly as constituents of the Universe. The energy released in their annihilation has slowed down the rate at which the Universe cools, and the neutrinos, which do not get any of this extra heat, are now 8 per cent cooler than the electrons, positrons and photons. From now on, if we refer to the temperature of the Universe, we will mean the temperature of the photons. At this temperature, it is now cool enough for stable nuclei like helium to form but the nuclei of deuterium (or heavy hydrogen) are blasted apart as soon as they form, so heavier nuclei do not get a chance to be produced. Neutrons are still being converted into protons, but much more slowly than before. The balance is now 17 per cent neutrons and 83 per cent protons.

Stage 5: Universe at 10^9 K

Three minutes and two seconds have elapsed since the temperature of 10^{11} K. The electrons and positrons have mostly disappeared, and the constituents of the Universe are now photons, neutrinos, and antineutrinos. The energy released in electron-positron annihilation has given the photons a temperature 35 per cent higher than that of neutrinos. The Universe is now cool enough for tritium and helium-three, as well as ordinary helium nuclei, to hold together, but deuterium nuclei still do not hold together long enough to allow appreciable numbers of heavier nuclei to be built up. The collision of neutrons and protons with electrons, neutrinos, and their antiparticles have now ceased, but the decay of free neutrons is now beginning to be important. In each 100 seconds 10 per cent of the remaining neutrons decay into protons. The neutron-proton balance is now 14 per cent neutrons and 86 per cent protons.

At some time after the temperature of 10^9 K, a dramatic event occurs. The temperature drops to a point where deuterium nuclei can hold together. As soon as deuterium can form, almost all the remaining neutrons are immediately cooked into helium nuclei. At the ratio of 10^9 photons per nuclear particle, nucleosynthesis will begin, with the temperature at 9×10^8 K. At this time, three minutes and forty six seconds have passed since the temperature of 10^{11} K.

This is the final stage in our discussion of the sequence of matter creation, but to see better what has been accomplished, let us take a last look at the Universe after one more drop in temperature.

Stage 6: Universe at 3×10^8 K

Thirty-four minutes and forty seconds have elapsed since the temperature of 10^{11} K. The electrons and positrons have now completely annihilated except for the small (one part in 10^9) excess of electrons needed to balance the charge of the protons. The energy released in this annihilation has now given the photons a temperature permanently 40.1 per cent higher than the temperature of the neutrinos. Nuclear processes have stopped – the nuclear particles are now for the most part either bound into helium nuclei or are free protons (hydrogen nuclei), with about 22 to 28 per cent helium by weight. There is one

Reproduced by Sabinet Gateway under licence granted by the Publisher (dated 2013.)

electron for each free or bound proton, but the Universe is still much too hot for stable atoms to hold together. For the next 700 000 years not much of interest will occur. After that, the temperature will drop to the point where electrons and nuclei can form stable atoms, the lack of free electrons will make the Universe transparent to radiation, and the decoupling of matter and radiation will allow matter to begin to form into galaxies and stars. The radiation, which now expands freely, will be observed by human beings after another 10^{10} years or so, as the microwave background radiation.

The creation of matter took place at the quantum level and quantum effects, in particular the energy/time uncertainty, played a major role.

The Planck Era

This is the final part of our journey back in the history of the Universe to describe the creation of matter. I deal with this era last because we can only apply quantum theory in our quest to understand what happened then: the extreme temperatures and densities existing at that time make it impossible to calculate the behaviour of matter under such conditions. Yet, the first one-hundredth of a second is important since the very building blocks of matter (quarks and leptons) were created (the quarks, of course, eventually formed protons and neutrons). There are many other types of particles known to modern physics (muons, pi mesons, and so on) apart from neutrons and protons. The temperatures and densities would have been so high that these particles would have been present in large numbers in thermal equilibrium, and all in a state of continual mutual interaction.

But let us start right at the beginning. Imagine, if you can, nothing at all! This is the primordial vacuum of space. There is complete darkness here, no light yet exists. The number of dimensions was probably not the three that we are so accustomed to but may even be as high as eleven, according to the supergravity theory! In this emptiness, random fluctuations occurred that, ever so slightly, within the limit of the uncertainty principle, changed the energy of the vacuum at various points in space.

Eventually, one of these fluctuations attained a critical energy and began to grow. As it grew, very massive particles called leptoquarks were created, causing the expansion to accelerate. This is very much like a ball rolling down a hill that moves slowly at first and then gains momentum. The expansion of the proto-Universe, in turn, caused still more leptoquarks to be created.

As the Universe expanded it borrowed energy from the gravitational field to create more matter. This furious cycle continued until, at last, leptoquarks decayed into quarks, leptons (electrons, muons, etc.) and their antiparticles, and the Universe emerged from what is known as the Planck era.

At about 10^{-5} seconds the quarks all became locked up into baryons as the temperature of the Universe fell below 10^{13} K, and protons and neutrons were created.

At intervals shorter than 10^{-43} seconds (the Planck time) the notion of time has no meaning. At this Planck scale the energy of a particle is so high that it is inside a black hole. During the period up to 10^{-36} seconds the four forces – gravity, electromagnetism, weak and strong nuclear – were one superforce. In that situation, (quantum) gravity became the dominant force and created very massive particles.

Reproduced by Sabinet Gateway under licence granted by the Publisher (dated 2013.)

A basic prediction of particle physics is that matter at very high energies (like those expected during the formation of the Universe) can assume a variety of unusual forms, including one state that turns gravity upside-down. In this case massive particles repel rather than attract each other. What's more, matter in such a topsy-turvy state possesses another strange property: its density remains constant, even as the volume of space it inhabits expands exponentially (Guth's theory of inflation). But such an antigravity field is, as we know, subject to quantum fluctuations. We also know that virtual particles are being created in such a vacuum, subject to the uncertainty principle. Particle creation stopped once the fluctuations in the geometry of space subsided.

So we are left with the remarkable possibility that there existed, quite literally, nothing at all and from it emerged nearly all of the matter and radiation that we now see. In the words of physicist Frank Wilkcyk: 'The reason that there is something instead of nothing is that nothing is unstable'.

A ball sitting on the summit of a steep hill needs but the slightest tap to set it in motion. A random fluctuation in space was apparently all that was required to unleash the incredible latent energy of the vacuum, thus creating matter and energy and an expanding Universe from nothing at all.

The Universe did not spring into being instantaneously but was created a little bit at a time in a 'bootstrap' process. Once a few particles were created by quantum fluctuations of the empty vacuum, it became easier for a few more to appear and so, in a rapidly escalating process, the Universe gushed forth from nothingness.

How long did this take? The primordial vacuum could have existed for an eternity before the particular fluctuation that gave rise to our Universe happened. The physicist Edward Tyron expresses this best by saying, 'Our Universe is simply one of those things that happens from time to time.'

Conclusion

The Standard Model as a theory of the origin of the Universe is inconsistent with quantum mechanics since it does not make provision for the uncertainty principle. Statistical mechanics allows us to calculate the behaviour of particles, but the creation of matter took place at the quantum level, and unless the uncertainty principle is taken into account, the creation of matter simply cannot adequately be accounted for. Furthermore, the Standard Model does not explain the creation of massive bosons such as the gluon (with a mass of about 140 MeV more than 200 times the mass of the electron).

If we accept the notion of quantum fluctuations in a primordial vacuum, it means that everything in the Universe, if we can call it the Universe, was dominated by quantum effects. Irrespective of whether we accept the primordial vacuum as an explanation of the origin of the Universe, the fact remains that everything we see around us can only be explained by duly taking into consideration the role of quantum effects in the creation of matter.

Bibliography

Aczel, A (2000) God's Equation: Einstein, Relativity and the Expanding Universe. Judy Piatkus Ltd., London.

Bodanis, D (2000) $E = mc^2$: A Biography of the World's Most Famous Equation. Macmillan, London.

Reproduced by Sabinet Gateway under licence granted by the Publisher (dated 2013.)

Gribbin, J (1988) In Search of the Big Bang, Quantum Physics and Cosmology. Corgi, London.

Hawking, S (1996) The Illustrated A Brief History of Time. Transworld Publishers, London.

Hawking, S (2001) The Universe in a Nutshell. Transworld Publishers, London

Hawking, S & Penrose R (1996) The Nature of Space and Time. Princeton University Press, Princeton, New Jersey.

Hawkins, M (1997) Hunting Down the Universe: The Missing Mass, Primordial Black Holes and Other Dark Matters. Little Brown and Company, London.

Odenwald, S (1983) The Decay of the False Vacuum. Kalmbach Publishing.

Odenwald, S (1984) The Planck Era. Kalmbach Publishing.

Odenwald, S (1987) Beyond the Big Bang. Kalmbach Publishing.

Rees, M (1999) Just Six Numbers: The Deep Forces that Shape the Universe. Orion Books Ltd., London.

Thorne, K (1994) Black Holes and Time Warps: Einstein's Outrageous Legacy. W. W. Norton and Company, New York.

Weinberg, S (1997) The First Three Minutes: A Modern View of the Origin of the Universe. Second Edition. Andre Deutsch, London.

Reproduced by Sabinet Gateway under licence granted by the Publisher (dated 2013.)