passing that of the atomic bomb. For all we know, there may be stellar systems other than ours that are built from such inverted material, in which case any ordinary rock thrown from our system to one constructed the other way, or vice versa, will turn into an atomic bomb as soon as it lands.

At this point we must leave these somewhat fantastic speculations about inverted atoms, and consider still another kind of elementary particles, which, being probably no less unusual, have the merit of actually participating in various observable physical processes—the so-called "neutrinos" which came into physics "through the back door" and, in spite of the "cries of Boeotians" rising against them from many quarters, now occupy an unshakable position in the family of elementary particles. How they were found and recognized constitutes one of modern science's most exciting detective stories.

The existence of *neutrinos* was discovered by a method that a mathematician would call "reductio ad absurdum." The exciting discovery began, not with the fact that something was there, but rather that something was missing. The missing thing was energy, and since energy, according to one of the oldest and most stable laws of physics, can be neither created nor destroyed, discovery that energy that should have been present was absent indicated that there must have been a thief, or a gang of thieves, who took it away. And so the detectives of science, having orderly minds that like to give names to things even when they cannot see them, called the energy thieves "neutrinos."

But that is a bit ahead of the story. To go back into the facts of the great "energy robbery case": As we have seen before, the nucleus of each atom consists of nucleons, about half of them neutral (neutrons), the rest positively charged with electricity. If the balance between the relative number of neutrons and protons in the nucleus is destroyed, by adding one or several extra neutrons or extra protons,[8] an electric adjustment must necessarily take place. If there are too many neutrons some of them will turn into protons by ejecting a negative electron, which leaves the nucleus. If there are too many protons, some of them will turn

[8] This can be done by the method of nuclear bombardment described later in this chapter.

into neutrons emitting a positive electron. Two processes of this kind are illustrated in Figure 60. Such electric adjustments of an atomic nucleus are usually known as the beta-decay process, and electrons emitted from the nucleus are known as beta (β)-particles. Since the internal transformation of a nucleus is a well-defined process, it must always be connected with the liberation of a definite amount of energy, which is communicated to the ejected electron. Thus we should expect that the β-electrons

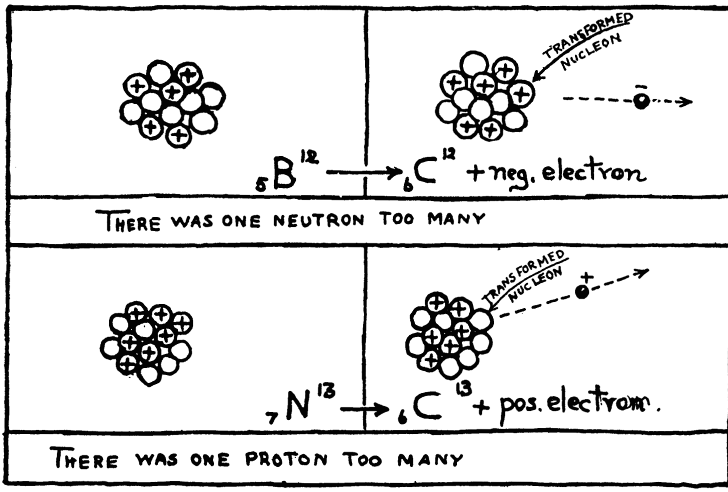

FIGURE 60

The scheme on negative and positive beta decay (for the convenience of presentation all nucleons are drawn in one plane).

emitted by a given substance must all move with the same velocity. The observational evidence concerning the processes of beta decay stood, however, in a direct contradiction to this expectation. In fact it was found that the electrons emitted by a given substance have different kinetic energies from zero to a certain upper limit. Since no other particles were found and no radiation that would balance this discrepancy, the "case of the missing energy" in the processes of beta decay became quite serious. It was believed for awhile that we were facing here the first experimental evidence of the failure of the famous law of energy conservation, which would be quite a catastrophe for all the elaborate building of physical theory. But there was another possibility: perhaps the missing energy was being carried away by some new kind of particles, which had escaped without having been noticed by any of our observational methods. It was suggested by Pauli that the role of such "Bagdad thieves" of nuclear energy could be played by hypothetical particles called *neutrinos,* which carry no electric charge and whose mass does not exceed the mass of

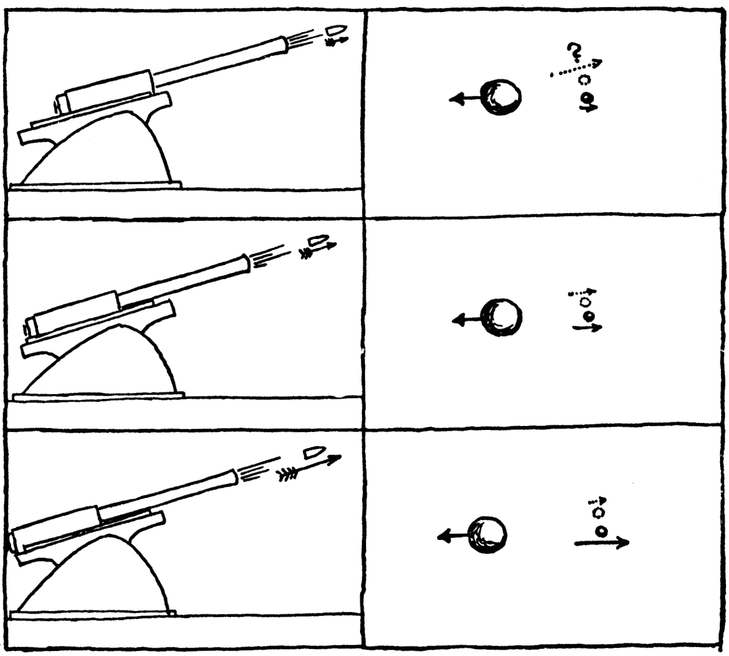

FIGURE 61

The recoil problem in artillery and nuclear physics.

an ordinary electron. In fact, one could conclude from the known facts concerning the interaction of fast-moving particles and matter, that such chargeless, light particles could not be noticed by any existing physical apparatus, and would pass without any difficulty through enormously large thicknesses of any screening material. Thus, whereas the visible light would be completely stopped by a thin metallic filament, and the highly penetrating

X- and gamma radiations would require several inches of lead to be substantially reduced in intensity, a beam of *neutrinos* would go without much difficulty through the thickness of several light-years of lead! No wonder that they escape from any possible observation, and can be noticed only because of the deficit of energy caused by their escape.

But although we cannot catch these neutrinos once they have left the nucleus, there is a way of studying the secondary effect caused by their departure. When you shoot a rifle it hits back against your shoulder, and a big gun rolls back in its carriage after ejecting a heavy shell. The same effect of mechanical recoil is to be expected from atomic nuclei shooting out fast particles, and, in fact, it was observed that the beta-decaying nuclei always acquire a certain velocity in the direction away from the ejected electron. The peculiar property of this nuclear recoil lies however in the observed fact, that no matter whether a fast or a slow electron is being ejected, the recoil velocity of the nucleus is always about the same (Figure 61). This seems very strange since we would naturally expect a fast projectile to produce a stronger recoil in a gun than a slow one. The explanation of the riddle lies in the fact that along with the electron the nucleus always emits a neutrino, which carries the balance of energy. If the electron moves rapidly, taking most of the available energy, the neutrino moves slowly, and vice versa, so that the observed recoil of the nucleus is always strong, owing to the combined effect of *both* particles. If this effect does not prove the existence of the neutrino nothing ever will!

We are ready now to sum up the results of the foregoing discussion and to present a complete list of the elementary particles participating in the structure of the universe, and the relationships that exist among them.

First of all we have the nucleons, which represent the basic material particles. They are, so far as the present state of knowledge can say, either neutral or positively charged, but it is possible that some are negatively charged.

Then we have the electrons representing the free charges of positive and negative electricity.

There are also the mysterious neutrinos, which carry no electric charge and are presumably considerably lighter than electrons.[9]

Finally there are the electromagnetic waves, which account for the propagation of electric and magnetic forces through empty space.

All these fundamental constituents of the physical world are interdependent and can combine in various ways. Thus a neutron can go into a proton by emitting a negative electron and a neutrino (neutron → proton + neg. electron + neutrino); and a proton can go back into a neutron by emitting a positive electron and a neutrino (proton → neutron + pos. electron + neutrino). Two electrons with opposite electrical charges can be transformed into electromagnetic radiation (pos. electron + neg. electron → radiation) or on the contrary can be formed from the radiation (radiation → pos. electron + neg. electron). Finally the neutrinos can combine with electrons, forming the unstable units observed in the cosmic rays and known as *mesons* or, rather incorrectly, as "heavy electrons" (neutrino + pos. electron → pos. meson; neutrino + neg. electron → neg. meson; neutrino + pos. electron + neg. electron → neutral meson).

Combinations of neutrinos and electrons are overloaded with internal energy that makes them about a hundred times heavier than the combined mass of their constituent particles.

Figure 62 shows a schematic chart of elementary particles participating in the structure of the universe.

"But is this the end?" you may ask. "What right have we to assume that nucleons, electrons, and neutrinos are really elementary and cannot be subdivided into still smaller constituent parts? Wasn't it assumed only a half a century ago that the atoms were indivisible? Yet what a complicated picture they present today!" The answer is that, although there is, of course, no way to predict the future development of the science of matter, we have now much sounder reasons for believing that our elementary particles are actually the basic units and cannot be subdivided further. Whereas allegedly indivisible atoms were known to show a great variety of rather complicated chemical, optical, and other proper-

[9] The latest experimental evidence on this subject indicates that a neutrino weighs no more than one tenth as much as an electron.

ties, the properties of elementary particles of modern physics are extremely simple; in fact they can be compared in their simplicity to the properties of geometrical points. Also, instead of a rather large number of "indivisible atoms" of classical physics, we are now left with only three essentially different entities: nucleons, electrons, and neutrinos. And in spite of the greatest desire and

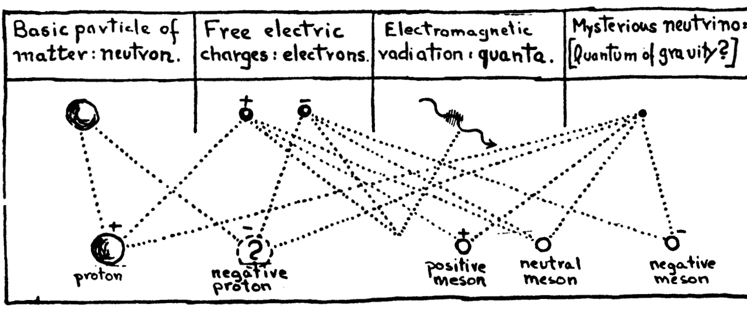

FIGURE 62
The chart of elementary particles of modern physics and of their different intercombinations.

effort to reduce everything to its simplest form, one cannot possibly reduce something to nothing. Thus it seems that we have actually hit the bottom in our search for the basic elements from which matter is formed.

2. *THE HEART OF THE ATOM*

Now that we have become thoroughly acquainted with the nature and properties of the elementary particles participating in the structure of matter, we may turn to a more detailed study of the nucleus, the heart of every atom. Whereas the structure of the outer body of the atom can be to a certain extent compared to a miniature planetary system, the structure of the nucleus itself presents an entirely different picture. It is clear first of all that the forces holding the nucleus together are not of a purely electric nature, since one half of the nuclear particles, the neutrons, do not carry any electric charge, whereas another half, the protons, are all positively charged, thus repelling each other. And you cannot possibly get a stable group of particles if there is nothing but repulsion between them!

would be to devise some mechanism that would remove from the interior the energy liberated in contraction. If, for example, the opacity of stellar matter could be reduced by a factor of several billions, the contraction would be accelerated in the same proportion, and a contracting star would collapse within a few days. This possibility is, however, quite excluded, since the present theory of radiation definitely shows that the opacity of stellar matter is quite definitely a function of its density and temperature, and can hardly be reduced even by so much as a factor of ten or a hundred.

It was recently proposed by the author and his colleague, Dr. Schenberg, that the real cause of stellar collapses is due to the

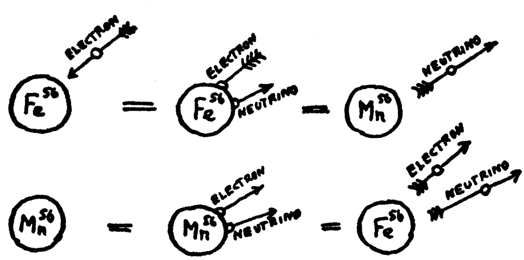

FIGURE 125

The Urca process in iron nucleus leading to the unlimited formation of neutrinos.

mass formation of *neutrinos,* those tiny nuclear particles that are discussed in detail in Chapter 7 of this book. It is clear from the description of the neutrino that it is just the right agent to remove the surplus energy from the interior of a contracting star, since the entire body of the star is just as transparent for neutrinos as a windowpane is for ordinary light. It remains to be seen whether the neutrinos will be produced, and produced in sufficiently large numbers in the hot interior of a contracting star.

The reactions that must be necessarily accompanied by emission of neutrinos consist in the capture of fast-moving electrons by the nuclei of various elements. When a fast electron penetrates inside the atomic nucleus, a high-energy neutrino is immediately emitted, and the electron is retained, transforming the original nucleus into an unstable nucleus of the same atomic weight. Being unstable, this newly formed nucleus can exist only a definite period of time, and subsequently decays, emitting its electron in the company of another neutrino. Then the process begins again from the beginning, and leads to a new neutrino emission. . . . (Figure 125).

If the temperature and density are high enough, as they are in the interior of contracting stars, the energy losses through

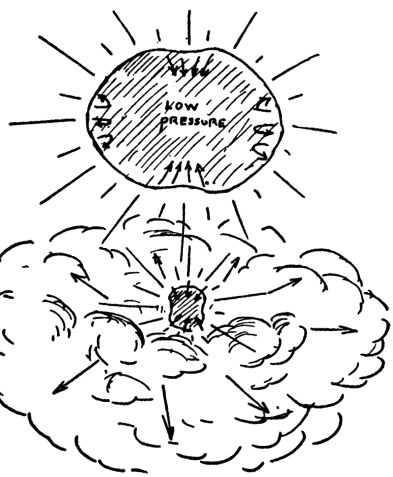

FIGURE 126

An early and a late stage of a supernova explosion.

neutrino emission will be tremendously high. Thus, for example, the capture and re-emission of electrons by the neuclei of iron atoms will transform into neutrino energy as much as 10^{11} ergs per gram per second. In the case of oxygen (where the unstable product is radioactive nitrogen with the decay period of 9 seconds) the star can lose even as much as 10^{17} ergs per second per gram of its material. The energy losses in this latter case are so high that the complete collapse of the star takes place in only twenty-five minutes.

Thus we see that the beginning of the neutrino radiation from the hot central regions of contracting stars gives us the complete explanation of the causes of stellar collapses.

It must be stated, however, that although the rate of energy losses through neutrino emission can be estimated comparatively easily, the study of the collapse process itself presents many mathematical difficulties, so that only the qualitative explanation of the events can be given at present.

It must be imagined that, as the result of the deficiency of gas pressure in stellar interiors, the masses that form its giant outside body begin to fall toward the center driven by the forces of gravity. Since, however, every star is usually in a state of more or less rapid rotation, the process of the collapse proceeds asymmetrically, and the polar masses (i.e., those located near the axis of rotation) fall in first pushing the equatorial masses outward (Figure 126).

This brings out the material previously hidden deep in the stellar interior, and heated up to the temperatures of several thousand million degrees, a temperature which accounts for the sudden increase of stellar luminosity. As the process goes on the collapsing material of the old star condenses in the center into a dense white dwarf star, whereas the expelled masses gradually cool down and continue to expand forming the sort of nebulosity observed in the Crab Nebula.

3. *PRIMORDIAL CHAOS AND THE EXPANDING UNIVERSE*

Thinking of the universe as a whole, we are at once confronted by vital questions concerning its possible evolution in time. Must we assume that it always was, and will always remain, in approximately the same state as we observe it now? Or does the universe continuously change, passing through different evolutionary stages?

Examining this question on the basis of empirical facts collected from widely different branches of science, we come to a quite definite answer. *Yes, our universe is gradually changing*; its state in the long-forgotten past, its state in the present, and that which it will become in the distant future are three very different

SCIENCE

ONE TWO THREE... INFINITY

George Gamow

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