by ***George Gamow***

THE REALITY OF NEUTRINOS

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The author, a theoretical physicist, treats here of the neutrino, a particle known by its absence rather than by its presence, from its role in nuclear transformations to its possible role in a quantum theory of gravitation.

In the year 1914 a young (at that time) British physicist, James Chadwick, who was sent to Germany to study the phenomena of radioactive decay, came across a rather interesting but, as it looked then, not very important discovery. He found that electrons emitted by radioactive substances in the process called beta transformation do not all possess the same velocity. In fact their velocities vary over a rather wide range.

This discovery did not at first attract much attention. It was believed that the difference in velocity between one emitted electron and another occurs simply because the slower electron loses some energy in escaping from a deeper layer within the radioactive material. It was only thirteen years later that this seemingly natural assumption was questioned and disproved by two other British physicists, C. D. Ellis and W. A. Wooster. They took some radium E, a beta-active element, and arranged to measure the heat liberated by radioactive decay both inside and outside the parent body. They chose radium E because it has no appreciable gamma radiation, which would confuse the issue. They were also careful to subtract from the total heat measured the part supplied by alpha particles given off by the polonium into which radium E decays.

In this experiment the electrons escaping from the radium E were absorbed in the walls of a lead box in which the radium had been put. The rise in temperature of both the box and what it contained was measured. One would expect that dividing the total measured heat by the number of electrons which escaped would give an energy value coinciding with the highest energies recorded for any electron, because the total heat measured included the energy supposedly 'lost' within the parent body. The actual result was quite different: the average heat energy per particle coincided exactly with the *average* energy of electrons as estimated from direct observations. This could only mean that the electrons emitted were not losing any appreciable energy within the parent body, but were actually leaving the nuclei with widely varying velocities.

The experiment of Ellis and Wooster was later repeated by L. Meitner and W. Orthmann, who used thicker lead walls to be sure that nothing got away. But they got the identical result. Thus it became apparent that there was a serious discrepancy in the energy balance of these nuclear transformations.

It was suggested by W. Pauli that the law of conservation of energy can be saved in this case by assuming a new kind of extremely penetrating elementary particle which would accompany the emission of beta electrons, and which would take along with it the missing fractions of the total transformation energy. This hypothetical particle had to be electrically neutral because the change in electric charge of the radioactive nucleus was already accounted for. It would also have a rather small mass, not more than that of an electron, since the atomic weight was known not to change essentially in the process of beta transformation.

Such electrically neutral particles of very small mass could be expected to possess a very high penetrating power because they could pass very close to other particles without being captured. This would easily account for the failure to detect them in the heat experiments of Ellis and Wooster, and Meitner and Orthmann.

In discussing this new hypothetical particle, Pauli referred to it as a "neutron." When the particles we now call neutrons were discovered by J. Chadwick in 1932, and E. Fermi was reporting their discovery at a colloquium at the University of Rome, one of the students asked whether the "Chadwick neutron" was the same "neutron" proposed by Pauli for the phenomena of beta transformation. "No," answered Fermi, "il neutrone di Pauli è molto più piccolo, cio è un neutrino." The name stuck, and the term "neutrino" is now used universally for the electron's companion in the radioactive beta transformations.

Apart from its primary task, which was to fix up the law of conservation of energy, the neutrino also had to take on itself another no less important job of balancing nuclear angular momentum. Angular momentum is the tendency of any spinning mass to continue spinning, like a billiard ball with heavy English. The spin of the atomic nucleus can be measured experimentally, and always turns out to be an even or odd number multiplied by a certain basic quantity in quantum mechanics. Furthermore, this spin is even or odd depending on whether the sum of all the protons and neutrons in any atomic nucleus is even or odd.

Now, an electron is emitted in a beta transformation. (It must be kept in mind that electrons do not represent a constituent part of the nucleus, but are formed from the electric charge released in the transformation of a neutron into a proton or vice versa.) Since electrons have odd spin, one would expect the spin of the whole nucleus to show a change in its angular momentum from even to odd or vice versa. But it does not show it! So, in order to satisfy the law of conservation of angular momentum, we must find somewhere a spin which would balance that taken away by the emitted electron. Quite independently of the discrepancies in energy balance, we are forced to the assumption of another elementary particle with the necessary spin which must accompany the emission of the beta electron.

Neutrino-Recoil Experiments

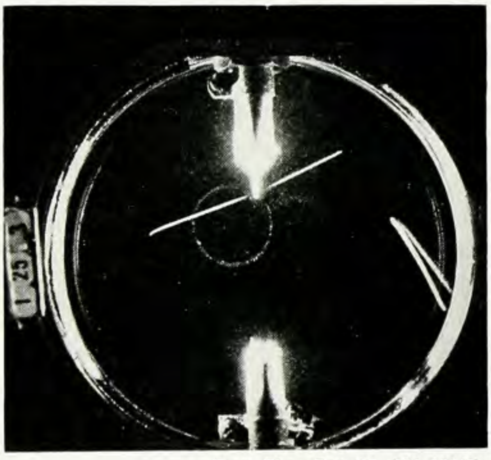
Both the absence of electric charge and the vanishingly small mass of the new hypothetical particle suggest that, once emitted, the neutrino will interact only very weakly with the atoms of the material through which it moves, so there is very little hope of detecting it by any kind of absorption measurements. The most promising way of getting more information on the neutrino lies in studying its effects on the nucleus during the emission process. The most direct effect of this kind is the additional recoil of the nucleus caused by the ejection of the neutrino.

If electrons were the only particles emitted in the process of beta transformation, we would expect that nuclei ejecting fast electrons would suffer a strong recoil, whereas those ejecting slow electrons would recoil very gently. Assuming the neutrino hypothesis, we should expect a much larger proportion of fast nuclear recoils, since even in the case of the low energy electron there must be a considerable recoil due to ejection of the high-energy neutrino. The first experimental attempt to solve this question was made by A. I. Leipunski who studied the energy distribution of recoil nuclei coming from a thin layer of a beta-active substance. His results, which indicated a considerable excess of fast recoils, can be considered the first positive proof of the existence of neutrinos.

Two years later similar experiments were carried out by H. R. Crane and J. Halpern who studied the individual acts of beta disintegration by the Wilson-cloud-chamber method (a standard technique for observing and identifying atomic particles by the foggy tracks they leave). In the figures above are reproduced two of their photographs showing the tracks of the electron and the recoil nucleus in the beta transformation of radiophosphorus. Measuring the energy of the emitted electron (the curved track), and of the recoil nucleus (the short bulky-looking track in the lower part of the photographs), Crane and Halpern concluded that in many cases the recoil nucleus moves with much higher velocity than would be expected.

This means some other particle must have been ejected at the same time as the electron. These single-process experiments leave little doubt that a third particle must be involved, though it does not leave a track in the chamber because it is not electrically charged, but they give no definite indication in which direction the neutrino is emitted since the shortness of nuclear-recoil tracks does not permit directional measurements.

A somewhat different technique was used in more recent experiments of Christy, Cohen, Fowler, Lauritsen, and Lauritsen. Unstable heavy lithium nuclei were produced by directing a beam of heavy hydrogen at a lithium target. Soon after the heavy lithium is formed it breaks up into two alpha particles, an electron, and a neutrino. Above is one of several thousand Wilson-chamber photographs of the disintegration process taken by these authors. We can see two tracks of alpha particles and the track of the electron bent into a circle (moving clockwise) by the magnetic field in which the chamber was placed.



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The momenta of the three particles can be calculated from the photographs. One finds again that they do not satisfy the law of conservation of linear momentum, and in order to fix it up one must assume a neutrino moving with a fairly high energy towards the lower right-hand corner of the photograph. Although, in this particular case, the electron and the neutrino seem to be emitted almost in the same direction, other photographs show a wide variation of the angle between these two particles, and lead to the provisional conclusion that there is no strongly expressed correlation between the two directions.

Still more recent studies of the same problem, carried out by Chalmers W. Sherwin for recoil nuclei emerging from a single layer of radiophosphorus molecules, seem to indicate that there is a slight preference for the electron and the neutrino to be emitted in opposite directions.

K-Capture Experiments

Another set of experiments which give evidence of nuclear recoil from neutrino emission is based on the study of the so-called K-capture processes.

If we consider an atom which may eject a positive electron from its nucleus, we may expect that in many cases the nucleus will instead absorb one of the two negative electrons closest at hand. (These two electrons form the K-shell, hence the name.) Now, the absorption of a single negative electron by a nucleus would lead to the same kind of violation of angular momentum law as the emission of an electron; we must conclude that such a process is impossible without another particle participating in it which would balance the spin. We can visualize it as the simultaneous absorption of the K-shell electron and of a neutrino which comes somewhere from outside or, lacking such an incoming neutrino, as the absorption of the K-shell electron followed by the emission of a similar particle which may be called an 'antineutrino.'

From what we know now, the distribution between the neutrino and the antineutrino is purely academic. It is introduced for the sake of symmetry in terminology. We may think of the relationship between neutrino and antineutrino as being similar to the relationship between negative and positive electrons. However, since the neutrino is not charged (an attribute which makes it easy to distinguish, experimentally, between the two kinds of electrons), the difference between the neutrino and antineutrino can lie only in the possibility of their mutual annihilation. There does not seem to be much chance to observe such a neutrino-annihilation process at present because the density of neutrino beams is extremely small and there is practically no chance that two neutrinos will collide.

On the other hand, the process of K-capture, which is allegedly accomplished through the emission of an antineutrino, represents a well-established fact of nuclear physics, and its experimental studies supply us with an additional ponderous argument in favor of these elusive elementary particles. The observed probability of K-capture processes is also in excellent agreement with the value predicted by Fermi's theory.

The role of the antineutrino in the process of K-capture is best demonstrated by the experiments of James S. Allen who studied nuclear recoil following the K-capture in the nucleus of beryllium. He was able to show that the observed energy of recoil nuclei was very close to the expected energy of the recoil produced by antineutrinos emitted in the process of K-capture. The fact that the measured recoil energy falls somewhat short of the predicted upper limit may be due to the overestimate of the theoretical values which were based on the assumption that the mass of the neutrino is vanishingly small.

The Mass of the Neutrino

Although from the very beginning, when the notion of the neutrino was first introduced into nuclear physics, it was clear that its mass is certainly not larger and is probably considerably smaller than the mass of an electron, finding its exact value involves very serious experimental difficulties. The most direct method for determining the mass of the neutrino would be to measure very exactly the total energy balance of some beta process for which we have an equally exact knowledge of the masses of all other particles involved.

Unfortunately measurements of that kind have as yet failed to show any noticeable difference in excess of experimental error, which amounts to one-twentieth of an electron mass. Though the latest work of D. J. Hughes and C. Eggler, who measured the energy balance in some nuclear reactions, gives for the mass of the neutrino in one case two-thousandths of an electron mass and in another case eight-thousandths of an electron mass, these figures are still uncertain within one-twentieth the mass of an electron, i.e., the experimental error. One can safely conclude from these figures only that the mass of the neutrino is not larger than one-twentieth of the electron mass.

An entirely different semitheoretical method for obtaining information on the mass of the neutrino was suggested recently by Emil J. Konopinski, who comes to the conclusion that the actual mass of the neutrino must be less than about one-twentieth of an electron mass. The arguments use by Konopinski are not quite free of all possible objections, so that further studies are necessary to settle the question in a definite way.

Absorption and Scattering of Neutrinos

We do not have any experimental evidence on how neutrinos are absorbed in the material through which they pass, but the problem can be attacked theoretically. It seems that the only reasonable way in which a neutrino can be absorbed by an atomic nucleus which it encounters consists in the reversal of K-capture. In this case the neutrino enters a nucleus which then emits an electron that ultimately dissipates its energy in colliding with other particles in the absorbing material.

The likelihood of this process, which can be directly calculated on the basis of Fermi's theory, can be also evaluated from the observed probability of K-capture processes. The result is that for neutrinos of one million electron volts energy, the capture cross section, i.e., the size of the target, is expected to be in the neighborhood of 10^{-42} square centimeter. To get the physical meaning of that very small value, we estimate the thickness of a lead shield necessary to absorb neutrinos effectively to be two hundred million million miles or thirty-five light years of lead! No wonder that they have escaped capture in the heat measuring arrangements of Ellis and Wooster and Meitner and Orthmann.

The possibility is not excluded that there is more likelihood that neutrinos will be deflected by glancing off atomic particles than there is that they will be captured by them. Not knowing the law of forces governing these processes, we are unable to obtain any theoretical estimate, but we can turn here to the experimental data. An attempt to observe the effect of this was made by M. E. Nahmias. He found that the cross section for neutrino-electron collision is definitely smaller than 10^{-31} square centimeter. In recent experiments on collisions between neutrinos emerging from the Clinton pile and nuclei

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NEUTRINOS

Continued from page 7

of hydrogen atoms, E. O. Wollan is in general agreement with this figure.

The experiments of Nahmias and Wollan give an upper limit, i.e., they indicate that the cross section for collision cannot be any greater than 10^{-31} square centimeter, but it can be smaller. But this is enough information for us to calculate at least how penetrating a beam of neutrinos must be. (If it is smaller than Nahmias' and Wollan's upper limits, it will be even more penetrating.) We can ask ourselves, for example, whether or not the neutrinos which are produced by thermonuclear reactions taking place in the center of the sun would be able to get out through its giant body. We find, according to these figures that only about one percent of all neutrinos will be absorbed before escaping from the sun.

Urca Processes

In all nuclear processes described so far, the emission of the neutrino is subsidiary to the main reaction, and its presence introduces only a certain discrepancy into the observed energy balance of the reaction. However, as was suggested by the author and his colleague Mario Schönberg, the production of neutrinos may become the major process under certain circumstances when matter is subjected to extremely high temperatures.

Let us consider some stable nuclear species which are subjected to such a high temperature that the energy of thermal motion becomes comparable to the energies involved in ordinary beta transformations. In this case we would expect the emission of an antineutrino with the absorption of a free electron, similar to the ordinary K-capture process. In many cases the newly produced nucleus will be unstable and will then re-emit an electron along with a neutrino.

If these reactions take place in an enclosure which is quite impenetrable to all the particles involved, they will attain a certain state of equilibrium depending on the temperature. Since, however, no known walls, not even the thick bodies of the stars, can stop the neutrinos, the process started by a sufficiently high temperature will continue indefinitely, and the neutrinos and antineutrinos formed in the reversible reactions stated above will escape in a steady stream.

Thus we see that processes of that kind, which were named urca processes,* will serve as certain energy-sinks in material heated to a sufficiently high temperature. The urca process is expected to take place in a number of elements, and a few typical examples have been calculated to show the rate of energy loss. It is enormous! Thus in the transformations between iron and manganese and between nitrogen and oxygen, the urca processes are expected to begin when the temperature of matter approaches about ten and forty billion degrees centigrade, respectively, and the corresponding rates of energy losses will be one thousand billion ergs per second per gram for iron, and even more for oxygen. Let us remember, for the sake of comparison, that the rate of energy production by thermonuclear reactions in the center of the sun is only about one hundred ergs per gram per second.

Because of the very high temperatures necessary for initiating urca processes, one may expect them to play an important role only in cosmical processes, and in particular in the evolutionary life of stars. It is well known now that the temperatures of stars at their centers is maintained at a stable level of about twenty million degrees centigrade by the energy-producing thermonuclear reactions (carbon-cycle) which lead to the steady transformation of stellar hydrogen into helium. As soon, however, as the original hydrogen supply of the star is exhausted (which can be expected in the present epoch for stars of rather high mass and luminosity), the star is bound to begin a slow gravitational contraction. During this process the temperature in the center of the star increases inversely proportional to its radius, and can rise from its present value of twenty million degrees centigrade to the values necessary for urca processes in iron when the radius of the star is reduced to a fraction of a percent of its original value. The beginning of urca processes will prevent further increase of the central temperature, and, as can be easily shown on the basis of the theory of stellar equilibrium, will lead to a catastrophic collapse of stellar body.

During the process of such a collapse the heat energy stored in the body of the star will escape into the surrounding space in a sudden flash of light, and we will observe the astronomical phenomena usually described as stellar explosions. It seems, in fact, that the vast stellar explosions known as "super-novae" are due to this particular collapse process, a conclusion which is supported by the fact that the observed total energy liberation in such explosions is of the same order of magnitude as the estimated total heat content of big stars.

Physical Nature of the Neutrino

In spite of the fact that the existence of the neutrino can, for the present, be considered well established, very little can be said about its actual physical nature and its relation to other known elementary particles. We know that this particle always accompanies the emission or absorption of the electron in nucleonic transformations, and it may also play an essential role in the decay of heavy and light mesons observed in cosmic rays.

It also appears that the presence of the neutrino in various types of beta transformations is primarily responsible for the comparative slowness of these processes. Whereas the emission of an electron pair (a positive and a negative electron) by an excited nucleus takes only one ten-thousand billionth of a second, the process of electron-neutrino pair emission of the same energy takes days or weeks. Looking for other physical emission processes which possess comparable or still smaller rates, we stumble on the phenomena of emission of gravitational waves by accelerated mass points.

The emission probability of a gravitational quantum, which can be calculated on the basis of Einstein's general theory of relativity, comes out to be as many times smaller compared with electron-neutrino emission probability, as the latter is smaller compared with the emission probability of an ordinary electron pair.

With a due amount of phantasy, this numerical relation can be interpreted as suggesting that there may be some physical relation between the quantum of gravity and the neutrino-antineutrino pair. We may think that neutrinos play the same role in respect to the field of gravity as the electrons play in respect to the electromagnetic field, and that the above-mentioned hypothetical neutrino-annihilation process may result in the emission of a gravitational quantum. But, fascinating as they are, such considerations must necessarily wait for the further development of the theory of elementary particles.

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* The name *urca* may be interpreted as standing for "un-recordable cooling agent," or as stressing the analogy between the traceless disappearance of energy caused by this process and a similar phenomenon happening to the gambler's money at the roulette tables of the famous Casino da Urca in Rio de Janeiro.

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