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*PROBLEMS OF PRESENT-DAY PHYSICS AND ASTRONOMY**

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1. INTRODUCTION

THIS article gives a survey of the state of our knowledge about elementary particles and the theory of gravitation. It is designed for readers who are not specializing in particle physics, and gives only a general review. It may be that because of the simplified exposition and the absence of mathematical apparatus the article will also be interesting to a wide circle of physicists, and not only to astrophysicists, for whom the report was prepared.

The reader who wishes to learn to read independently in the field of elementary particles must use the more difficult articles of L. B. Okun'[1] and V. B. Berestetskiĭ.[2] Any who find the present article too specialized and difficult can turn to the review by Salam,[3] which gives a good idea of the atmosphere of the actual research. Finally, we mention two more reviews, a book by Feynman[74] and an article by Sakurai.[75]

The choice of material inevitably reflects the interests of the author; in particular, this article conveys almost nothing of the rush of new ideas in the theory of strong interactions, which is associated with the names of Landau, Pomeranchuk, Gribov, Gell-Mann, Mandelstam, and Chew; this new development undoubtedly calls for a separate treatment.

2. EXACT CONSERVATION LAWS IN THE INTERACTION OF PARTICLES

As long ago as 3–5 years the number of elementary particles was already more than 33. Among these, besides stable particles, there are spontaneously decaying particles with lifetimes from 10 min to 10^{-19} sec. Quite recently a number of short-lived particles (or states) have been discovered, with lifetimes of the order of 10^{-21}–10^{-23} sec. In this field not even the terminology is clear: should we call these particles elementary particles, or what is the criterion of elementariness? This lack of clarity has recently extended to the classical particles as well: are the proton and neutron elementary? (this is briefly discussed in Sec. 14).

Even from aesthetic considerations, which play a large part in the development of theoretical physics (by the "beauty" of a theory one means essentially the manifestation of the unity of nature), there is a need for the formulation of some small number of fundamental laws for the interconversions of particles.

The number of laws must be much smaller than the large number we have given for the number of particles to which the laws relate. We begin with an exposition of the laws, and not with a table of the particles.*

1. Law of conservation of electric charge. This law is already formulated in classical physics as a relation between the charge density and the current. The law of conservation of charge was long ago (since the time of Lorentz) formulated in atomic language as a consequence of the indestructibility of electrons and protons—the only carriers of charge then known.

We now know of a large number of different types of particles which undergo interconversions. The law of conservation of electric charge is valid for any elementary act of interconversion.

2. Law of conservation of nuclear charge (baryon number). One can assign to each particle a baryon number, which is 1 for nucleons (proton and neutron) and hyperons (Λ, Σ, Ξ), and is 0 for mesons (π, K) and leptons (μ, e, ν). Experiment shows that in all processes that have been studied the baryon number is conserved, i.e., the sum of the baryon numbers is the same before and after a process.

Can we extrapolate the experimental result to energy ranges not yet investigated, or can we expect that there may be failures of this conservation?

Quantum mechanics comes to our help with the idea of "tunnelling" through barriers and of the uncertainty of energy: if the nuclear charge were not conserved at some extremely high energy, then as a low-probability "tunnel" effect it would also fail to be conserved in ordinary nuclei. The stability of nuclei indirectly proves the universality of the law of conservation of nuclear charge.

The conservation of baryon charge is of decisive importance for the general energy balance of the universe and the stars. In the nuclear processes in stars there is transmutation of hydrogen into helium, carbon, oxygen, iron. The energy released equals the product of the square of the speed of light and the mass defect—that is, the difference between the atomic weight of hydrogen, A = 1.008 and the ratio of the atomic weight of the product nucleus (or more exactly, atom) (He, C, O, Fe) to the number of nucleons it contains:

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*This article was developed from an introductory lecture given at the astrophysical summer school in Tartu.

*A table of particles is given later, in Sec. 16; a table of shortlived particles is given in Sec. 14.

$$\frac{4.0039}{4} = 1.000975 \quad \text{for } He_4,$$
$$\frac{16.000}{16} = 1{,}000 \quad \text{for } O_{16},$$
$$\frac{55.9568}{56} = 0.999228 \quad \text{for } Fe_{56}.$$

Thus the energy released is less than $0.01\ Mc^2$. The impossibility of the complete annihilation of ordinary matter (hydrogen, iron, etc.) with the release of the total Mc^2 depends precisely on the conservation of nuclear charge. This is why it is so important that this law is not violated even under the most unusual conditions, in particular in stars.

3. Conservation of the leptonic charge. As is well known, in β decay the production of an electron is accompanied by that of an antineutrino $\tilde{\nu}$, $n \to p + e^- + \tilde{\nu}$. The two preceding laws do not forbid a process which would give $2p \to 2n + 2e^+$, but it is not observed, just as the analogous process $K^+ \to \pi^- + 2e^+$ is not observed. Therefore it is natural to suppose that there is still another conservation law with $l = +1$ assigned to e^-, μ^-, ν, $l = -1$ to e^+, μ^+, $\tilde{\nu}$, and $l = 0$ to other particles (Zel'dovich,[4] Konopinski and Mahmoud,[5] Marx[6]). Then the $\mu \to e$ decay goes by the scheme $\mu \to e^- + \nu + \tilde{\nu}$. Thus the conservation of l-charge does not forbid $\mu^- \to e^-$ (with transfer of part of the momentum and energy to a nucleus near which the μ^- decays, or to a γ-ray quantum).

Since $\mu^- \to e^-$ does not occur experimentally (just as the process $\mu^- \to 2e^- + e^+$ does not occur[77]), the presumption arose (Pontecorvo,[7] Lee and Yang,[8] Lipmanov[9])* that there are really two conservation laws, and accordingly, two kinds of ν's and $\tilde{\nu}$'s. Then there is one number, the electron leptonic charge l_e, with $l_e = +1$ for e^-, ν_e, $l_e = -1$ for e^+, $\tilde{\nu}_e$, and $l_e = 0$ for other particles, including $\mu^\pm$, ν_μ, $\tilde{\nu}_\mu$, and another number, the muon leptonic charge $l_\mu = +1$ for μ^-, ν_μ, $l_\mu = -1$ for μ^+, $\tilde{\nu}_\mu$, and $l_\mu = 0$ for other particles.

Then in reactions producing ν or $\tilde{\nu}$ one must specify which ν (i.e., ν_μ or ν_e) is produced. For example, $\mu^- \to e^- + \nu_\mu + \tilde{\nu}_e$, and $\mu^- \to e^-$ is impossible. Further possible reactions are

$$\pi^- \to \mu^- + \tilde{\nu}_\mu, \tag{1}$$

$$\tilde{\nu}_\mu + p \to n + \mu^+, \tag{2}$$

but the reaction

$$\tilde{\nu}_\mu + p \nRightarrow n + e^+ \tag{3}$$

is impossible.

At the Geneva conference on high-energy physics (July, 1962) work done by a group of American authors was reported. They had observed 50 cases in which neutrinos from reaction (1) produced reaction (2) in their chamber, without finding any case of reaction (3).

If there were not two separate conservation laws for l_e and l_μ, then reaction (3) would be easier energetically, and one should observe more cases of (3) than of (2). Thus it was proved that there exist two different types of neutrinos (see the published paper[78]).

A detailed review of experimental work on neutrinos in the preceding period was published recently in UFN.[10]

3. ANTIPARTICLES

In formulating the conservation laws we have mentioned pairs of particles with opposite charges. This experimental fact forms one of the principles of present-day physics.

All the laws are invariant under charge conjugation, which is simultaneous change of the signs of all charges. This means that to each particle with a given set of four numbers, the electric charge Z, the nuclear charge n, and the leptonic charges l_e and l_μ, there corresponds another particle with the opposite signs of all four of these numbers. The masses, angular momenta, lifetimes (if they are unstable), and so on, of these two particles are exactly equal.

We emphasize that only the simultaneous change of the signs of the 4 numbers leads to an antiparticle; we shall give an example in which this condition is not satisfied:

$$\begin{gathered}\Sigma^+ \text{ has } Z = 1,\ n = 1,\ l_e = l_\mu = 0;\\ \Sigma^- \text{ has } Z = -1,\ n = 1,\ l_e = l_\mu = 0;\\ M(\Sigma^+) = 1189.4 \text{ MeV},\ M(\Sigma^-) = 1196 \text{ MeV},\\ t(\Sigma^+) = 0.8 \cdot 10^{-10} \text{ sec},\ t(\Sigma^-) = 1.7 \cdot 10^{-10} \text{ sec},\end{gathered}$$

and therefore Σ^+ and Σ^- are not a "particle-antiparticle" pair. The antiparticle of Σ^+ is $\tilde{\Sigma}^+$ with $Z = -1$, $n = -1$, $l_e = l_\mu = 0$.

Here the electric charge of $\tilde{\Sigma}^+$ is the same as that of Σ^-, but

$$m(\tilde{\Sigma}^+) = 1189.4 \equiv m(\Sigma^+) \neq m(\Sigma^-).$$

The main difference between $\tilde{\Sigma}^+$ and Σ^- appears in the behavior in interaction with ordinary matter: the system $\tilde{\Sigma}^+ + p$ has baryonic charge 0 and therefore can change into mesons, but the system $\Sigma^- + p$ has baryonic charge 2 and therefore can only change into neutron + proton + mesons; for the second case the number and energy of the mesons are smaller than for the first case by a factor 10. A large release of energy in interaction with ordinary matter, which consists of baryons, is a general property of antibaryons.

Particles which have all four numbers equal to zero go over into themselves under charge conjugation—that is, they do not have to have antiparticles.

Examples of this are light quanta (quanta of the electromagnetic field), π^0 mesons, gravitons. The

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*See also the detailed listing of the literature in the experimental paper[78]. The special achievement of B. M. Pontecorvo was to point out a way to check the question experimentally.

number of such particles can change in a process without any change in the numbers or types of other particles; an example is the emission of a light quantum by an excited atom or nucleus. For a pair made up of a particle and an antiparticle the sum of the charges is zero. Therefore such pairs can always vanish by conversion into π^0's or photons, or simply with a change of the energy (temperature) of the medium.

Historically the principle of charge conjugation appeared already in the Dirac theory of relativistic electrons, where an important part was played by ideas about negative-energy levels filled up with particles obeying the Pauli principle. This view is hopelessly antiquated, however; there are also particle-antiparticle pairs which do not obey the Pauli principle, for example the bosons* π^+ and π^-. Therefore the old ideas about a background and holes must be abandoned. For more details about antiparticles and charge conjugation see the review [11].

4. CLASSIFICATION OF INTERACTIONS. STRANGENESS

Experiment shows that among processes allowed by the conservation laws one can distinguish a class of processes which go by strong interaction; in collisions these are characterized by cross sections of the order of the geometrical cross section, and in decays, by widths of the order of the particle mass (for the connection between width and decay probability see Sec. 14).

These processes occur only in the group consisting of the baryons and the π and K mesons. Not all conceivable processes in this group go in this way, however; we can introduce another number, the strangeness S, which is conserved in the strong interactions.

Roughly speaking, we can say that processes in which the laws of Sec. 3 hold but S changes, $\Delta S = \pm 1$, go with probabilities smaller by factors 10^{-10}—10^{-12}. The probabilities of processes with $\Delta S = \pm 2$ are evidently smaller by still another factor of this order. We write out the classification (the tilde on top denotes an antiparticle):

$S = 0$: $p, n, \tilde{p}, \tilde{n}, \pi^+, \pi^-, \pi^0$;
$S = -1$: $\Lambda, \Sigma^+, \Sigma^-, \Sigma^0, K^-, \tilde{K}^0$;
$S = -2$: Ξ^-, Ξ^0;
$S = +1$: $\tilde{\Lambda}, \tilde{\Sigma}^+, \tilde{\Sigma}^-, \tilde{\Sigma}^0, K^+, K^0$;
$S = +2$: $\tilde{\Xi}^-, \tilde{\Xi}^0$.

Therefore, for example, the process $\pi^- + p \rightarrow \Lambda + K^0$ is allowed in S (goes by strong interaction), but the process $\pi^- + p \rightarrow \Lambda + \pi^0$ is forbidden in S and in fact does not occur in collisions. The decay $\Lambda \rightarrow p + \pi^-$ is forbidden in S, and therefore the lifetime of Λ, of the order of 10^{-10} sec, corresponds to a width $\hbar/\tau \sim 10^{-5}$ eV $\sim 10^{-13} m_\pi c^2$. On the time scale of particles, 10^{-10} sec is an extraordinarily long time. The Ξ^- hyperon with $S = -2$ decays into $\Lambda + \pi^-$, in a process with $\Delta S = 1$, and then the Λ decays into $p + \pi^-$; there is a "cascade" of decays. Ξ is called the "cascade particle;" the direct decay $\Xi^- \rightarrow p + 2\pi^-$ with $\Delta S = +2$ is not observed.

Thus the first class of interactions is the strong interaction of heavy particles satisfying the condition of conservation of strangeness, $\Delta S = 0$. The second class of interactions is the weak interaction. The typical process involves 4 particles with spin $\frac{1}{2}$ (4 fermions) in a decay $A \rightarrow B + C + D$ or a reaction (in particular, a scattering) $A + B \rightarrow C + D$, for example $n \rightarrow p + e^- + \tilde{\nu}$ or $\tilde{\nu} + p \rightarrow n + e^+$ (both processes have been observed in the last ten years, see [10]). A characteristic of the strength of the interaction is the expression for the interaction energy density*

$$\Delta H\left(\frac{\text{erg}}{\text{cm}^2}\right) = g\Psi_A\Psi_B\Psi_C\Psi_D.$$

Since $\Psi^2 = \rho$ is the particle density (cm^{-3}) the dimensions of the product of four functions Ψ are cm^{-6}, and the dimensions of g are erg cm^3.

Using the energy unit Mc^2 *and the length unit* $\hbar/Mc$, where M is the nucleon mass, we find, using the experimental value of g,

$$g \sim 10^{-49}\ \text{erg-cm}^3 \sim 10^{-5} Mc^2 \left(\frac{\hbar}{Mc}\right)^3 = 10^{-5}\frac{\hbar^3}{M^2c}.$$

The number 10^{-5} is a dimensionless characteristic of the weak interaction.

An interaction of the type of $\pi^+ \rightarrow \mu^+ + \nu$ can be reduced to the 4-fermion type if we assume that it goes in two stages, one of them by the strong interaction: $\pi^+ \rightarrow p + \tilde{n} \rightarrow \mu^+ + \nu$.

It then turns out that the same universal constant g satisfactorily characterizes both processes involving neutrinos and those processes involving strongly interacting particles in which $\Delta S = 1$, for example, $\Lambda \rightarrow p + \pi^-$. The description of this process in terms of the 4-fermion mechanism is†

$$\Lambda \rightarrow p + \tilde{p} + n \begin{array}{l} \nearrow p + \pi^-, \\ \searrow n + \pi^0. \end{array}$$

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*Bosons are particles which obey Bose statistics. The classic example of a boson is the light quantum. The Pauli principle does not hold for such particles: a light wave of large amplitude represents a large number of light quanta which are in the same state.

*Some of the four wave functions occur as complex conjugates (the functions which correspond to particles produced in the process). This is of no importance for what follows.

†In intermediate states particles can have energy and momentum which do not satisfy the relation $E^2 - c^2p^2 = (Mc^2)^2$ that holds for freely moving particles; in popular terms we can say that in intermediate states which last a short time the energy is indeterminate, not conserved, although it is exactly the same for the left and right members, i.e., for the initial and final states.

Instead of saying that the interaction constants are equal, we can in a cruder way formulate the following rule applying to the decays of particles. The probability of decay of a particle owing to weak interaction, with transition into one quantum state of the decay products, is the same in order of magnitude for all weak interactions; the difference between the decay periods, for example of the neutron (10 min) and of the μ meson (2×10^{-6} sec), is caused by the difference in the decay energies; the larger the energy, the larger the number of individual states (the "phase volume") for the decay products.

5. THE THREE-PARTICLE MODEL

The rule $\Delta S = 0$ in strong interactions and the two exact conservation laws of strongly interacting particles can be interpreted intuitively in this model: there are three types of fundamental particles, and all elementary particles are built from these fundamental ones (and their antiparticles) as molecules are built from atoms. An example: p, n, and Λ are fundamental, and the other particles, such as π^+, $\widetilde{K}^0$, Σ^+, Ξ^-, are constructed from them in the following way:

$$\pi^+ = (p, \widetilde{n}), \quad \widetilde{K}^0 = (\Lambda, \widetilde{n}), \quad \Sigma^+ = (p, \Lambda, \widetilde{n}), \quad \Xi^- = (\Lambda, \Lambda, \widetilde{p}).$$

This scheme was proposed in 1948 by Fermi and Yang (U.S.A.)[12] with p and n as the basis, and later, after the discovery of strange particles, was developed by the Japanese Sakata with Λ included[13]. Similar ideas were put forward by M. A. Markov[14]; an important contribution to the development of the Sakata scheme and its comparison with experiment is due to L. B. Okun'.[1,15]

In this scheme the "strangeness" S of a system is simply the negative of the number of Λ particles involved in its composition; for example, $S = -2$ for Ξ^-, in accordance with the expression given above. Antiparticles are counted with the opposite signs, so that the strangeness of K^+, which is represented as $(p, \widetilde{\Lambda})$ is $S = +1$.

The conservation of strangeness in strong interactions simply means that Λ particles are conserved —that is, the algebraic number of such particles is conserved (with the minus sign for Λ and plus for $\widetilde{\Lambda}$).

The electric charge is the number of protons, and in this scheme the conservation of charge is simply the conservation of protons.

The baryon number is the sum of the numbers of Λ's, p's, and n's. Therefore the conservation of the number of neutrons n together with the conservation of Λ's and p's secures the conservation of the baryon number.

The additional assumption that all properties of p and n are entirely analogous (unlike those of Λ) leads to the conception if isotopic invariance; a consequence of this assumption is the experimentally observed identity of the properties of the three π mesons π^+, π^-, π^0, of the properties of the three Σ particles, and of those of the two Ξ particles. In other words, the particles are divided into groups, the so-called isotopic multiplets.

The identity of properties is true of the masses of the particles (see Table II in Sec. 16) and of their properties in the strong interaction.

We should not be discouraged by the difference between the decay times of the particles of a multiplet, since the decay depends on the weak and electromagnetic interactions. It is clear that p and n are similar only with respect to nuclear forces, but by no means so with respect to electromagnetic properties (and also not with respect to the weak interaction). The electromagnetic interaction also produces a small difference between the masses of the particles in a multiplet.

The Fermi-Yang-Sakata-Okun' scheme enables us to understand the conservation of strangeness intuitively. It made possible, for example, the prediction[16] of the decay through the reaction $\pi^+ \rightarrow \pi^0 + e^+ + \nu$, recently detected in Dubna.[17] Let us write this decay as $(P\widetilde{N}) \rightarrow (N\widetilde{N}) + e^+ + \nu$. It can be seen from this that the process can be regarded as the β decay of a bound proton, i.e., as a different form of the β decay observed in nuclei. At the Geneva conference there were reports on the experiments of Prokoshkin and his collaborators, and also on work done at CERN,* which confirmed the theoretical value of the decay probability. In the domain of weak interactions the Sakata-Okun' scheme gives a large number of predictions which are confirmed by experiment (concerning its difficulties see below, end of Section 13).

At the same time, since there does not exist any quantitative theory to describe the combinations of the fundamental particles (the "fundamentons" p, n, Λ) into the observed elementary particles, predictions as to the masses of the particles and as to which "compounds" will exist remain beyond the scope of the theory, and these facts are taken from experiment. The actual choice of three fundamentons is not unique; one can, for example, put everything together from Ξ^-, Ξ^0, Λ, and their antiparticles, cf. [18]. Only the number three, equal to the number of conservation laws (electric, nuclear, strangeness) is firmly established.

The conservation laws are then formulated as the principle that particles are produced or annihilated only in the form of pairs, "particle + corresponding antiparticle."

We note, finally, that in the three-particle concept only fermions with spin $\frac{1}{2}$ are fundamental particles. The mesons π and K with spin 0, being bosons, are compound particles. The three-particle concept relates only to the strong interactions. In processes

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*The European Center for Nuclear Research, Geneva. Staff members of the Joint Institute for Nuclear Research also took part in this work (cf. [79]).

which go by the weak interaction it is possible for one type of fundamental particle to be converted into another ($\Lambda \rightarrow n$). Photons and leptons are not considered at all in the Sakata-Okun' theory. This wise restriction to strongly interacting particles distinguishes the three-particle theory from a multitude of fruitless and baseless attempts to describe photons as neutrino-antineutrino pairs, and the like.

6. THE ELECTROMAGNETIC INTERACTION

The school doctrine of the electromagnetic field as the source of a force acting on charges is elevated into a principle. It is called the principle of "minimal" or "most economical" electromagnetic interaction, and states that the electromagnetic field affects only the motions of particles, but does not cause conversions of particles into other particles.

Only one stipulation is needed here: the production (or destruction) of a pair, particle + antiparticle, is everywhere in modern theory equated to a change of motion of a single particle, and treated just like the transition of a particle from one state to another. Therefore the direct production of pairs by the electromagnetic field is not prohibited when it is a matter of a legitimate pair e^+e^- or $p\tilde{p}$, but is forbidden for mixed pairs $e^+\mu^-$ or $n\tilde{\Lambda}$.

There are cases in which the transmutation of particles is accompanied by the emission of γ-ray quanta. Examples are $\Sigma^0 \rightarrow \Lambda^0 + \gamma$, or $\pi^0 \rightarrow 2\gamma$, or the unobserved though possible process $\Lambda^0 \rightarrow n + \gamma$. In these cases *we postulate that the transmutation is the result of the action of a strong or weak interaction along with the electromagnetic interaction.*

In the examples given one can imagine chains such as

$$\Sigma^0 = \Lambda^0 + \pi^- + \pi^+ = \Lambda^0 + \pi^- + \pi^{+\prime} + \gamma = \Lambda^0 + \gamma.$$

Here the first step goes by the strong interaction. The second step is merely a change of the motion of the π^+ meson (as indicated by the prime) on account of the electromagnetic interaction; the third step is again the strong interaction.

The decay of π^0 was predicted by Oppenheimer according to the chain

$$\pi^0 = p + \tilde{p} = p' + \gamma_1 + \tilde{p} = \gamma_1 + \gamma_2.$$

Again the first step is the strong interaction; the second (change of motion of the proton) and third (annihilation of a proton-antiproton pair) are electromagnetic interactions. Similarly we can write

$$\Lambda^0 = p + \pi^- = p + \pi^{-\prime} + \gamma = n + \gamma.$$

Here the first step is weak interaction, the second, electromagnetic, and the third, strong interaction.

The mathematical realization of the minimal interaction is as follows: in the equations of motion the momentum p is replaced by $p - (e/c)A$, where A is the vector potential of the electromagnetic field. Another formulation of this is: the energy of interaction of particles with the field is given by the expression $-Aj$, the scalar product of the vector potential of the electromagnetic field and the electric current vector. Both vectors are four-dimensional, so that the expression includes the A_4j_4 of the fourth components, i.e., of the electrostatic potential φ and the charge density ρ, or the electrostatic energy.

In quantum mechanics the current vector j is given by the expression

$$j = e[(\Psi_1^*, \Psi_1) + (\Psi_2^*, \Psi_2) + \ldots],$$

where $\Psi_1, \Psi_2, \ldots$ are the wave functions of positively charged particles (proton, positron, etc.). Each parenthesis contains the functions of one particular particle (and also of its antiparticle); Ψ_1 and Ψ_2 are not intermixed. This expresses the fact that the electromagnetic interaction causes only changes of motion, not transmutation of particles.

Interactions of the field with neutral particles are observed experimentally; an example is the magnetic moment of the neutron. As V. V. Vladimirskiĭ[19] has pointed out, one can even devise a magnetic field distribution in which slow neutrons are trapped and cannot get out of a definite region!

From the point of view of the principle of minimal interaction the field acts on neutral particles only through the inclusion of a strong or weak interaction; for example, a scheme for the neutron is

$$n = p + \pi^- = p + \pi^{-\prime} + \gamma = n' + \gamma.$$

We can only mention here that in principle the weak interaction can give a new type of electromagnetic properties of a particle[20-22]; on account of weak interaction *even the neutrino acquires some electromagnetic properties.*[23] The weak-interaction effects are extremely small, however, and are far beyond the range of experimental observability.*

7. CONSERVATION OF CHARGE AND THE ELECTROMAGNETIC INTERACTION

The electromagnetic interaction can be connected in a very orderly way with the conservation of electric charge.

We shall multiply the wave function which describes the creation of a particle with the charge Z by $e^{i\alpha Z}$, where α is a real number. The adjoint function, which describes the annihilation of such a particle, is then multiplied by $e^{-i\alpha Z}$.

An expression made up of several functions will not depend on α if the sums of the charges of the created and annihilated particles are equal, i.e., if the expres-

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*For a discussion of the possibility that unstable particles have dipole moments on account of the weak interaction see [21], [80], [81].

sion describes a process which is allowed under charge conservation.

Here the charge Z_k appears as an integer $(+1, 0,$ or $-1)$ ascribed to the k-th particle; multiplication of Ψ_k by $e^{i\alpha Z_k}$ is a simple way to count up the charges of all the particles in a given process.

An important step is to generalize the idea of independence of α to the case $\alpha = \alpha(\mathbf{x})$. Since the theory involves derivatives of the Ψ function, terms of the form

$$\frac{\partial}{\partial x}\Psi \to \frac{\partial}{\partial x}\Psi e^{i\alpha Z} \to e^{i\alpha Z}\frac{\partial\Psi}{\partial x} + e^{i\alpha Z}\Psi iZ\frac{\partial\alpha}{\partial x}$$

appear.

Since in quantum theory derivatives with respect to the coordinates play the role of momentum, this means that the multiplication by $e^{i\alpha Z}$ brings in instead of the momentum p the combination

$$\mathbf{p} + Z\,\mathrm{grad}\,\alpha.$$

In order to compensate the additional term it is necessary that a potential **A** exist. In all this we are concerned with four-dimensional vectors and gradients; **p** is the momentum four-vector, whose fourth component is the energy, and **x** includes the three space coordinates and the time.

A theory which from the beginning contains instead of **p** the combination

$$\mathbf{p} - Z\mathbf{A},$$

is invariant with respect to multiplication of Ψ by $e^{iZ\alpha(\mathbf{x})}$, provided that at the same time one makes the transformation

$$e\mathbf{A}' = e\mathbf{A} + \mathrm{grad}\,\alpha.$$

But a theory which involves $\mathbf{p} - eZ\mathbf{A}$ is just the theory of the motion of a particle of charge Z in an electromagnetic field with the four-potential **A**. In such a theory the term $eZ\mathbf{A}$, which acts on the particle along with the momentum operator, describes the action of the field on the particle. The important point is that this interaction is exactly proportional to the constant Z —the charge, that is, the number which appears in the conservation law.

The conservation law was at first formulated purely arithmetically, as a counting up of certain numbers before and after a reaction, which could as a rule be done on the fingers of one hand. Now we have been able to modify the theory so that these numbers play the role of charges in the sense of interaction with the field.

The theory must also contain a statement (the Lagrangian) of the properties of the free electric field. The condition of invariance under the substitution

$$e\mathbf{A} \to e\mathbf{A} + \mathrm{grad}\,\alpha$$

imposes the requirement that the physically observable quantities are not the potentials **A**, but the fields

$$F_{\mu\nu} = \frac{\partial A_\mu}{\partial x^\nu} - \frac{\partial A_\nu}{\partial x^\mu};$$

then obviously the replacement of A_μ by $A_\mu - \partial\alpha/\partial x_\mu$ makes no change of the fields $F_{\mu\nu}$. The absence of **A** itself in the free-field Lagrangian means that the electromagnetic field has quanta of mass zero.

Thus the broadened requirement of invariance under $\Psi \to e^{iZ\alpha}\Psi$ with $\alpha = \alpha(\mathbf{x}, t)$ leads to the concept of the electromagnetic field with all of its properties—Coulomb's law, conservation of charge, zero mass of the quanta, and so on.*

8. INTERACTION OF BARYONS

The question naturally arises whether there exist fields corresponding to the other conservation laws for particles—to the nuclear charge (Yang and Lee[25]) and the lepton numbers l_e, l_μ.

By analogy it is clear that such a field will lead to an interaction of the type of Coulomb's law. In addition to the universal attraction proportional to m_1m_2/r_{12}^2 there will be a repulsion proportional to N_1N_2/r_{12}^2, where N_1 and N_2 are the numbers of nucleons in the two bodies with the masses m_1 and m_2. But the experiments of Eötvös, repeated in 1961 by Dicke,[26] indicate that there are no corrections to Newton's law. At the same time, the values of m for different substances are not exactly proportional to N because of the different mass defects. The accuracy of the experiments is much greater than the deviations of m/N from a constant value. Thus experiment disproves an interaction of the form N_1N_2/r_{12}^2, or, more exactly, limits the interaction of nucleons with the hypothetical field to an amount smaller by a factor 10^{-15} than the electromagnetic charge e.†

The suggestion has been made (Kobzarev and Okun'[27]‡) that the hypothetical field differs from the electromagnetic field by having quanta with a rest mass, so-called vectons. In this case the difficulty with the long-range force of nucleons disappears; the law is

$$\frac{N_1N_2}{r^2}e^{-\frac{\mu cr}{\hbar}},$$

where μ is the mass of the vecton. The interaction vanishes at macroscopic distances at which it might be detected by experiments of the Eötvös type. On the other hand, we lose the invariance of the theory under the substitution

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*This theory and its development are treated in detail in a review article by Adamskiĭ,[24] which also gives references to the original literature.

†Some curious cosmological objections to the existence of such a field have been put forward by Dicke.[82]

‡See also a survey[78], a paper[83] by Sakurai, and a paper by Fujii.[84]

$$\Psi \to \Psi e^{ina(x,\,t)},$$

which would connect the theory of the field with the conservation of the particles, and there remains only an analogy with this sort of theory.

But then why is a theory of vectons which have mass and interact strongly with baryons attractive? This theory precisely completes the three-particle scheme. In fact, at small distances, $r < \hbar/\mu c$, the vectons function qualitatively like the electromagnetic field, giving an attraction of unlike particles and a repulsion of like particles.

An attraction between baryons and antibaryons is just what is needed in the three-particle scheme to hold mesons together: for example, if $\pi^+ = p + n$, this presupposes that proton and antineutron attract each other with an enormous force. A measure for it is the binding energy, i.e., the mass defect. The masses are $m_p = 1836 m_e$, $m_n = 1838 m_e$, but they combine to give a π^+ with mass $273 m_e$, so that the difference $1836 + 1838 - 273 = 3401$ is released as binding energy!

An analogous combination is $p + \widetilde{\Lambda} = K^+$ with almost the same amount of energy released. Vectons cause a repulsion of like particles; in fact, experiments on the scattering of protons and neutrons at high energies show that there is evidently a strong repulsion at the smallest distances. In the literature this effect has received the name "hard core"—a hard, rigid, impenetrable center or shell.*

The well known attractive nuclear forces, which cause the very existence and stability of complex nuclei, are much weaker than the repulsive vecton forces (potentials of $30-80\, m_e c^2$), but act at larger distances. Nuclear forces and the existence of nuclei do not contradict the vecton theory; from the vecton point of view they are small higher-order corrections, since the nuclear forces are carried by mesons, which are themselves compound structures.

We emphasize in conclusion that with all its qualitative attractiveness the vecton theory not only is not experimentally proved, but can hardly be formulated quantitatively, since it is concerned with the theory of the strong interaction, whose very structure is still not clear.

9. THEORY OF THE NEUTRINO

A remarkable property of the neutrino is its zero rest mass; a consequence is that ν is always emitted with the speed of light—its speed is c in any coordinate system.

Light quanta have the same property; in this case the classical Maxwell theory automatically makes the rest mass identically zero, since the theory provides for the existence of radio waves with arbitrarily small frequency.

Neutrinos have spin $\frac{1}{2}$ and obey the Pauli principle and Fermi statistics. A theory for such particles with zero mass was proposed by Weyl soon after the development of the Dirac relativistic electron theory, but remained obscure until 1957. The neutrino is described by a two-component wave function φ and satisfies the equation

$$E\varphi = i\hbar \frac{\partial \varphi}{\partial t} = -c(\sigma, p)\varphi,$$

where σ_x, σ_y, σ_z are the well known Pauli spin matrices, and p is the momentum operator, expressed as usual in terms of differentiations with respect to the coordinates.

This equation gives identically $E = c|p|$, i.e., it describes a particle moving with the speed of light and having zero rest mass.

In addition, the spin of the particle is $\frac{1}{2}$ and is necessarily directed opposite to the momentum vector ("left-handed particle"). This is the peculiarity of the theory. The assertion that the spin is directed opposite to the momentum can be made only for a particle moving with the speed of light. If the particle were moving more slowly, then in a coordinate system overtaking the particle the direction of the momentum would change its sense while the spin stayed the same, and the relation between the directions of spin and momentum would be broken. Thus the property "spin opposite to momentum" is closely connected with the zero mass.*

On the other hand, the spin corresponds to a rotation, and the "direction" of the spin is a convention connected with the choice of a right-handed coordinate system, in which counterclockwise rotation is taken as positive. The rigorous formulation of this is that spin is an axial vector, in contradistinction to the polar vector of momentum.

The property "spin opposite to momentum" is destroyed by the change from a right-handed coordinate system to a left-handed system, i.e., by inversion of the coordinate system. Therefore in the period when there was no doubt of parity conservation—that is, of the invariance of all the laws of physics under inversion—this theory of the neutrino was not taken seriously.

When, however, parity nonconservation in weak interactions was discovered,[30] Landau[31] at once suggested that the neutrino be regarded as a two-

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*For an interaction potential of two nucleons which gives a good description of the observations and includes a repulsion at small distances, see, for example,[28]. For deductions from the strong vector interaction relating to the equation of state of extremely dense nuclear matter (baryons), see [29].

*One consequence of this property of the neutrino is the 100 percent complete polarization of μ mesons produced in the decay $\pi^+ \to \mu^+ + \nu$, since the spin of the π^+ is zero and the spin of the μ must exactly balance that of the ν. Alikhanov, Eliseev, Lyubimov, and others[85] have measured the direction of the spins of μ mesons in cosmic rays and thus determined the direction of the neutrino spin.

component particle, thus connecting its role in beta decay (see Sec. 11) and its zero mass.* This theory includes the assertion that the antineutrino is "right-handed," with its spin directed with the momentum.

As is well known, according to Landau[34] the laws of physics are not invariant under inversion, but are invariant under simultaneous space inversion and charge conjugation, or change from particles to antiparticles; this joint transformation is called "combined inversion." An example of inversion is reflection in a mirror; according to a story announced at the celebration of Landau's fiftieth birthday, the idea came to him at the sight of a girl turning in front of a mirror.

The idea of combined inversion has great general significance in physics; it reconciles the nonconservation of parity and the predominance of one direction of rotation in nuclear beta decay with the complete symmetry of vacuum, the symmetry of physical space with respect to right and left, since the vacuum is symmetrical with respect to particles and antiparticles.

10. FERMIONS WITH MASS

The Dirac equation of a particle with mass m requires that the function Ψ have four components. It is well known that it can be written in terms of two two-component functions φ and χ, so that under Lorentz transformations (without inversion!) the transformed function φ' is expressed in terms of φ, and χ' in terms of χ—that is, they are not mixed together.

The Dirac equation is of the form

$$E\varphi = -c(\sigma, \mathbf{p})\varphi + mc^2\chi,$$
$$E\chi = c(\sigma, \mathbf{p})\chi + mc^2\varphi.$$

This form is extremely remarkable. It can be interpreted as follows: there are right-handed (χ) and left-handed (φ) particles, which can be converted into each other. Furthermore (χ) and (φ) are not particle and antiparticle, but two kinds of particle with the same charge, for example right-handed negative electrons and left-handed negative electrons. Their interconversion is described by the last term of each equation, which is proportional to the mass—that is, the mass plays the part of an interaction constant, a conversion probability.

Without this interconversion the system of equations would fall apart into two independent equations describing two kinds of particles moving with the speed of light. For $m \neq 0$ the system has solutions corresponding to the motion of a particle with mass m, and we have

$$E^2 = c^2p^2 + (mc^2)^2.$$

In a popular way we can say that a particle with mass m and a given spin direction* s which moves in the direction s with the speed v less than the speed of light is a superposition of two states: χ, with the speed of motion c along the spin and φ, with the speed of motion c opposite to the spin. If the particle moves parallel to the spin, then in the superposition the probability for finding the particle in the state χ is larger than that for finding it in the state φ. This picture corresponds to a paradox known since the 1930's: in the Dirac equation the absolute value of an eigenvalue of the speed is c, and a motion with average speed not equal to c must be described as a "trembling" of the particle, with a speed which at each instant has absolute value c but which changes direction frequently (the "Zitterbewegung," in Schrödinger's phrase).

The splitting of the writing of Ψ into (φ, χ) does not bring anything really new into the well known Dirac theory.

There is some pedagogical and methodological advantage for the treatment of processes involving fast electrons (their production or scattering) with $E \gg mc^2$: In this case we can regard mc^2/E as a small parameter. In zeroth approximation in this parameter we find, for example, that a φ-electron remains a φ-electron during scattering (we neglect m, i.e., the conversion of φ into χ), so that it is seen at once that longitudinal polarization is preserved in scattering, the spin turning together with the turning of the momentum vector (Yennie, Ravenhall, and Wilson[35]).

This idea has recently been developed in [36,37]. In particular, in dealing with the problem of the mass of a particle a very useful formulation is the "converse theorem" to the statement made above. The mass can be regarded as a constant which characterizes the probability of conversion of right-handed into left-handed particles, and conversely.* Consequently only those interactions of a particle with various fields which can lead to conversion of a right-handed into a left-handed particle can alter the mass of the particle. From this one can get very strong restrictions on the possibility of an interaction's affecting the mass.[39]

The most important heuristic significance of this concept, however, is in connection with the theory of the weak interaction.

11. WEAK INTERACTION. BETA DECAY

Experiment shows that the interaction expression on which weak processes depend involves only "left-handed" two-component functions of the particles p, n, ν, e^- in the case of β decay:

$$H_{\text{int}} = (\varphi_p^*\varphi_n\varphi_e^*\varphi_\nu) + \text{comp. conj}.$$

For the neutrino this is trivial, since it is postulated that there exists in nature only the left-handed neutrino with the function φ_ν. For the other par-

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*The same idea was put forward independently by Salam[32] and by Lee and Yang.[33]

*Here the vectors are three-dimensional!

†See also a remark in an article by B. M. Pontecorvo.[38]

ticles, however, which have mass, this unexpectedly leads to important consequences, and in particular shows the deep meaning of the separation of the four-component function Ψ into two two-component functions φ and χ.

The expression H_{int} must be a relativistic invariant; from a pair of adjoint "left-handed" functions $\varphi^*\varphi$ one can make only a four-vector (but not a scalar and not a tensor of the second rank). Therefore without losing generality we can represent H as the scalar product of two four-vectors, each of which is formed from two functions:

$$H=(\varphi_1^*\varphi_2)_\alpha(\varphi_3^*\varphi_4)_\alpha+\text{ comp. conj.}$$

The index α runs through four values, corresponding to the time and the three space coordinates. The sum over α is taken. The components of the vector are formed from the wave functions by means of the well known Pauli matrices σ_x, σ_y, σ_z and the unit matrix I:

$$(\varphi_1^*\varphi_2)_0=(\varphi_1^*\,\mathrm{I}\,\varphi_2),\ \ (\varphi_1^*\varphi_2)_x=(\varphi_1^*\sigma_x\varphi_2),$$

$$H=(\varphi_1^*\,\mathrm{I}\,\varphi_2)_0(\varphi_3^*\,\mathrm{I}\,\varphi_4)_0-(\varphi_1^*\sigma_x\varphi_2)(\varphi_3^*\sigma_x\varphi_4)-(\varphi_1^*\sigma_y\varphi_2)(\varphi_3^*\sigma_y\varphi_4)$$
$$-(\varphi_1^*\sigma_z\varphi_2)(\varphi_3^*\sigma_z\varphi_4).$$

In principle one can group the particles in pairs in any way in treating one process; that the H formed from four φ functions is symmetrical under interchanges of these functions is a consequence of the relativistic invariance of H. Let us divide the four functions into the pair of functions describing the heavy particles and the pair for the leptons:

$$H=g\,(\varphi_p^*\varphi_n)_\alpha(\varphi_e^*\varphi_\nu)_\alpha+\text{ comp. conj.}$$

The expression for H contains complete information about the β process. After it had been proposed[40] by Gell-Mann and Feynman* (in spite of some discrepancies with the supposed experimental facts), and after the experimenters had been shown what the results ought to be, they straightened matters out and found excellent agreement with the theory.

The most important results can be found from the expression for H without calculations:

1) Only φ appears in the expression. Consequently, relativistic electrons must be produced in β decay with $\varphi \gg \chi$, i.e., *they are produced as left-handed electrons with a strong longitudinal polarization* (calculation gives the degree of polarization equal to v/c) (see the experimental results[90]).

2) The expression involves left-handed functions for the nucleons and therefore describes nonconservation of parity in β decay, in particular the historic experiment of Wu on the effect of the orientation of the spin of the nucleus on the direction of emission of β rays.

3) In β decay we have to do with nucleons almost at rest—nonrelativistic particles. The expression for H consists of two parts: the product of the fourth (time) components and the products of the space (x, y, z) components.

It can be shown that the time component corresponds to conversion n → p without change of the spin direction, and the spacelike vector describes the process with reversal of the spin and transfer of angular momentum to the leptons. In other words, the β process goes both according to Fermi selection rules and according to Gamow-Teller rules.

An especially important possibility for astrophysics is that of the conversion of two protons which collide *with antiparallel spins into a deuteron* (*spins of* n *and* p *parallel*). According to the Pauli principle the spins must be antiparallel in order for the protons to approach each other closely.

We note that the strong interaction of the nucleons changes the coefficient of the product of the spacelike vectors, but the term $g(\varphi_p^*\varphi_n)_0(\varphi_e^*-\varphi_\nu)_0$ remains unchanged (Zel'dovich and Gershteĭn,[41] Gell-Mann and Feynman[40]). Therefore the experimental data enable us to determine the constant g in the original interaction ΔH, in spite of the fact that the strong interaction distorts its primeval beauty. We also note that this beauty is achieved through a definite choice of the "particles."

According to the Landau theory left-handed antiprotons correspond to right-handed protons. Therefore if we were to call $\tilde{p}$, $\tilde{n}$, ν, e^- the "particles," the expression for ΔH would have to be written

$$\Delta H=(\chi_{\tilde{n}}^*\chi_p)_\alpha(\varphi_{e^-}^*\varphi_{\tilde{\nu}})_\alpha,$$

and the symmetry of the four functions would disappear.

12. WEAK INTERACTION—UNIVERSALITY OF THE PRODUCT OF CURRENTS

Besides β decay there are other processes which belong to the weak interaction. The one most studied is the decay of the mu meson. It is described by:

$$\Delta H=g\,(\varphi_{\nu_\mu}^*\varphi_{\mu^-})_\alpha(\varphi_{e^-}^*\varphi_{\nu_e})_\alpha.$$

In accordance with the latest data (see Sec. 2) we distinguish two kinds of neutrinos; in the preceding section we should have written ν_e, but for simplicity did not do so. Owing to the absence of strong interactions of any of the particles in the mu decay, the expression for ΔH does not require any corrections; all of the conclusions drawn from it have been tested by experiment and have received complete quantitative confirmation.

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*Literally, the formulation of Gell-Mann and Feynman is a bit different; they work with a single two-component function which satisfies a second-order equation and thus replaces the four-component function Ψ. An independent, and perhaps somewhat earlier suggestion of the same expression, in a different formulation, was made by R. Marshak and E. Sudarshan.[86]

The constant g agrees with striking accuracy (2 to 3 percent) with the constant for β decay.* The μ-capture process $\mu^- + p \rightarrow n + \nu_\mu$ has also been investigated.

Here the agreement between experiment and theory is poorer (of the order of 20 percent),[88] but in any case the expression

$$\Delta H = g\,(\varphi_p^*\varphi_n)_\alpha\,(\varphi_{\mu^-}^*\varphi_{\nu_\mu})_\alpha + \text{comp. conj.}$$

with the same value of g as for β decay is not in contradiction with the available data.†

Finally, the observed decays of strange particles (hyperons and K mesons) can be reduced to the three interactions:

$$\Delta H = g_1\,(\varphi_p^*\varphi_\Lambda)_\alpha\,(\varphi_{e^-}^*\varphi_{\nu_e})_\alpha + \text{comp. conj.}$$
$$\Delta H = g_2\,(\varphi_p^*\varphi_\Lambda)_\alpha\,(\varphi_{\mu^-}^*\psi_{\nu_\mu})_\alpha + \text{comp. conj.}$$
$$\Delta H = g_3\,(\varphi_p^*\varphi_\Lambda)_\alpha\,(\varphi_n^*\varphi_p)_\alpha + \text{comp. conj.}$$

Here $g_1 = g_2$, but the value is much smaller than g; g_3 is of the order of g. In these last three reactions, however, which involve the strange particle Λ, there is no law that the observed constant is independent of the strong interaction. Therefore the fact that g_1, g_2, and g_3 differ from g has no great significance, whereas the agreement of the values of g for the first three reactions (β decay, μ decay, μ capture) is very remarkable.

How should one construct a theory so that the agreement of the values of g for β decay, μ decay, and μ capture will be natural? For this purpose Gell-Mann and Feynman suggest writing the interaction as the product of a "current"‡ and its complex conjugate:

$$\Delta H = gJJ^+,$$

where J is the four-vector

$$J_\alpha = (\varphi_p^*\varphi_n + \varphi_p^*\varphi_\Lambda + \varphi_{\nu_e}^*\varphi_{e^-} + \varphi_{\nu_\mu}^*\varphi_{\mu^-})_\alpha.$$

It is clear that this means that all of the four-fermion expressions corresponding to the various processes are automatically obtained with the same constant g.

After this one must add arguments showing that in the (p^*, n) terms one component does not depend on the strong interaction, and precisely this term is used for the experimental verification, whereas in (p^*, Λ) all the terms are changed on account of the strong interaction, so that $g_1 = g_2 \neq g_3$, and, finally, the term ($p^*\Lambda$)(np^*) can be especially strongly changed—and general agreement with experiment is achieved.

Starting with the purpose of explaining the equality of the constants for the three processes, we have obtained a multitude of new predictions. Expanding the product of currents, we get, in addition to the six experimentally observed interactions listed above, four new ones (we omit the symbol for wave function):

$$g\,(p^*n)\,(n^*p), \quad g\,(p^*\Lambda)\,(\Lambda^*p), \quad g\,(\mu^{-*}\nu_\mu)\,(\nu_\mu^*\mu^-),$$
$$g\,(e^{-*}\nu_e)\,(\nu_e^*e^-).$$

The first two give small corrections to the scattering of strongly interacting particles, and are therefore not of much physical importance. Nevertheless it may be relatively easy to detect them, since one can observe the first-order effect in g owing to the interference with the strong interaction, and distinguish it by the parity nonconservation. The last interaction can be of enormous astrophysical importance, as B. M. Pontecorvo has pointed out.[42]

This interaction leads not only to the scattering of neutrinos by electrons, but also to the emission of neutrino pairs by an electron:

$$e^- \rightarrow e^- + \nu_e + \tilde{\nu}_e.$$

Just like the emission of a photon by an electron, $e^- \rightarrow e^- + \gamma$, the process occurs only in the field of some third body; otherwise the laws of conservation of energy and momentum cannot be satisfied simultaneously. A calculation of this process has been made by G. M. Gandel'man and V. S. Pinaev.[43] Under certain conditions, at a temperature of the order of 5×10^7 degrees and a density of 10^4 g/cm^3, the neutrino luminosity of a star becomes larger than its optical luminosity, since along with the larger probability for emission of photons they also have a larger probability of absorption and scattering, and therefore only have a small probability of getting out of the star, whereas once produced a ν or $\tilde{\nu}$ carries its energy out of the star immediately and completely.*

Later other processes were suggested[45-49] which are consequences of the new interaction:

$$\gamma + e^- = \gamma + e^- + \nu + \tilde{\nu}, \qquad \gamma + \gamma = \nu + \tilde{\nu},$$

γ + Z (nucleus) → Z + ν + $\tilde{\nu}$, e^- + Z (nucleus) → (e^-Z, bound) + ν + $\tilde{\nu}$, and, finally, $e^- + e^+ \rightarrow \nu_e + \tilde{\nu}_e$.

The last process mentioned, unlike the others, goes directly by the weak interaction without the inclusion of any supplementary electromagnetic interaction. At thermal equilibrium at temperatures larger than m_ec^2 the number of e^+e^- pairs is of the order of the number of photons, and the last process is the most important.

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*For the latest measurements and a possible explanation of the 2-percent discrepancy see [87]; also see below, Sec. 15.

†This is also confirmed by very recent experiments in Dubna on the reaction $\mu^- + He^3 \rightarrow T + \nu_\mu$.[89]

‡Note the similarities and differences between this current and the current that appears in the electromagnetic interaction.

*The first to advance the idea that neutrinos can carry away ("steal") the energy of a star were Gamow and Schoenberg.[44] They considered a medium in which two processes occur at a high temperature: the decay of beta-radioactive nuclei and the production of such nuclei in the collisions of fast electrons with stable nuclei; in both cases a neutrino irreversibly carries away part of the energy. The probability of this process, which the authors called the "urca process," is proportional to $\exp(-Q/\Theta)$, where Q is the decay energy and Θ is the temperature. In most cases the processes considered in the text are stronger.

A detailed review of the astrophysically important subject of neutrino radiation is given in a report by V. S. Pinaev.[50]

13. UNSOLVED PROBLEMS OF THE THEORY OF THE WEAK INTERACTION

First of all let us emphasize again that the interaction $(e\nu)(\nu e)$, which is extremely important for astrophysics, cannot be regarded as rigorously proved either theoretically or experimentally; this interaction is only a consequence of an elegant, but not obligatory, way of writing the known interactions. It would be extremely important to prove the existence of such an interaction directly by an experiment of the same type as that of Reines and Cowan,[10] which detected the process $\tilde{\nu} + p \rightarrow n + e^+$ near a nuclear reactor.

The cross section and number of acts of scattering for $\tilde{\nu} + e^- \rightarrow \tilde{\nu} + e^-$ is not much smaller than for the reaction $\tilde{\nu} + p$, but the result of the process is much less specific.

The background of fast electrons from cosmic rays, from the natural radioactivity of the surroundings and of the apparatus itself, and so on, is much larger than the background of simultaneous appearances of a neutron and a positron. Therefore the experiment is extremely difficult.

Let us turn to the structure of the interaction as the product of two currents, JJ^+. These currents are "charged"; J contains, for example, (p^*n) (production of a proton and annihilation of a neutron), i.e., as an operator J increases the electric charge of the system by $+e$; this applies to all the terms in J. On the other hand, J^+ decreases the charge, so that JJ^+ leaves the charge unchanged, and JJ^+ corresponds to the allowed processes.

To describe the decay of strange particles it would be desirable to introduce in addition to the product of charged currents JJ^+ a product of neutral currents $J_0J_0^+$, where

$$J_0 = n^*\Lambda + n^*n - p^*p.$$

Then one would automatically get the correct ratio of the two channels $\Lambda \rightarrow p + \pi^-$ and $\Lambda \rightarrow n + \pi^0$ (the rule $\Delta T = 1/2$, where in the language of nuclear physics T is the isospin).* The introduction of neutral currents in complete analogy with the charged currents,

$$J_0 = n\Lambda^* + nn^* - p\rho^* + \mu_-^*\mu_- - \nu_\mu^*\nu_\mu + e_-^*e_- - \nu_e^*\nu_e,$$

is, however, clearly impossible; the product $J_0J_0^+$ would lead to a number of processes which are not observed experimentally, such as

$$K^+ = \pi^+ + \nu + \tilde{\nu}, \quad K^+ = e^+ + e^- + \pi^+.$$

Therefore the question as to the existence and structure of neutral currents remains an open one.

We note, finally, that the three-particle scheme *leads to definite restrictions on the decays of strange* particles, which have been pointed out by Okun'.[1,15] The primitive process is $\Lambda \rightarrow p + e^- + \nu$. Therefore the decay $\Sigma^- \rightarrow n + \tilde{p} + \Lambda \rightarrow n + \tilde{p} + p + e^- + \nu \rightarrow n + e^- + \nu$ is possible, but $\Sigma^+ \rightarrow n + e^+ + \nu$ is impossible (only $\Sigma^+ \rightarrow p + \tilde{n} + \Lambda \rightarrow p + \tilde{n} + p + e^- + \tilde{\nu} \rightarrow p + \pi^+ + e^- + \tilde{\nu}$ is possible).

In an analogous way the theory predicts that the decay $K^0 \rightarrow \Lambda + \tilde{n} \rightarrow p + e^- + \tilde{\nu} + \tilde{n} \rightarrow \pi^+ + e^- + \tilde{\nu}$ is possible, but the decay of K^0 to e^- is impossible.

Very recently there has appeared a report by Fry and co-workers[51] on the detection of the decay of $\tilde{K}^0$ to e^- (for a confirmation see [94]). One case of $\Sigma^+ \rightarrow n + \mu^+ + \nu$ has been observed (see [95]). All of this contradicts the three-particle scheme, or at least means that this scheme is useful only for the *enumeration of possible strong interactions*, as a substitute for the abstract concept of strangeness. As yet, however, the experiments are not sufficiently reliable, and the question remains an open one.

14. SUPERNEW PARTICLES AND THE NEW APPROACH TO PARTICLE THEORY

In the last two or three years a number of new *particles have been discovered with extremely short* lives, less than 10^{-20} sec. In such cases it is impossible to fix the track of the particle or even the distance from the place it is produced to the place it decays. The existence of these particles is established in a different way.

Let us consider the example of the discovery of the neutral particle ω, which decays into $\pi^+ + \pi^- + \pi^0$.[52]

The process $\tilde{p} + p \rightarrow 2\pi^+ + 2\pi^- + \pi^0$ is investigated. If all of the π mesons produced in the reaction are independent, they can have arbitrary relative velocities. Let us suppose that three of the five particles, $\pi^+ + \pi^- + \pi^0$, have been produced in two steps: first a new meson ω was produced, and then it decayed. We change to a coordinate system in which the center of mass of the three particles is at rest. In this system the ω meson which produced them was at rest. Thus in this coordinate system the energy of the three particles is exactly equal to the mass (rest energy) of the ω.

According to the theory of relativity we have in any reference system

$$E_{123} = \sqrt{(E_1 + E_2 + E_3)^2 - (\mathbf{p}_1 + \mathbf{p}_2 + \mathbf{p}_3)^2c^2} = M_\omega c^2.$$

For three independent particles E_{123} can have any value, but for the decay products it can only be equal to $M_\omega c^2$. Thus the "ω particle" gives a narrow line against the background of the continuous spectrum of E_{123}.

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*Recently the exact validity of the rule $\Delta T = 1/2$ in the decays of strange particles has been subjected to doubt (Geneva, 1962).

According to the uncertainty principle the lifetime of the particle is directly related to the width of the line. There is, however, also broadening of the line owing to instrumental causes (errors of measurement).

The observed width is of the order of the instrumental width, so that we can speak only of a lower limit on the lifetime; a width of about 10 MeV corresponds to a time of about

$$\tau=\frac{\hbar}{\Delta E}=\frac{10^{-27}}{10\cdot 1{,}6\cdot 10^{-6}}\approx 10^{-22}\ \text{sec}$$

or more exactly $\tau \geq 10^{-22}$ sec. On the other hand, ω is produced in more than 10 percent of the cases of the reaction. Therefore there is no doubt that ω is a particle which interacts strongly with pions, and its lifetime cannot be large. In this way a number of short-lived particles have been discovered. Before listing them, however, we shall expound the ideas which enable us to classify these particles.

Quite recently the outlines of a new approach to the theory of strongly interacting particles have appeared. We can explain the essence of this in a very simple way by using an analogy with ordinary quantum mechanics.

Let us think of a system of two particles—a hydrogen atom. Such a system must have a definite angular momentum (in units $\hbar$). The Schrödinger equation for the calculation of the energy contains in addition to the potential energy (in this case the Coulomb potential $u(r) = -e^2/r$) also the centrifugal potential $(\hbar^2/2m)\times l(l+1)/r^2$. The equation for the radial wave function is of the form

$$-\frac{\hbar^2}{2m}\frac{d^2\varphi}{dr^2}+\left[u(r)+\frac{\hbar^2}{2m}\frac{l(l+1)}{r^2}-E\right]\varphi=0.$$

Therefore states with different angular momenta also have different energies; by replacing $1/r^2$ by some average value $1/\bar{r}^2$ we find for two similar levels

$$E_1-E_2=\frac{\hbar^2}{2m\bar{r}^2}\{l_1(l_1+1)-l_2(l_2+1)\}.$$

Let us suppose that elementary particles (or at least the strongly interacting particles) are also some sort of "systems."

We do not know what these systems consist of, and there is no Schrödinger equation, but nevertheless it is assumed that the system can exist in states with different values of l, and that the larger l, the larger the energy. The order of magnitude of $\bar{r}$ can be regarded as known; experiment gives a reasonable value of about $\hbar/2m_\pi c$. One compares states with the same baryon charge and the same strangeness and isotopic spin. One does not worry about the fact the angular momenta (spins) of the particles are half-integral.

Thus the particles are divided into "families," and one introduces a sort of classification of the particles, or, if you prefer, of the states. For example, with the ordinary nucleons (neutron and proton) with spin $j = 1/2$, strangeness 0, and mass about 930 MeV one associates particles N^* with spin $j = 3/2$ and mass about 1512 MeV, and N^{**} with spin $5/2$ and mass 1688 MeV. Since the mass 1512 MeV is larger than the sum of the masses of a nucleon and a π meson, N^* is unstable and decays. Experimentally N^* manifests itself as a resonance in the scattering of π mesons by nucleons. The width of the resonance characterizes the lifetime of the particle; to the width 1 MeV there corresponds a time of the order of 10^{-21} (the time is inversely proportional to the width).

Table I shows the families of baryons. The headings give the general properties of the families and list the lower states. The entries in each cell give: 1) the spatial spin, 2) the mass in MeV, 3) the width in MeV. Particles which decay only by the weak or electromagnetic interaction are treated as stable (width 0).

The common isotopic spin for each line of the table means that all of the particles of the group can have the same charges; for example N^{**} can be neutral or positive, like the neutron and proton, Ξ^* can be neutral or negative, like Ξ, and so on. Besides the indicated baryons there are at present indications of the existence of the following mesons which decay by the strong interaction*;

Strangeness 0:	Strangeness 1:
$\xi(\xi^+, \xi^0, \xi^-)$: 0, 560	
η^0: 0, 550, < 12,	K^{+*}, K^{0*}: 1, 885,50.
ω^0: 1, 780, < 12,	
$\varrho(\varrho^+, \varrho^0, \varrho)$: 1, 750, $50 \div 100$,	

There are further applications of the theory to the scattering of strongly interacting particles. The scattering is characterized by the value of the amplitude; the square of the amplitude is proportional to the probability of scattering. It is assumed that the amplitude is an analytic function of the variables (the momenta, energies, and angular momenta—spins—of the particles) on which it depends, so that one can apply the methods of the theory of functions of a complex variable.

The energy of a particle emerging after the scattering can only be positive and larger than mc^2. One can, however, also continue the function (the amplitude) into the negative-energy region. It turns out that the values of the function for $E < -mc^2$ describe the process in which the antiparticle goes into the reaction. The scattering cross section and its behavior as the energy is varied are determined by the properties (spin, mass) of the particles which are transferred between the interacting particles during the scattering: the Coulomb interaction is a transfer of photons,

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*For the properties of the long-lived π and K mesons see Table II. The principle of the experiment by which ω_0 was discovered is described in detail at the beginning of this section (for a peculiarity of the decay of ξ see [96]); the numbers after the symbol for a particle are the spin, the mass (MeV), and the width (MeV).

Table I

<table>
<tr><td colspan="12">Strangeness 0, isotopic spin 1/2, nucleons n, p</td></tr>
<tr><td colspan="4">N</td><td colspan="4">N *</td><td colspan="4">N **</td></tr>
<tr><td colspan="4">1/2, 930, 0</td><td colspan="4">3/2, 1512, 130</td><td colspan="4">5/2, 1688, 140</td></tr>
<tr><td colspan="12">Strangeness −1, isotopic spin 0, lambda hyperon Λ</td></tr>
<tr><td colspan="3">Λ</td><td colspan="3">Λ *</td><td colspan="3">Λ **</td><td colspan="3">Λ ***</td></tr>
<tr><td colspan="3">1/2, 1115, 0</td><td colspan="3">?, 1405, 50 or 1</td><td colspan="3">?, 1520, 15</td><td colspan="3">?, 1815, 8</td></tr>
<tr><td colspan="12">Strangeness −1, isotopic spin 1, sigma hyperons Σ⁺, Σ⁰, Σ⁻</td></tr>
<tr><td colspan="6">Σ</td><td colspan="6">Σ *</td></tr>
<tr><td colspan="6">1/2, 1192, 0</td><td colspan="6">?, 1385, 50 or 25</td></tr>
<tr><td colspan="12">Strangeness −2, isotopic spin 1/2, xi (cascade) hyperons Ξ⁻, Ξ⁰</td></tr>
<tr><td colspan="6">Ξ</td><td colspan="6">Ξ *</td></tr>
<tr><td colspan="6">1/2, 1315, 0</td><td colspan="6">?, 1535, ?</td></tr>
<tr><td colspan="12">Strangeness 0, isotopic spin 3/2, 3–3 resonance Δ⁻, Δ⁰, Δ⁺, Δ⁺⁺</td></tr>
<tr><td colspan="6">Δ</td><td colspan="6">Δ *</td></tr>
<tr><td colspan="6">3/2, 1238, 145</td><td colspan="6">?, 1922, 185</td></tr>
</table>

nuclear forces are a transfer of pions, and so on.

The study of scattering at high energies is especially fruitful. In this region Pomeranchuk[53] has proved a theorem according to which the scattering cross sections of particles and antiparticles (for example, π^+-p and π^--p or p-p and $\tilde{p}$-p) are equal in the high-energy limit. Gribov and Pomeranchuk,[54] Gell-Mann,[55] and also Domokosh[56] have obtained relations of the type $\sigma_{\pi\pi}\sigma_{pp} = \sigma^2_{\pi p}$ for the cross sections at high energies.

The importance of these and similar relations is that they permit experimental checks on the ideas on which they are based.

The essence of the ideas is that "elementary particles" are not "elementary"[57,58] but are like systems. The physical meaning of this fashionable assertion still remains to be made clear (can we discuss what the "systems" consist of?); it is not excluded that a new physics is being born here, which will demand new concepts and the renouncing of old ones.

15. UNDISCOVERED PARTICLES

Earlier (Sec. 8) we considered a hypothetical vecton field causing attraction between baryon and antibaryon and repulsion between two baryons at short distances. The quantum of this field (that is, the corresponding particle) must be neutral, have a mass larger than that of the π meson, and have spin 1. It is not excluded that the new particle ω^0 is the vecton.

In connection with the theory of the weak interaction the idea has been suggested that there exists one further type of particles—charged X mesons, which play the role of intermediaries: instead of $n \rightarrow p + e^- + \tilde{\nu}$ we write $n \rightarrow p + X^-$, $X^- \rightarrow e^- + \tilde{\nu}$. On this assumption the primitive interaction is between the current J and the X field:

$$H = e'JX.$$

Observed processes depend on the second order in the theory—that is, on two successive acts (creation and destruction of an X). The interaction JX then takes on a similarity to the electromagnetic interaction—the interaction of the electric current and the vector potential of the electromagnetic field.*

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*The extremely close agreement of the interaction constants in nuclear β decay and in μ decay also indirectly supports the existence of the X^- meson.[87] Physics then contains along with $e^2/\hbar c = 1/137$ a new dimensionless number, $e'^2/\hbar c \approx 10^{-5}$. If X^+ and X^- exist, $(e\nu)$ scattering and the production of $(\nu, \tilde{\nu})$ pairs are inescapable.

If the X field and X mesons exist, the mass of X must be larger than the mass of K, and the lifetime must be smaller than 10^{-19} sec (if X were lighter than K, the decay $K^+ \rightarrow X^+ + \gamma$, $X^+ \rightarrow e^+ + \nu$ would occur more rapidly than the observed decay $K^+ \rightarrow \pi^0 + e^+ + \nu$).

In experiments on the interaction of high-energy neutrinos (from $\pi \rightarrow \mu + \nu$ decay in flight) with matter (see above, Sec. 2) some cases have been observed in which two charged leptons were evidently produced. Such a process can be thought of as going in two stages: 1) $\nu_\mu \rightarrow X^+ + \mu^-$ in the field of a nucleus, and 2) decay $X^+ \rightarrow \mu^+ + \nu_\mu$ or $X^+ \rightarrow e^+ + \nu_e$ in flight. The first process has been treated theoretically by Lee and Yang[8,59] and also by Solov'ev and Tsukerman.[60] For neutrino energies larger than the Mc^2 of the X meson the process at a heavy nucleus can be more probable than the weak interaction $\nu_\mu + p \rightarrow n + \mu^+$. The second step is a necessary consequence of the first, since X is unstable. Because of the small lifetime of X one will observe experimentally the production of two leptons at one point, $\nu_\mu \rightarrow \mu^+ + \mu^- + \nu_\mu$ or $\nu_\mu \rightarrow \mu^- + e^+ + \nu_e$ in the field of a nucleus.

Vectons and X mesons have a certain raison d'etre, being needed for definite purposes. There are further particles, constructed on the negative principle, "why shouldn't they exist"; in troubled times for theoretical physics, pretenders can arise.

Is the list of weakly interacting particles limited to the electron and the μ meson? The μ meson itself is a "mysterious" particle; it was found accidentally, in the search for particles which are quanta of the nuclear forces (that is, π mesons). The μ meson is called a "heavy electron." It exactly obeys the same Dirac equation as the electron, except that the value of one numerical constant (the mass) is different. Recent measurements of the magnetic moment of the meson, which achieved an accuracy of 0.001 percent, have completely confirmed this. The μ meson appears in the equation of the weak interaction in just the same way as the electron, and it also evidently does not interact strongly with anything (cf. [3]). The stability of the electron and the decay of the μ meson—this is a secondary effect of the difference of the masses.

If we did not know of the existence of μ mesons, no existing theory would predict it. Then we can ask, may there not be a continuation of the series e, μ, . . . toward higher masses. A particle of this type but heavier than the K particle would be exceptionally difficult to detect; its existence is not excluded (Zel'dovich, Lipmanov[61]) by the existing experimental data.

We remark that in the range below the mass of the μ meson special searches have been made, and it is known that there are no charged particles here.

Furthermore, there exist right-handed $\tilde{\nu}$'s and left-handed ν's (more exactly, right-handed $\tilde{\nu}_e$'s and $\tilde{\nu}_\mu$'s and left-handed ν_e's and ν_μ's) produced in weak interactions.

May there not also be left-handed $\tilde{\nu}$'s and right-handed ν's (Kobzarev, Okun') which are not involved in the weak interaction? We have no assurance on this point; the introduction of these new particles does not restore the symmetry of left and right, nor bring back parity, since the hypothetical right-handed ν's do not interact in the same ways as the left-handed ν's. But also we cannot reject this suggestion a priori. According to the idea of these authors the only interaction of the new particles is the gravitational interaction. In this case the production of these particles will be negligibly small even under the most extreme conditions of temperature and density and during cosmic times; astrophysics can neglect them in connection with the stars.*

16. TABLE OF PARTICLES

We give for reference a brief table of particles (Table II). We do not show the antiparticles (except for K^0), and also do not give ν_e and ν_μ separately. There is a curious situation in the system K^0—$\tilde{K}^0$. According to the three-particle scheme $K^0 = (n\tilde{\Lambda})$, $\tilde{K}^0 = (\tilde{n}\Lambda)$. Spontaneous changes $K^0 \rightarrow \tilde{K}^0$ and the reverse $\tilde{K}^0 \rightarrow K^0$ occurring in vacuum are possible, with a small probability, because the strangeness changes by two units. This interconversion occurs periodically and has just been observed experimentally. In this situation the things that behave like "particles" in vacuum are the superpositions

$$\frac{1}{\sqrt{2}}(K^0 + \tilde{K}^0) = K^0{}_1 \text{ and } \frac{1}{\sqrt{2}}(K^0 - \tilde{K}^0) = K^0{}_2.$$

The phenomenon was predicted by Gell-Mann, Pais, and Piccioni[62,63]; it has been described in Uspekhi Fizicheskikh Nauk in two reviews.[1,11]

Table II does not include the "resonance particles" which decay by the strong interaction and which were discussed in the preceding section.

17. GRAVITATIONAL INTERACTION. GENERAL THEORY OF RELATIVITY AND QUANTA OF THE GRAVITATIONAL FIELD

The interaction between particles is described classically with the concept of a field; the best example is the interaction of charged particles through the electromagnetic field. In quantum theory the field equations lead to the appearance of new particles, the quanta of the field; in the example just mentioned, they are quanta of the electromagnetic field (light quanta, γ-ray quanta). Another example is that of nuclear

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*In Gamow's version of a hot expanding universe, however, with a density decreasing from an infinite value, there can be thermodynamic equilibrium of gravitons and the new particles; in this case also, however, they produce no specific effects, and only cause a slight change of the numerical constant in the law connecting the temperature and the time.[102]

Table II

Name	Symbol	Electric charge	Baryon number	Lepton number	Strangeness	Rest mass, MeV	Spin	Lifetime, sec
Graviton		0	0	0	0	0	2	—
Photon	γ	0	0	0	0	0	1	—
Neutrino	ν	0	0	+1	0	0	1/2	—
Electron	e^-	−1	0	+1	0	0.51	1/2	—
μ meson	μ^-	−1	0	+1	0	106	1/2	$2\cdot10^{-6}$
π meson	π^+	+1	0	0	0	139.5	0	$2.55\cdot10^{-8}$
π meson	π^0	0	0	0	0	135	0	$(2.3\pm0.8)\cdot10^{-16}$
	K^+	+1	0	0	+1	493.9	0	$1.224\cdot10^{-8}$
	K^0	0	0	0	+1	497	0	$K_1^0\ 10^{-10}$
	$\widetilde{K}^0$	0	0	0	−1			$K_2^0\ 6.1\cdot10^{-8}$
	p	+1	+1	0	0	938.2	1/2	—
	n	0	+1	0	0	939.5	1/2	10^3
	Λ^0	0	+1	0	−1	1115.4	1/2	$2.51\cdot10^{-10}$
	Σ^+	+1	+1	0	−1	1189.4	1/2	$0.81\cdot10^{-10}$
	Σ^0	0	+1	0	−1	1191	1/2	$<0.1\cdot10^{-10}$
	Σ^-	−1	+1	0	−1	1196	1/2	$1.72\cdot10^{-10}$
	Ξ^0	0	+1	0	−2	1311	1/2	$1.5\cdot10^{-10}$
	Ξ^-	−1	+1	0	−2	1318	1/2	$1.3\cdot10^{-10}$

forces, for which, according to Yukawa's idea, the quanta are the pi mesons.

To what extent does this scheme apply to the gravitational interaction?

The gravitational interaction is similar to the electrostatic interaction; it obeys the same law, $F \sim 1/r^2$. The classical Newtonian theory of gravitation is completely analogous to the theory of the electrostatic potential. When we go over to relativity theory, however, the similarity disappears. Electrostatics is part of the theory of the electromagnetic field, in which the electric and magnetic fields are components of a single tensor when treated in flat Euclidean* space-time.

Meanwhile the theory of gravitation leads to the concept of a curved space, which had been discovered and developed mathematically by Lobachevskiĭ, Bolyai, and Riemann. The relativistic theory of gravitation is Albert Einstein's general theory of relativity (abbreviated GTR). This field has recently been attracting much attention, and new theoretical and experimental papers have been appearing.

Let us begin with the experiments. Attempts have been made[64] to detect the change of frequency of photons in the gravitational field (which can be interpreted as an effect of gravitation on the flow of time). These experiments should not be overvalued: their results follow necessarily from the relation $E = \hbar\omega$ for a photon, the relativistic dependence of mass on energy, $E = mc^2$ or $\Delta m = \Delta E/c^2$, and the fact that the effect of a gravitational field depends on the same mass m. By setting up a cycle—lowering of an excited nucleus, emission of a photon, raising of the unexcited nucleus, absorption of the photon—we arrive at the necessity of a change of frequency of the photon in order to avoid violation of the law of conservation of energy.

In fact: if the mass of the unexcited nucleus is M_0 and the excitation energy is E, then the mass of the excited nucleus is $M_1 = M_0 + E/c^2$. Consequently, when we lower the excited nucleus from the height h to height 0, we get the work M_1gh. In raising the unexcited nucleus, we expend the work M_0gh. If the photon emitted at height 0 by the excited nucleus could be absorbed at resonance by the unexcited nucleus at height h, the cycle would give a gain of work ghE/c^2, and a perpetual motion of the first kind would be possible.

The experiment consists in the fact that a photon emitted at height 0 is absorbed at resonance by a nucleus at the same height, but is out of resonance when the absorbing nucleus is higher (or lower) than the place where the quantum was emitted.

The fact that the inertial and gravitational masses are proportional, which was established by Bessel to accuracy 10^{-4} and by Eötvös to accuracy 10^{-8}, was again tested in 1960–61 by Dicke[26] in the U.S.A. and was confirmed to an accuracy of 10^{-10}. This goes 6 orders of magnitude beyond the difference of the mass defects of different kinds of nuclei. Consequently it is established with this accuracy that the force of gravity depends precisely on the total energy (in the sense $E = mc^2$), and not on the number of nucleons.

These data serve indirectly (but with a degree of conviction proportional to the experimental accuracy!) to refute every possibility of an antigravity of antiparticles, since antiparticles have positive energy, just as particles do.

Let us pass on to the theory. To what extent is the GTR with its idea of a noneuclidean space-time really inescapable? Could one not construct a theory of gravitation after the model of electromagnetic theory, as the theory of a special field in Euclidean space-time? Is the GTR necessary and inescapable, or only the most elegant theory?

The bending of light rays in the gravitational field of the sun and the precession of the perihelion of Mercury give quantitative confirmations of the Einstein theory. There still remains the question as to whether there is some theory which does not use the concept of curvature of space but explains the same facts.

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*More exactly, pseudoeuclidean, in view of the special role of the time.

From a general physical point of view quantum theory unexpectedly supplies a curious argument. In fact, as noted at the beginning of this section, the energy of a photon must change when the photon moves in a gravitational field. This is not surprising for the photon as a particle. The relation $E = \hbar\omega$, however, leads to the conclusion that the change of the energy of the photon is a change of its frequency, and thus must be interpreted as a change of the flow of time. Then, because space and time are connected even in special relativity, this leads to the ideas of the GTR.

More formally, let us use the approach which has been used for the electromagnetic interaction. It is well known that the laws of conservation of energy and momentum are due to the fact that the time and the coordinates do not appear directly (i.e., except in differentiations) in the laws of physics. The laws of physics are invariant under displacements in time and space. The connection between this invariance and the conservation of energy and momentum was established by the German woman mathematician Emmy Noether. Thus displacements Δt and Δx play the same role for energy and momentum that multiplication of ψ by $e^{iZ\alpha}$ does for the charge.

Now in analogy with the passage from a number α to $\alpha(x, y, z, t)$ let us suppose that Δt and Δx are themselves functions of x, y, z, t. We get a theory in which the interaction with the new field depends on the conserved quantities energy and momentum in exactly the same way that the interaction in electromagnetic theory depends on the conserved quantity charge.

But displacements of the time and the coordinates which depend on the x's and t themselves—that is, are different at different points of space—unavoidably lead to a curvature of space-time (Utiyama,[65] see also [24]). Thus the necessity of the scheme of the GTR is established.*

In the GTR the curvature of space depends on the presence of matter. The equations of GTR are local; they are differential equations connecting functions which characterize the properties of space-time at a given point (and their derivatives) with the density and flux of energy and momentum at that point. The GTR leads to the result that the gravitational interaction also is propagated not instantaneously, but with the speed of light.

In vacuum, i.e., in space in which there are no particles, besides static gravitational fields there are possible solutions which correspond to the propagation of so-called gravitational waves. For example, in the revolution of a planet around the sun, or of a double star, the gravitational field in the surrounding space varies periodically; because of the finite speed of propagation, however, the field at a distant point varies with a shift of phase relative to the instantaneous positions of the bodies.

The field of two stars differs from that of a point mass placed at the center of gravity. Nearby, where the phase shift is unimportant (i.e., at a distance r less than $l = cT$, where T is the period of revolution) the additional field is of the order of $\kappa Ma^2/r^4$, where a is the distance between the two stars and κ is the gravitational constant (the field of a point is $\kappa M/r^2$). For $r > l$, however, the field of two stars revolving around their common center of gravity falls off as r^{-1}; that is, it is of the order of $\kappa Ma^2/r(cT)^3$. This field at a great distance is a transverse field varying with a period equal to one-half the period of revolution of the stars; it is the field of a gravitational wave.

The energy of a system of two stars decreases in the course of time owing to the emission of gravitational waves; the energy loss per revolution is of the order of a fraction $(v/c)^5$ of the kinetic energy of the revolving bodies. Even over astronomical times this is a small loss. Estimates of the possibility of generating and detecting gravitational waves in terrestrial laboratories lead to quantities which are far beyond the bounds of present experimental techniques.

A particularly clear recent exposition of the theory of gravitational waves is that by Yu. B. Rumer.[66]* As in the case of electromagnetic waves, one can quantize the gravitational waves, introducing the concept of the quantum of this field—the graviton. In accordance with the speed of propagation, which is c, we must take the rest mass of the graviton to be zero. It can be shown that the spin of the graviton is 2; the projection of the spin on the direction of propagation can take two values, +2 and −2.

In processes such as the motion of double stars the frequencies are small; the field contains many quanta, and quantizing it is indeed as superfluous as giving a quantum treatment of the radiation from a powerful radio station.

In atomic and nuclear processes the emission of individual high-frequency gravitons is in principle possible. The probability of such a process is vanishingly small, however, because of the smallness of the gravitational interaction in comparison with the electromagnetic interaction. The probability of emitting gravitons is even smaller by a factor 10^{-10} than the probability of emitting neutrino-antineutrino pairs (see remark added at the end of [43]).†

May we suppose that the gravitational interaction violates the conservation laws, in particular the law of conservation of baryons? Could not annihilation of baryons occur with a probability proportional to the gravitational constant and therefore too small to observe under laboratory conditions? Such an assumption is in contradiction with the entire structure of the GTR. The gravitational field changes the trajectories of particles but does not (primarily or directly) cause

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*For another approach with the same conclusions, see Feynman.[99]

*See also the latest paper by S. Mandelstam.[100]

†The probability of the conversion of an electron-positron pair into two gravitons is calculated in [101].

interconversions among them; compare this assertion with the principle of the minimal electromagnetic interaction, Sec. 6.

This principle does not rule out processes in which the combined action of a strong or weak interaction and gravitation causes conversion of particle A into particle B in a gravitational field, or conversion of A into B plus a graviton. It is obvious, however, that such a mechanism can produce only those interconversions which are allowed by the conservation laws for the strong or weak interaction.

It is clear, moreover, that all conversions which can occur with the emission of a graviton can also occur according to the conservation laws with the emission of one or two photons and without that of the graviton. The probability of a process with the emission of a graviton is overwhelmingly small in comparison with that of the process without the graviton, because the gravitational constant (multiplied by the square of the mass of an elementary particle) is small in comparison with the square of the electric charge of a particle ($\kappa M^2/\hbar c \sim 10^{-38}$, where κ is the gravitational constant and M is the mass of a nucleon).

Therefore the emission of high-frequency gravitons in atomic and nuclear processes and in processes of interconversion of elementary particles is of no importance under any conditions—laboratory, stellar, or cosmic.

18. SPONTANEOUS CREATION OF MATTER AND VARIABILITY OF CONSTANTS

Some astrophysicists have put forward the idea of spontaneous creation of matter in the universe.[67,68] The reason for this hypothesis is the great discrepancy between the ages of the earth [$\sim(3-4) \times 10^9$ years] and the stars (up to 5×10^9 years) and the time of expansion of the universe, which in 1948—1950 was estimated at 1.3×10^9 years. Estimates of the time of expansion are based on the red shifts in the spectra of distant nebulas, which indicates that these nebulas are receding from us at speeds proportional to their distances (Hubble effect). Knowing the coefficient h in the expression $\mathbf{v} = h\mathbf{r}$, we can find the time $T = 1/h$ which has passed since the density of the universe was extremely great. Actually, because of the mutual attractions, the speed must have been even larger at earlier times, and thus the time of spreading out from a state of large density to the present state is $T \cong (2/3h)$, which for $h = 1.7 \times 10^{-17}$ sec^{-1} gave $T = 1.3 \times 10^9$ years. The whole picture of the universe agrees well with the Friedmann theory of a nonstationary world, which is based on GTR and envisages the possibility of the Hubble effect.

It seemed improbable that the earth was formed before the time when the density of matter was very large.

Therefore the idea has been proposed[67,68,103,104] that there is occurring everywhere a creation of matter in the form of neutrons or hydrogen atoms, at the rate of 10^{-43} g cm^{-3} sec^{-1}, or one atom in 1 m^3 in 300,000 years. The result of this creation of matter is that in spite of the spreading apart of the nebulas the mean density of matter in the universe remains constant, and that the present mean state of the universe is maintained for indefinitely long times, both in the past and in the future.

In recent years there has been a great change in our estimates of intergalactic distances, and the accepted value is now $T \sim 10 \times 10^9$ years. Thus the contradiction between the ages of the earth and the stars, on one hand, and the time of expansion of the universe, on the other, has disappeared. There have remained only not very convincing data as to ages of the order of 25×10^9 years for certain stellar systems.

The theory of spontaneous creation is now essentially unnecessary to astronomers, and is not supported by the indirect observational evidence.

Physicists, however, never did believe in this theory, since it requires renouncing the theory of relativity; the assumption was that matter was created at rest relative to the mean motion of the stars. This meant the introduction of definite privileged coordinate system. The laws of conservation of energy* and of conservation of the baryon charge were violated. The theory had never been formulated (and could not be formulated) in the language of the quantum theory of particles.

We note a curious comment of an experimenter[70]: when γ-ray measurements were made with an artificial satellite it was noted that if creation of nucleon-antinucleon pairs were occurring as suggested by Hoyle and Burbidge[104] and the antinucleons then were annihilated, the flux of γ-rays would be larger by two orders of magnitude than the flux actually observed.†

There have been statements (Fowler[70]) that in a closed world in the gravitational field, which has a gravitational mass defect, the creation of pairs would not violate the conservation of energy, since the mass of the closed world is and remains zero. The GTR,

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*The authors of the theory asserted that spontaneous creation agrees with conservation of energy: with their theory the mean energy per unit volume is preserved in spite of the expansion. This is a monstrous play on words: the law of energy conservation as usually understood certainly does not mean conservation of the mean energy of a volume out of which energy is flowing (in the course of an expansion). The conservation law is not $\partial\epsilon/\partial t = 0$, but $\partial\epsilon/\partial t = -\text{div}\, \mathbf{v}\epsilon$ (with $\rho = 0$).

†Recently Hoyle[103] has proposed a local and covariant type of creation theory. In this version of the theory the rate of creation depends on the density of matter at the given point. It had been pointed out[67] still earlier, however, that this kind of theory is inadmissible from the point of view of astrophysics (it would lead to a rapid change of the masses of stars). The creation of matter at a rate proportional to the density is easily disproved in laboratory experiments, since it would correspond to a radioactivity of every substance with a period of the order of 10^{10} years, an activity easily observable.

however, is a local theory; in the GTR there is a local law of conservation of energy in each volume element.

From the point of view of an observer located in a given volume element the creation of a pair always requires the energy $2Mc^2$; the gravitational potential at a given point does not affect the laws formulated in the coordinate system of an observer located at the point.

We remark in conclusion that the local character of the GTR is not in agreement with the attempts of some authors[71–73] to introduce an effect of the world as a whole on the phenomena occurring at a given point, and on the physical constants which appear in the laws of nature.

From such incorrect points of view one would have to expect as a consequence of the observed expansion of the entire universe that the physical constants would change with time, at a rate of the order of 10^{-10} of their values every year—this is the average rate of change of the distances between galaxies.

Dirac[71] writes frankly that this idea suggested by him is in contradiction both with the general theory of relativity and also with the special theory. Each new success and confirmation of the general theory of relativity refutes speculative assumptions about the variability of physical constants. There is a camouflaged form of the assumption that the constants vary: if we start from the Friedmann model of the world, the state of the world can be characterized by the mean radius of curvature of space. The curvature of space is a local concept. One now assumes in the framework of local theory that a length constructed from physical constants is proportional to the radius of curvature of space. Since in the Friedmann world the radius changes in the course of time, the conclusion is drawn that the physical constants also change in the course of time, and at a rate of the order of 1 in 10^{10} years —that is, slow enough to make observation difficult.

This pseudolocal point of view, however, cannot withstand criticism: the Friedmann solution has a constant curvature of space only when one makes the approximation of a strictly uniform distribution of the matter density! When we take into account the fact that the matter is concentrated in individual stars, the curvature varies very strongly from point to point, and a dependence of the constants on the true local value of the curvature would lead to great differences in the constants at the earth’s surface and near the sun, and so on, and hence is in complete contradiction with experience.

On the whole, unlike the questions of the theory of elementary particles, which are in the process of being formulated and developed, the theory of gravitation, in the form of the general theory of relativity, can be regarded as completed in its main principles. The problem of the theory of gravitation is to make the correct application of the theory to such complicated problems as stars and the universe as a whole.

In the past chemistry and astronomy have made great contributions to physics: the Mendeleev table, the doctrine of molecules, the laws of electrolysis, formed the basis of the ideas about the structure of matter, and astronomy provided the law of universal gravitation and the first measurement of the speed of light. Now, however, in the second half of the twentieth century, it is the deep conviction of the author (not shared, by the way, by many of his colleagues) that it would be naive to expect from astronomy new data about nuclear reactions, the creation of elementary particles, and the laws of the general theory of relativity.

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