Tests of electric charge conservation and the Pauli principle

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Usp. Fiz. Nauk **158**, 293–301 (June 1989)

This brief critical review discusses attempts to check the accuracy with which experiments confirm conservation of electrical charge and the Pauli principle. The unavailability is emphasized of an internally consistent phenomenological theory which could describe a violation of charge conservation and/or of the Pauli principle. Longitudinal photons play a fundamental role in nonconservation of charge. New proposals concerning verification of the Pauli principle are discussed.

Over the past 30 years, about 30 papers have been published on searches for violations of the law of conservation of charge and/or the Pauli principle. These two topics, which at first glance do not look close at all, are related because experimental searches for these two phenomena very frequently amount to the same thing. This review has four sections: 1. Experiments which have been carried out. 2. Theoretical papers on the nonconservation of electric charge. 3. Theoretical papers on violations of the Pauli principle. 4. Suggestions for future experiments.

1. EXPERIMENTS WHICH HAVE BEEN CARRIED OUT

1.1 Exclusive experiments with electrons. About 30 years ago, Feinberg and Goldhaber[1] carried out an experiment with a NaI detector with the goal of testing the stability of the electron. They searched for the characteristic x-ray lines which would correspond to transitions to levels vacated in the decay of an electron (Fig. 1). They concluded that there was a lower limit $\tau_e \gtrsim 10^{18}$ yr on the lifetime of an electron.

In 1965, Moe and Reines[2] raised this limit to 10^{20} yr. As the result of unsuccessful searches for γ rays with an energy of $m_e/2$, they also drew the conclusion $\tau(e\to\nu\gamma) \gtrsim 4\cdot 10^{22}$ yr.

In 1974 Reines and Sobel[3] used the results[2] of their searches for x-ray lines to establish a limit on the violation of the Pauli principle. On this occasion they examined the transition not to a vacant level but to a filled atomic shell (Fig. 2).

A corresponding search for x-ray lines was carried out by Steinberg *et al.*[4] in 1975. Using a germanium detector, they found $\tau_e > 5\times 10^{21}$. In 1979, Koval'chuk, Pomanskiĭ, and Smol'nikov[5] raised the limit in NaI to $2\cdot 10^{22}$ yr, and in 1983 Belotti *et al.*[6] found the same result for germanium.

In 1986, Avignone *et al.*[7] repeated the search made by Moe and Reines with a germanium detector: Seeking the decay $e\to\nu\gamma$, they found $\tau(e\to\nu\gamma) > 1.5\cdot 10^{25}$ yr.

All the experiments which have been carried out have checked electrons: They have involved a search for x-ray or γ-ray lines resulting from the decay of an electron or for x-ray lines resulting from a violation of the Pauli principle for electrons.

1.2. Exclusive experiment with nucleons. The same arguments which we mentioned above in connection with electrons apply also with respect to nucleons. In 1979, Logan and Ljubicic[8] tested the Pauli principle by searching for γ rays with an energy of the order of 20 MeV which should have accompanied the transition of a nucleon in a ^{12}C nucleus from the 2p shell to the filled 1s shell. They found a lower limit on the time for such a transition and thus on the time for the formation of a "non-Pauli" carbon nucleus $^{12}\tilde{C}$, containing five nucleons in the s ground shell: $\tau(^{12}C\to{}^{12}\tilde{C}\gamma)\geqslant 2\cdot 10^{20}$ yr.

1.3. Inclusive experiments with nucleons. Inclusive experiments differ from exclusive experiments in that they do not predetermine the specific reaction in which the phenomenon of interest occurs. Nothing is assumed about the mechanism for the effect. With regard to electric charge, for example, everything would look as it would if a charge Q_1 went into a "black box" and a charge Q_2 emerged from this box (Fig. 3). A first experiment of this inclusive type was carried out in 1979 by Norman and Seamster.[9] They established $\tau(^{87}\mathrm{Rb}\to{}^{87}\mathrm{Sr}) > 1.9\cdot 10^{18}$ yr. In 1980, Barabanov *et al.*[10] established $\tau(^{71}\mathrm{Ga}\to{}^{71}\mathrm{Ge}) > 2.3\cdot 10^{23}$ yr. That result was a by-product of the development of a radiochemical method for detecting low-energy solar neutrinos in a gallium detector. The construction of that detector was being carried out, and

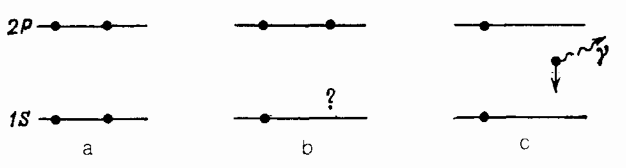

FIG. 1. a–Filled 1S and 2P shells of iodine; b–as the result of a hypothetical decay (?) which does not conserve electric charge, an electron disappears from the 1S shell; c–an electron goes from the 2P shell to the 1S shell, emitting characteristic x radiation.

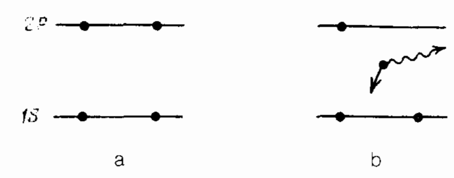

FIG. 2. a–Filled 1S and 2P shells of iodine; b–an electron goes from the 2P shell to the filled 1S shell, violating the Pauli principle.

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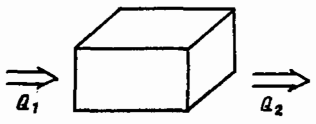

FIG. 3. A "black box" in which charge conservation is violated.

is still being carried out, at the Baksan neutrino observatory.

1.4. Global limit for the nonconservation of electric charge. A global approach to evaluating the nonconservation of electric charge was proposed in 1976 by Pomansky,[11] who analyzed the electric current balance in the earth's atmosphere and arrived at the conclusion that the disbalance current which might be caused by the decay of electrons and, in general, by charge nonconservation in the atoms of the earth could not exceed 200 A. Using $2\cdot 10^{51}$ as the number of electrons in the earth, he reached the conclusion $\tau_e > 5\cdot 10^{22}$ yr.

Experiments which have been carried out to test the validity of the Pauli principle and the conservation of electric charge are reviewed by Reines and Sobel[12] (1980).

2. THEORETICAL PAPERS ON THE NONCONSERVATION OF ELECTRIC CHARGE

In 1978, Zeldovich, Voloshin, and the present author[13,14] analyzed several questions which arise in attempts to derive a noncontradictory phenomenological theory of the violation of the conservation of electric charge.

2.1. Impossibility of a spontaneous violation of charge conservation. It was shown that, in contrast with the spontaneous violation of the electroweak theory, a spontaneous violation of the conservation of electric charge would be impossible since a photon differs from a Z boson in that it has an exceedingly small mass or (making the argument even stronger) absolutely no mass. As we know, a spontaneous breaking of gauge symmetry by means of the Higgs mechanism would require a charged scalar field, whose mass parameter would be approximately the same, within one or two orders of magnitude, as the mass of gauge bosons.

In the case of essentially massless photons we would therefore need the existence of a charged and essentially massless scalar boson. The emission and absorption of such bosons would have altered all electromagnetic processes to the point of unrecognizability, so their existence is undoubtedly ruled out.

2.2. Catastrophic bremsstrahlung in the case of an explicit nonconservation of charge. On the other hand, a nonspontaneous, explicit violation of the conservation of charge would have led to the catastrophic emission (bremsstrahlung) of longitudinal photons. In the case of conservation of charge (and current), the amplitude for the emission of a longitudinal photon would be proportional to em_γ/ω, where e is the electric charge, m_γ is the mass of the photon, and ω is its frequency (or energy; we are using units $\hbar$, $c = 1$). In the case of a nonconservation of charge, in contrast, we would have exactly the opposite situation: The amplitude for the emission of a longitudinal photon would be proportional to $\varepsilon\omega/m_\gamma$ and would become very large. As a result, the probability for the emission of two longitudinal photons would be higher than that for the emission of a single photon; that for the emission of three higher than that for the emission of two; and so forth.

If we assume, for example, that there exists a decay of an electron into three neutrinos with a very, very small constant g (Fig. 4a), then such a decay would actually have been accompanied by the emission of a huge number of longitudinal bremsstrahlung photons (Fig. 4b), and it would have been these photons, rather than neutrinos, which carried off all the energy released during the decay, which is equal to the mass of an electron. The same comments apply, of course, to the decay $e\to\nu\gamma$, which would convert into the decay $e\to\nu + N_\gamma\gamma$ (Fig. 5), where

$$N_\gamma \approx 3\left(\frac{\alpha}{4\pi} - \frac{m_e^2}{m_\gamma^2}\right)^{1/3} \approx 10^{14} - 10^{21}.$$

The first number here corresponds to an upper limit on m_γ, which is provided by the magnetic field of Jupiter: $1/m_\gamma \gtrsim 10^{11}$ cm. The second number is the less reliable limit $1/m_\gamma \gtrsim 10^{22}$ cm which follows from the observed dimensions of galactic magnetic fields. The probability for the decay of an electron here is given by the following expression, within coefficients of the exponential function:

$$\Gamma_e \sim m_e g^2 e^{N_\gamma}.$$

We see that all the decay energy goes into infra-infra-...-infrared photons, i.e., essentially into a static field. Consequently, the decay of an electron should not be accompanied by a γ line with an energy of $m_e/2$, and when an electron in an atom disappears there should be no x-ray lines: The entire phenomenon plays out over distances much greater than the size of an atom. There will be only an unobservable static field of longitudinal photons.

The exclusive experiments discussed above would thus be incapable of detecting the decay of electrons or nucleon conversions accompanied by a nonconservation of charge, even if such processes did occur.

Thus only inclusive and global limitations are meaningful.

2.3. Self-healing of radiative corrections. If the preceding subsection created the impression that a direct violation of the conservation of electric charge might serve as the foundation for a noncontradictory theory for this phenomenon, that impression is wrong. If the probability for the emis-

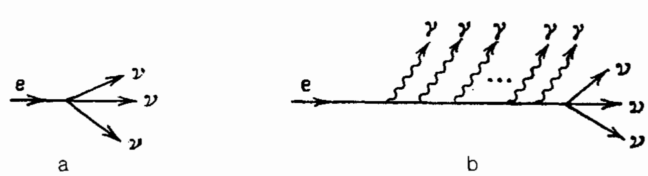

FIG. 4. a–The hypothetical decay $e\to\nu\nu\nu$, in which electric charge is not conserved; b–catastrophic bremsstrahlung accompanying this decay.

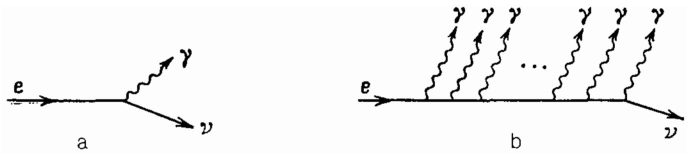

FIG. 5. a–The hypothetical decay $e \to \nu\gamma$, in which charge is not conserved; b–catastrophic bremsstrahlung emitted by the charge in this decay.

sion of a colossal number of real longitudinal phonons is large, the probability for the emission and absorption of a colossal number of virtual longitudinal photons by one and the same particle must also be large. In other words, the radiative corrections must be colossal. They are so large that they could be called "corrections" only by custom.

For real longitudinal photons one can show that their emission effectively occurs at that point in the Feynman diagram where charge conservation is violated (Fig. 6). For virtual photons, both an emission and an absorption occur at this point (Fig. 7). As a result, the original constant g of the decay $e \to \nu\nu\nu$ becomes renormalized to

$$\tilde{g} = g \exp\left(-\frac{\alpha}{4\pi}\frac{\Lambda^2}{m_\gamma^2}\right),$$

where Λ is a cutoff parameter. Since $\Lambda \gg m_e$, the amplification factor resulting from the emission of real photons would be more than balanced by the suppression factor due to virtual photons. The starting point of the theory should thus be an infinitely large seed charge-nonconservation constant g; that situation seems unlikely. We thus see that if the photon is to be essentially massless the theory will be "healed." The low mass of light stands guard over charge conservation.

2.4. Minicharged particles and spontaneous violation of charge conservation. In Subsection 2.1 we explained that a spontaneous violation of charge conservation due to the formation of a vacuum condensate of a scalar field with a unit charge ($Q_\phi = Q_e$) would contradict experiment. It may be, however, that a spontaneous violation would be possible under the condition $Q_\phi = Q_e/N_\phi$, where $N_\phi \gg 1$. Such a hypothesis was advanced in 1979 by Ignat'ev, Kuz'min, and Shaposhnikov.[15] For the electron to be unstable, we would need either a direct unrenormalizable interaction which leads to the decay $e \to \nu + N_\phi \phi$ or the existence of $N_\phi - 1$ heavy fermions ψ_i with charges

$$Q_e - \frac{Q_e}{N_\phi}, \quad Q_e - 2\frac{Q_e}{N_\phi},$$

$$Q_e - 3\frac{Q_e}{N_\phi}, \ldots, Q_e - \frac{N_\phi - 1}{N_\phi} Q_e = \frac{Q_e}{N_\phi}$$

and with a "ladder of vertices"

$$\bar{e}\phi\psi_1, \quad \bar{\psi}_1\phi\psi_2, \quad \bar{\psi}_2\phi\psi_3, \ldots, \bar{\psi}_{N_\phi - 1}\phi\nu.$$

Voloshin and the present author[14] calculated $N_\phi \gtrsim 100$. According to an estimate by Voloshin,[21] we would have $N_\phi \gtrsim 10^8$. Otherwise, ordinary capacitors would discharge too rapidly by virtue of the creation of $\phi\bar{\phi}$ pairs.

2.5. Theoretical papers of the last two years. The question of charge nonconservation has recently attracted more interest among theoreticians. In 1986, Nakazato *et al.*[16] discussed problems concerning the renormalization of a theory with an explicitly nonconserved electromagnetic current. Three papers appeared in 1987: Huang[17] made an attempt to violate charge conservation spontaneously in a broken SU(5) symmetry. Nussinov[18] examined the effect of an external potential on the decay of an electron. Mohapatra[19] proposed a theoretical model according to which charge nonconservation would result from electron-positron oscillations. He suggested that such a theory would contain only logarithmic infinities. In 1988, a preprint by Suzuki[20] on minicharged particles appeared. All these papers (except Ref. 20) were subjected to a critical analysis in 1988 by Tsypin,[21] whose primary assertion is that the conclusions of Refs. 13 and 14, which we discussed above, remain in force.

3. THEORETICAL PAPERS ON VIOLATIONS OF THE PAULI PRINCIPLE

3.1. The years 1930–1980. A nonconformist approach to the Pauli principle on the basis of quantum mechanics dates back to Dirac and Fermi. In his famous book,[22] whose first edition appeared in 1930, Dirac leads the careful reader to the conclusion that in quantum mechanics with a commutation-invariant Hamiltonian transitions to a filled shell are forbidden, regardless of whether the Pauli principle is violated, since such transitions would alter the commutation symmetry of the wave function of the given set of particles. This assertion is also made in the 1958 edition.

In 1934, in one of his popularizing papers,[23] Fermi discussed how the properties of atoms would have varied over time if electrons were just a tiny bit nonidentical.

In 1971, Lyuboshits and Podgoretskiĭ[24] examined a model in which an electron was a superposition of a large number of nearly degenerate states with a given mass. The properties of the electron are of course functions of the time in this case.

In 1980, Amado and Primakoff[25] used arguments similar to those in Dirac's book to interpret the experiments of

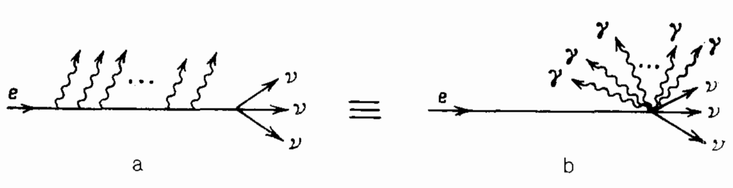

FIG. 6. The diagrams of part a are equivalent to those of part b, in which all the photons are emitted at a common vertex.

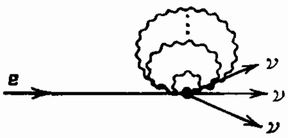

FIG. 7. Virtual longitudinal photons renormalize the $e \to \nu\nu\nu$ vertex.

Reines and Sobel[3] and Logan and Ljubicic.[8] They reached the conclusion that if one is to remain in the framework of quantum mechanics then the Pauli-forbidden transitions which were discussed in Refs. 3 and 8 could not occur, even if the Pauli principle were violated.

3.2. Studies of the last two years. The burst of interest in the possibility of a small violation of the Pauli principle began in 1987 with a paper by Ignat'ev and Kuz'min.[26] As is well known, the standard fermion creation and annihilation operators a^+ and a, respectively, are reminiscent of 2×2 Pauli matrices with a single nonzero matrix element:

$$a^+ \sim \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}, \quad a \sim \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}.$$

Ignat'ev and Kuz'min introduced 3×3 matrices with two nonzero matrix elements:

$$a^+ \sim \begin{pmatrix} 0 & \beta & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix}, \quad a \sim \begin{pmatrix} 0 & 0 & 0 \\ \beta & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix},$$

where the parameter β satisfies $\beta \ll 1$. Using these matrices, Ignat'ev and Kuz'min described one level which could be (1) vacant, (2) filled by one electron, or (3) filled by two electrons, with spins in the same direction, of course. (In the case $\beta = 0$, there is a transition to standard fermions.) Attempts to generalize this idea to field theory (an infinite number of levels) were undertaken by Greenberg and Mohapatra[27,28] and the present author.[29–31]

Explicit tensor products of 3×3 matrices were used in Refs. 29 and 30 to construct creation and annihilation operators for particles in each given level. The anticommutators $[a^+,a^+]$ and $[a,a]$ turned out to be not zero, as for standard fermions, but proportional to the small parameter β. Such a theory, however, would obviously violate locality and the superposition principle, and it would not have a limiting transition from two infinitely close states to a single state. The latter property is manifested particularly clearly by so-called ferbons (fermion bosons).[31] The ferbon creation operators anticommute when two states are not the same, but the number of ferbons in any given state can be arbitrarily large. The conclusions reached in Refs. 29 and 30 with regard to the possibility of constructing an acceptable theory with a slight violation of the Pauli principle were pessimistic.

Greenberg and Mohapatra optimistically entitled their paper[27] "Local quantum field theory of possible violation of the Pauli principle." It is based on the trilinear commutation relation

$$[c_1 a_i^\dagger a_j + c_2 a_j a_i^\dagger,\ a_k]_- = -\delta_{ik} a_j,$$

where i, j, k are the indices of states, and

$$c_1 = (2\beta^2 - 1)(\beta^4 - \beta^2 + 1)^{-1},$$
$$c_2 = (\beta^2 - 2)(\beta^4 - \beta^2 + 1)^{-1}.$$

The particle number operator in a given state is

$$N_i = c_i a_i^\dagger a_i + c_2 (a_i a_i^\dagger - 1).$$

The properties of the vacuum are fixed by the relations

$$a_k|0\rangle = 0, \quad a_k a_l^\dagger|0\rangle = \delta_{kl}|0\rangle.$$

Working from these relations, and using the trilinear commutator, one can construct an arbitrary state vector. In a theory of this sort we have locality and a superposition principle, but, as Govorkov has shown[32] on the basis of his own earlier and more general studies, certain states in this theory have a negative norm (a negative probability). The simplest of them contains four symmetrized electrons, three of which are in a common level, while the fourth is in some other level. A direct calculation easily verifies the relation

$$|a_i^\dagger(a_k^\dagger a_i^\dagger - a_i^\dagger a_k^\dagger)|^2 < 0.$$

In a paper which appeared just recently,[33] Greenberg and Mohapatra discuss Govorkov's arguments and reach the conclusion that it is impossible to construct a free field theory with a small violation of Fermi or Bose statistics. Greenberg and Mohapatra do not believe that interactions will alter the situation.

The failure of attempts to violate the Pauli principle (on paper) is a consequence of some extremely general theorems based on the fundamental properties of field theory. Corresponding bibliographies, which complement each other, are given in Refs. 30 and 33. By some strange chance those bibliographies omit the important paper[34] by Lüders and Zumino.

I would like to conclude this subsection by citing a recent lecture published by Feynman.[35] Feynman gives a very clear explanation of how the Pauli principle leads to the self-consistency of quantum electrodynamics.

4. SUGGESTIONS FOR FUTURE EXPERIMENTS

Several new experimental searches for a slight violation of the Pauli principle have been proposed over the past two years.[26–30,36,37] Among the entities under discussion are non-Pauli molecules, atoms, nuclei, and hadrons. Let us take a look at some of these ideas.

A $^3S_1$ ground state of ortho-helium can be sought by means of a spin-resonance technique[28–30] or by means of a Zeeman splitting of an atomic beam.[36]

A sodium atom with three electrons in its K shell lacks its valence electron and should be similar to neon chemically, but the optical spectrum of this false neon should be radically different from the spectrum of actual neon. After separation and enrichment, false neon could be sought by the method of resonant excitation and photoionization[29,30,37] or by neutron-activation analysis.[37]

There is also the suggestion of seeking x radiation or electrons might be sought by passing through a source a high electric current, which might carry "new," nonantisymmetrized electrons.[27,28]

If the Pauli principle is violated at the quark level,[28] there should exist a 70-plet of baryons with quarks in an S wave, which would contain in particular an octet with $J^P = 3/2^+$ and a decuplet with $J^P = 1/2^+$. Some of these baryons should be stable.

There is the saying that "something new is something old which has been well forgotten." Thus some of the experiments which have been proposed over the past two years are very similar to experiments which were carried out many years ago, at a time when not all physicists were absolutely convinced that β particles were identical to ordinary electrons, rather than being some other particles having the same spin, charge, and mass. In 1948, for example, Goldhaber and Scharff-Goldhaber[38] carried out some experiments in which β particles from ^{14}C were stopped in lead, and a search was made for x-ray lines of lead. The investigators established a 3% upper limit on the existence of such lines and concluded that the β particles are identical to electrons. (Some earlier studies pertinent to the establishment of the identity of β particles and electrons are described in the review by Crane.[39])

In 1968, Fishbach, Kirsten, and Shaeffer[40] carried out a search for "false ^{9}He," which they called ^{9}Be′: a beryllium atom whose K shell has two ordinary electrons and two "false electrons e′." They established that the abundance of such false ^{9}He in the atmosphere was less than 10^{-6} of the abundance of ordinary ^{4}He.

Today we have no doubt that there exists only a single particle having the mass and charge of the electron: the electron itself. If "another" electron and "another" positron did exist, they would have been produced in abundance along with pairs of ordinary electrons and positrons in (in particular) electron-positron colliders, and they would have disrupted the excellent agreement between quantum electrodynamics and the huge set of extremely accurate experiments. These old searches may thus be thought of today as searches for a violation of the Pauli principle.

Leaving the Pauli principle to return to charge conservation, we should emphasize the major possibilities of gallium detectors of solar neutrinos at Baksan (60 metric tons of Ga) and at Gran Sasso (30 metric tons of Ga). These detectors might be able to raise the lower limit on the time for the Ga→Ge conversion from 10^{23} to 10^{26}–10^{27} yr.

Although we do not today have a noncontradictory phenomenological model to describe the violation of the charge conservation law and/or the Pauli principle, it would be wrong for experimentalists to abandon their tests of these fundamental positions of modern physics. If something in fundamental physics *can* be tested, then it absolutely *must* be tested.

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Translated by Dave Parsons