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DOUBLE BETA DECAY AND THE PROPERTIES OF THE NEUTRINO

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THE development of our knowledge on beta decay of radioactive nuclei can be divided into two distinct historical stages. The start of each of them was heralded by mighty scientific discoveries, each of which necessitated the fundamental review of the earlier concepts concerning this phenomenon. The first was Fermi's theory of beta decay, constructed under the assumption that the neutrino, a new particle postulated by Pauli, exists. The second was the observation of parity nonconservation in weak interactions in the experiments by Wu, based on a theory developed by Yang and Lee, Landau, and a number of other scientists.

The time interval elapsed between these two events is characterized not only by further knowledge of the nature and properties of the beta processes and their theoretical interpretation on the basis of the "classical" beta-decay theory, but also by an increased interest in the neutrino, the particle emitted by the nucleus simultaneously with the electron. This particle does not carry away any electric charge from the nucleus, but does carry away energy and angular momentum. The mass of this particle should either be exactly equal to zero or exceedingly small. Being practically a non-interacting particle, it escaped direct observation for a long time. The properties of this "illusory" particle are the subject of the branch of beta-decay physics created at that time, namely neutrino physics. Empirical studies of the neutrino properties entail, as a rule, very difficult research carried out "at the feasibility borderline" of the existing experimental technology.

It was precisely in that period that the problem of double beta decay arose and evolved, and the first theoretical predictions were made concerning the features of this process as functions of the properties of the neutrino [1-4]. However, approximately ten years were to elapse before progress in experimental techniques made possible the first attempts to observe this phenomenon [5-7]. Since that time, double beta decay was "discovered" many times, but all these discoveries were either refuted by further experiments, or were subjected to serious doubts for various reasons.

The observation of parity nonconservation in weak interactions and the information it yielded on processes connected with emission or absorption of light particles led to a radical break with our earlier concepts concerning the mechanism of weak interactions [8-10]. The earlier rather simple treatment of double beta processes has given way to a complicated and rather confused situation.

1. OCCURRENCE AND DEVELOPMENT OF THE PROBLEM

In 1933, Pauli [11] advanced the neutrino existence hypothesis. This hypothesis afforded a way out of the apparent contradiction between the conservation laws and the beta-decay phenomena. Using this hypothesis, Fermi developed in 1934 a beta-decay theory [12] which explained a number of regularities of this phenomenon and covered practically the entire experimental material accumulated by that time. Soon after the announcement of this theory, Goeppert-Mayer [1] published a paper devoted to a theoretical investigation of the possible properties of the neutrino. This paper contained the first statement of the hypothetical feasibility of double beta decay. As is well known, there are two types of beta decay: electronic decay

$$n \to p + e^- + \tilde{\nu} \tag{1a}$$

and positronic

$$p \to n + e^+ + \nu^*. \tag{1b}$$

This immediately raises the question whether the neutral light particles emitted in both these processes simultaneously with the beta particles, and designated by us ν and $\tilde{\nu}$, are identical or different. In the case of the latter possibility, these particles should be antiparticles, and it is therefore customary to refer to ν and $\tilde{\nu}$ as neutrino and antineutrino, respectively.

Ordinary beta decay, which proceeds in accord with (1a) or (1b), involves the transformation of an initial nucleus into a lighter neighboring nucleus, accompanied by unity change in charge. There exist in nature, however, a rather large number of pairs of stable isobaric nuclei with identical mass numbers and with charges differing by two units. As a rule, these are even-even nuclei. The existence of such isobars is due to the fact that the intermediate isobar, whose charge differs from the charge of the outer isobars by unity, has a mass larger than the latter, and consequently the transformation of one of the

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*We are considering here the decay of a nucleon in the field of other nucleons (i.e., inside nuclei), and we can therefore ignore the satisfaction of the energy and momentum conservation laws for individual nucleons.

outer isobars into a lighter one cannot proceed via two successive simple beta decays. In some cases such a double successive decay is impossible in practice even when the mass of the intermediate nucleus lies between the masses of the outer nuclei, and their apparent stability is due to a high degree of forbidenness, connected for example with the very large change in spin.

For nuclei having the foregoing properties, a transition to the neighboring nucleus is impossible, but there is a possible decay in which a direct atomic-number change of two units and simultaneously emission of two beta particles, accompanied by two neutrinos or antineutrinos,

$$2n \rightarrow 2p + 2e^- + 2\tilde{\nu} \tag{2a}$$

or

$$2p \rightarrow 2n + 2e^+ + 2\nu. \tag{2b}$$

As a result of such a process, the nucleus (A, Z) is transformed into the nucleus (A, Z ± 2):

$$(A, Z) \rightarrow \begin{cases} (A, Z + 2) + 2e^- + 2\tilde{\nu} \\ (A, Z - 2) + 2e^+ + 2\nu. \end{cases} \tag{3}$$

The probability of this transformation, which is called two-neutrino double beta decay, has turned out, in accordance with the calculations of Goeppert-Mayer, to be exceedingly small, the half-life of the nucleus relative to double decay with emission of two neutrinos amounting to about 10^{21} years.

In 1937 Majorana[2] showed theoretically that if we assume the existence of only one type of neutrino, having no antiparticle (i.e., $\nu \equiv \tilde{\nu}$), then the deductions of the beta-decay theory remain unchanged, and Racah[3] noted that in this case a neutrinoless double beta decay becomes possible, i.e., a process in which the two beta particles emitted when the nucleus (A, Z) is transformed into the nucleus (A, Z ± 2) are not accompanied by neutrinos:

$$(A, Z) \rightarrow (A, Z \pm 2) + 2e^{\mp}. \tag{4}$$

Two years later, Furry[4] investigated the neutrinoless method of double beta decay. He introduced the following scheme, which is employed to this day, for considering this process. The initial nucleus (A, Z) emits one beta particle and goes over into a virtual intermediate nucleus (A, Z ± 1) plus a virtual neutrino, which, interacting with this intermediate nucleus, "induces" its decay with emission of the second beta particle and is itself absorbed. The result of such a transformation is indeed written into Eq. (4). However, Furry estimated incorrectly the probability of this double beta transition. A correct estimate of the lifetime of the nucleus relative to neutrinoless double beta decay was subsequently made by L. A. Sliv[13].

If a neutrinoless double beta decay can be realized in nature, it should have a much higher probability than the two-neutrino decay. This is explained qualitatively by the following considerations. In the two-neutrino double beta decay, the number of states corresponding to the simultaneous emission of two beta particles is determined by the volume of the phase space of the two neutrinos, a volume bounded by the total decay energy. In the neutrinoless method of double beta decay, the neutrino is a virtual particle, which appears only in the intermediate state of the nucleus. Therefore the energy of the neutrino is bounded only by the condition that its wave function not have an alternating sign within the nucleus, in other words, the contribution of the proper intermediate state to the matrix element and to the transition probability tends to zero. This condition limits the neutrino energy in the intermediate state to a value on the order of 40 MeV (for medium nuclei). The latter quantity is many times larger than the neutrino energy which is possible in the two-neutrino decay, and this circumstance leads to an increase in phase volume of the intermediate state and consequently to an increase in the decay probability.

All the theoretical lifetime calculations in the double-beta-decay problem have low accuracy. This annoying circumstance is due to our lack of knowledge of the numerical value of the nuclear matrix element, which is estimated in all concrete calculations by starting from a definite nuclear model and from data known from experiments with ordinary beta decay. Such an approximation usually leads to an error of approximately two orders of magnitude. Nonetheless, the ratio of the lifetime of the two-neutrino process to the lifetime of the neutrinoless process should be much more accurate, since the values of the matrix elements for both variants of the theory are close to each other.

The probability of double beta decay processes was calculated by several workers[1,13-16]. The overwhelming majority of these calculations were made under the assumption that a scalar-tensor interaction is realized. We confine ourselves only to a concise review of the results of two papers, namely those of Zel'dovich, Luk'yanov, and Smorodinskiĭ[14] and of Konopinski[15]. The first contains a rather detailed calculation of the probability of the neutrinoless process, on the basis of which it is easy to determine the form of the spectrum of the single electrons. In the second paper, the probabilities of both possible double beta decay variants were calculated. Konopinski's result, while less accurate than the calculation of Zel'dovich, Luk'yanov, and Smorodinskiĭ, is convenient for a comparison of double beta decay for the cases $\nu \equiv \tilde{\nu}$ and $\nu \not\equiv \tilde{\nu}$.

When double beta decay occurs without neutrino emission, almost the entire decay energy is divided between the two electrons, since the fraction of the energy going into the recoil of the nucleus is negligibly small. Thus, in an experimental observation of the process, the spectrum of the total electron energy should have the form of a narrow peak (provided the energy resolution of the apparatus is sufficient), the position of which on the energy scale should correspond to the decay energy. The law governing the partition of the energy between the two electrons is governed in this case by the form of the energy spectrum for the single electron. The probability of observing an electron with total energy lying in the interval ($\mathcal{E}_1$; $\mathcal{E}_1 + d\mathcal{E}_1$) for a decay energy W_0 and for a second-electron energy $\mathcal{E}_2 = W_0 - \mathcal{E}_1$ (the energy is in units of m_0c^2 throughout) is determined by the formula

$$\omega(\mathcal{E}_1)\,d\mathcal{E}_1 = \mathrm{const}\cdot F(\mathcal{E}_1)\,F(\mathcal{E}_2)\,[(\mathcal{E}_1-1)^{1/2}(\mathcal{E}_2-1)^{1/2}]$$
$$\times(\mathcal{E}_1\mathcal{E}_2-1)(\mathcal{E}_1-\mathcal{E}_2)^2\,d\mathcal{E}_1, \tag{5}$$

where

$$F(\mathcal{E}_i)=\frac{2\pi\eta_i}{1-\exp(-2\pi\eta_i)}; \qquad \eta_i=\frac{Ze^2}{hv_i},$$

Z is the charge of the nucleus and e and v are the charge and velocity of the electron. In the case of sufficiently heavy elements (and only for these is double beta decay possible), we can neglect the exponential in the denominator of $F(\mathcal{E}_1)$, and then $F(\mathcal{E}_i) = 2\pi Ze^2/\hbar v$.

If we confine ourselves to electrons with total energy in the interval $2 \leq \mathcal{E}_i \leq W_0 - 2$, i.e., when the velocity is close to that of light, then $F(\mathcal{E}_i) \approx 2\pi Ze^2/\hbar c = \mathrm{const}$. Under this assumption, going over in (5) from total energies to kinetic energies $W_0 = E_0 + 2$, $E = \mathcal{E} - 1$, where E_0 is the difference between the atomic masses of the initial and final nuclei (for the case of electronic decay) in units of m_0c^2, we can obtain the following expression for the spectrum of the single electrons:

$$\omega(x)\,dx = \mathrm{const}\,(2x-1)^2$$
$$\times\left(x-x^2+\frac{1}{E_0}\right)\sqrt{x(1-x)}\,dx, \tag{6}$$

where

$$x=\frac{E}{E_0};\ 1\leqslant E\leqslant E_0-1.$$

A plot of this function, calculated for $E_0 = 8.45 m_0c^2$ (Ca^{48}), is shown in Fig. 1. As seen from the plot, in the neutrinoless method of double beta decay the partition of energy between the two electrons is such that the most likely to be recorded is one electron with energy 85% of maximum and another electron with 15%. The emission of electrons having equal energy or energy close to the extreme values is practically impossible. It should be noted that the function (5) gives only one of the possible variants of the spectrum, but all similar spectra, calculated under different initial assumptions [16], have the same characteristic features. Knowledge of these features of the spectrum is important in the practical realization of the experiment.

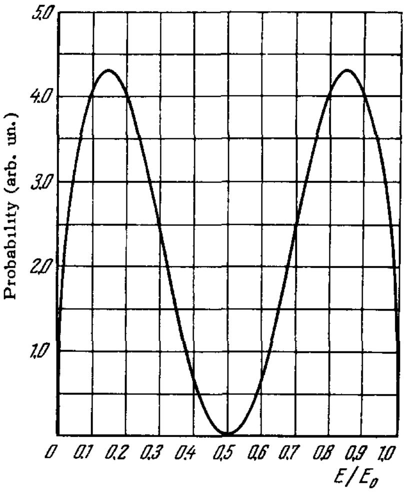

FIG. 1. Energy spectrum for one of the coinciding electrons in the case of neutrinoless double beta decay.

If the double beta decay is accompanied by the emission of two neutrinos, then the energy of the decay is distributed among four light particles (we can neglect the nuclear recoil energy). The spectrum of the total energy of the two electrons, unlike the preceding case, should be continuous. The form of the energy spectrum for this variant of the theory was calculated only recently, and we shall consider it in one of the following sections.

The half-lives calculated by Konopinski for both variants of the decay are given by the following roughly approximate formulas:

$$T_{1/2(\nu\pm\tilde{\nu})} = 10^{18}\left(\frac{10}{\varepsilon}\right)^{11}\left(\frac{60}{Z}\right)^{2}\ \text{years} \tag{7}$$

$$T_{1/2(\nu\equiv\tilde{\nu})} - 1.5\cdot10^{15}\left(\frac{8}{\varepsilon\quad 2}\right)^{6}\left(\frac{60}{Z}\right)^{2}\left(\frac{A}{150}\right)^{2/3}\ \text{years}. \tag{8}$$

Here ϵ is the total realizable energy of the nucleus in units of m_0c^2. The results obtained on the basis of these formulas for a number of elements in which double beta decay is possible are shown graphically in Fig. 2. The upper group of full points in this figure gives the half-life as a function of the maximum possible total kinetic energy of the electrons in the two-neutrino double beta decay, and the lower one gives the same for the neutrinoless decay. The experimental data, in which seemingly double beta decay was observed, are shown by the light circles, and those of experiments giving negative results, and thus establishing only the lower limit of the half-life, are shown by short horizontal bars. It is seen from the figure that the most promising for experimental attempts at observing double beta decay are Ca^{48}, Zr^{96}, Nd^{150}, and Te^{130}. It is seen from the same figure that the half-lives calculated for the cases $\nu \equiv \tilde{\nu}$ and $\nu \not\equiv \tilde{\nu}$ differ by 3–4 orders of magnitude:

$$\frac{T_{1/2(\nu\not\equiv\tilde{\nu})}}{T_{1/2(\nu\equiv\tilde{\nu})}} - 10^3 - 10^4.$$

At the present level of the experimental capabilities it is hardly meaningful to speak of measuring the

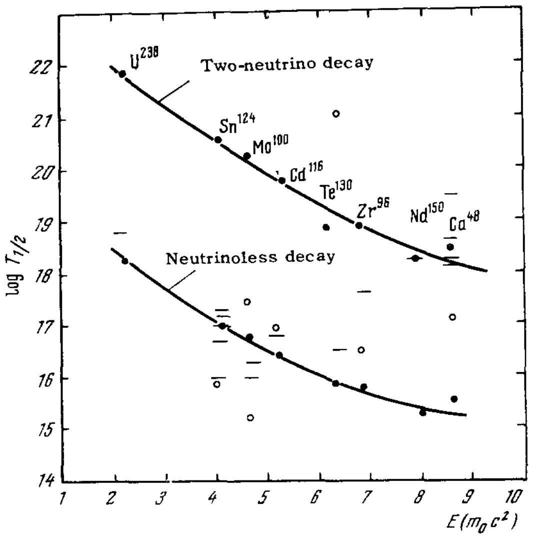

FIG. 2. Half-lives of $\beta\beta$-active nuclei. Theoretical and experimental results of [17].

angular correlation between the electrons of the double beta decay, but this circumstance should possibly be taken into account in the final reduction of the experimental results. Many investigators believe that the electrons emitted from the sample completely lose their initial angular correlation in the sample, and are thus already registered with an isotropic mutual distribution. This is a sufficiently likely hypothesis if it is recognized that most experiments are carried out with "thick" samples, as much as 100 mg/cm^2.

The electron angular correlation function for the neutrinoless double beta decay was calculated by Primakoff[16]:

$$F(\theta)=1+f(E_1,\ E_2)\cos\theta, \tag{9}$$

where f is a complicated function of the electron energy, which depends on the assumed variant of beta interaction. In a rough approximation, assuming realization of first-forbidden nuclear double beta transitions, when $f(E_1, E_2)\approx 1$, we have

$$F(\theta)\approx 1+\cos\theta. \tag{10}$$

A plot of this function is a cardioid, and consequently emission of two electrons from the nucleus in exactly opposite directions is excluded. The most probable is the angular correlation $-\pi/2\le\theta\le\pi/2$. This circumstance greatly reduces the efficiency of registration of the coincidences, lowering it by an approximate factor of 3.

Thus, during the first stage of development of beta-decay theory, when it was assumed that the parity is conserved in weak interactions, the theoretical investigations, based on an approximation of the experimental data obtained in the study of simple beta decay, have led to the following conclusions concerning the double beta decay: If the neutrino has an antiparticle ($\nu\not\equiv\tilde{\nu}$), then the spectrum of the summary energy of the electrons is continuous. Otherwise ($\nu\equiv\tilde{\nu}$), this spectrum has the form of a sharp peak in the region corresponding to the total energy of the decay of the $\beta\beta$-active nucleus. The latter process is more probable than the former by 3–4 orders of magnitude. For both variants, calculation formulas were obtained for the expected half-lives. A comparison of the theoretical estimates with the experimental results is shown in Table I.

If we disregard studies that yielded an affirmative result and were subsequently refuted by later research, as well as the studies[33,34] carried out by the "geological" method and whose affirmative results are quite doubtful for various reasons (see below), and if we finally take into account the error in the theoretical calculations (two orders of magnitude), then all that is left from the entire table are the investigations made with Ca^{48}, the results of which seem to go outside the limits of errors of the calculated lifetime for the neutrinoless double beta decay. However, if we take into account the possible decrease in the coincidence counting efficiency due to the proposed strong angular correlation of the electrons, then the results can still not be regarded as final evidence in favor of the realization of double beta decay with emission of two neutrinos. At the same time, these investigations cast doubts on the correctness of the assumption that $\nu\equiv\tilde{\nu}$.

2. DOUBLE BETA DECAY AND PARITY NONCONSERVATION IN WEAK INTERACTIONS

Our views concerning beta decay processes changed radically when the violation of the parity conservation law in weak interactions was established. This circumstance could likewise not fail to influence the problem of double beta decay. A complete discussion of this question at the contemporary level is contained in the review articles of Primakoff and Rosen[38] and of Fiorini[39]. We confine ourselves only to a concise exposition of the main modifications introduced in the problem of double beta decay by the new discoveries of nuclear physics.

The most interesting situation has developed for the neutrinoless double beta decay, the realization of which would be unrefutable evidence against the principle of lepton-charge conservation[40-44]. If the two-component neutrino theory is completely valid, then there is no such type of double beta decay at all. This theory[8] starts from the assumption that the rest mass of the neutrino is exactly equal to zero and that the parity is violated in weak interactions. The Dirac equation gives in this case two independent solutions corresponding to two different choices of the relation between the coupling constants, parity conserving or nonconserving (C_i and C_i', respectively, where i = S, V, T, A, P). Both solutions lead to equivalent results and differ only in that the neu-

Table I. Comparison of theoretical estimates with the experimental results

Transition	Realizable kinetic energy, MeV	Calculated half-life, years[17]		Experimental values of the half-lives, years
		Neutrinoless	Two-neutrino	
${}_{20}Ca^{48} \rightarrow {}_{22}Ti^{48}$	4.3 ± 0.1	$4 \cdot 10^{15}$	$4 \cdot 10^{18}$	$1{,}6 \cdot 10^{17}$? 18 $> 1 \cdot 10^{18}$ 19 $> 2 \cdot 10^{18}$ 20 $> 7 \cdot 10^{18}$ 21 $> 5 \cdot 10^{19}$ 22 $> 3 \cdot 10^{18}$ $(\nu \equiv \tilde{\nu})$ 22 $> 2 \cdot 10^{20}$ *) 65 $> 5 \cdot 10^{18}$ $(\nu \not\equiv \tilde{\nu})$*) 65
${}_{40}Zr^{96} \rightarrow {}_{42}Mo^{96}$	3.4 ± 0.3	$7 \cdot 10^{15}$	$9 \cdot 10^{18}$	$\approx 2-6 \cdot 10^{16}$? 23 $> 5 \cdot 10^{17}$ 20
${}_{42}Mo^{100} \rightarrow {}_{44}Ru^{100}$	2.3 ± 0.2	$6 \cdot 10^{16}$	$2 \cdot 10^{20}$	$\approx 1{,}5 \cdot 10^{16}$? 24 $> 3 \cdot 10^{17}$ 25
${}_{48}Cd^{116} \rightarrow {}_{50}Sn^{116}$	$2{,}6 \pm 0.1$	$3 \cdot 10^{16}$	$6 \cdot 10^{19}$	$> 1 \cdot 10^{17}$ 25 $> 6 \cdot 10^{16}$ 26 $> 1 \cdot 10^{17}$ 24
${}_{50}Sn^{124} \rightarrow {}_{52}Te^{124}$	$1{,}5 \pm 0.4$ 27 2.0 ± 0.2 28	$1 \cdot 10^{17}$	$4 \cdot 10^{20}$	$\approx 4-9 \cdot 10^{15}$? 5 $> 5 \cdot 10^{16}$ 29 $> 2 \cdot 10^{17}$ 30 $> 1 \cdot 10^{17}$ 31 $> 5 \cdot 10^{16}$ 32 $> 1{,}5 \cdot 10^{17}$ 23
${}_{52}Te^{130} \rightarrow {}_{54}Xe^{130}$	3.2 ± 0.1	$7 \cdot 10^{15}$	$9 \cdot 10^{18}$	$\approx 1{,}4 \cdot 10^{21}$? 33 $3{,}3 \cdot 10^{21}$? 34 $\approx (8{,}2 \pm 0{,}64) \cdot 10^{20}$ 64
${}_{60}Nd^{150} \rightarrow {}_{62}Sm^{150}$	3.7 ± 0.1	$2 \cdot 10^{15}$	$2 \cdot 10^{18}$	$> 2 \cdot 10^{18}$ 35 $> 2 \cdot 10^{15}$ 36
${}_{92}U^{238} \rightarrow {}_{94}Pu^{238}$	1.1	$2 \cdot 10^{18}$	$6 \cdot 10^{21}$	$> 6 \cdot 10^{18}$ 37

*This result is discussed at the end of Sec. 4.

trino polarization directions are opposite. Thus, if $C_i = -C_i'$, then the relative directions of the spin of the neutral lepton emitted in the decay of the neutron ("antineutrino") and of its momentum can be arbitrarily denoted by ↑↓, and those of the neutral lepton obtained in positron decay ("neutrino") by ↑↑. On the other hand, if $C_i = C_i'$, then the "antineutrino" should be marked ↓↑ and the "neutrino" ↓↑. Yang and Lee did not consider the possibility of simultaneous realization of both solutions of Dirac's equation and confined themselves to one of them. An argument in favor of such a choice was the failure to observe double beta decay in the experiments.

Goeppert-Mayer and Telegdi[45] proposed the theory of "neutrino twins," using both solutions of the Dirac equation. This theory is characterized by the presence of two "neutrino - antineutrino" pairs, the neutrino of the first pair having a longitudinal polarization identical with that of the antineutrino of the other pair, and vice versa. The first pair is identified with transitions of the scalar and axial type, and the second with the vector and the tensor transitions. Thus, according to this theory the decay of nucleon can proceed in two ways:

$$\left.\begin{array}{l} n \xrightarrow{S(A)} p + e^- + \tilde{\nu}_1(\uparrow) \\ p \xrightarrow{S(A)} n + e^+ + \nu_1(\downarrow) \end{array}\right\} \text{ or } \left.\begin{array}{l} n \xrightarrow{T(V)} p + e^- + \tilde{\nu}_2(\downarrow) \\ p \xrightarrow{T(V)} n + e^+ + \nu_2(\uparrow) \end{array}\right\}, \qquad (11)$$

where $\nu_1 \equiv \nu_l$ and $\nu_2 \equiv \nu_r$. The arrows denote arbitrarily the directions of the neutrino spin, and ν_l and ν_r denote the left- and right-helical polarization respectively. Such a theory, without contradicting the available experimental data, admits in principle the existence of a neutrinoless double beta decay.* Its authors believe that such a process is connected with an additional forbiddenness. Since each degree of forbiddenness entails a decrease in the probability of the double beta decay by approximately 4—5 orders, this means an increase in the expected lifetime for the neutrinoless process, in the case of Ca^{48}, to 10^{19}—10^{20} years.

There are two other ways that leave room for neutrinoless double beta decay. The first presupposes that the neutrino has a finite mass, and the second is connected with denial of total longitudinal polarization of the neutrino in the virtual intermediate state. Both possibilities were considered in a paper by Greuling and Whitten[48].

Let us dwell in greater detail on modern theoretical

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*Touschek [46] in 1948 and Tiomono [47] in 1950 proposed a similar theory, postulating, however, the conservation of parity in weak interactions. According to these authors, a neutrinoless double beta decay is also possible with $\nu \equiv \tilde{\nu}$, but of course with violation of the conservation of the lepton charge.

Table II. Half-lives for the two-neutrino process with account of parity nonconservation[38]

Transition	Realized energy, MeV	Calculated half-life $T_{1/2}$, years
${}_{52}Te^{130} \rightarrow {}_{54}Xe^{130}$	3.0	$2\cdot 10^{21\pm 2}$
${}_{92}U^{238} \rightarrow {}_{94}Pu^{238}$	1.0	$3\cdot 10^{25\pm 2}$
${}_{50}Sn^{124} \rightarrow {}_{52}Te^{124}$	2.2	$4\cdot 10^{22\pm 2}$
${}_{48}Cd^{116} \rightarrow {}_{50}Sn^{116}$	2.7	$6\cdot 10^{21\pm 2}$
${}_{42}Mo^{100} \rightarrow {}_{44}Ru^{100}$	2.3	$4\cdot 10^{22\pm 2}$
${}_{48}Cd^{106} \rightarrow {}_{46}Pd^{106}$	0.9	$2\cdot 10^{28\pm 2}$
${}_{40}Zr^{96} \rightarrow {}_{42}Mo^{96}$	3.3	$1\cdot 10^{21\pm 2}$
${}_{20}Ca^{48} \rightarrow {}_{22}Ti^{48}$	4.3	$4\cdot 10^{20\pm 2}$
${}_{60}Nd^{150} \rightarrow {}_{62}Sm^{150}$	3.7	$2\cdot 10^{20\pm 2}$
${}_{30}Zn^{64} \rightarrow {}_{28}Ni^{64}$	1.1	$1\cdot 10^{30\pm 2}$

results for both types of double beta decay. The reviews of Primakoff and Rosen and of Fiorini contain calculations of the half-life for both variants. In particular, the results for the two-neutrino decay is listed in Table II. For the case of Ca^{48}, a similar estimate was made by Belyaev and Zakhar'ev[49], who used the nuclear shell model. Their result, $T_{1/2} = 1 \times 10^{19}$ years, is in good agreement both with data of the table and with the data of Fiorini ($8 \times 10^{19\pm 2}$ years).

It is easy to note that the results presented in Table II agree with earlier theoretical estimates of the half-life listed in Table I.

The form of the total-electron-energy spectrum for the two-neutrino double beta decay was calculated by Rosen[50]. As expected, this is a continuous spectrum with a broad maximum near $E_0/2$, where E_0 is the realized kinetic energy of the decay. Such a spectrum, calculated for Ca^{48}, is shown in the upper part of Fig. 3. In the lower part of the same figure is shown the expected single-electron spectrum for the same process.

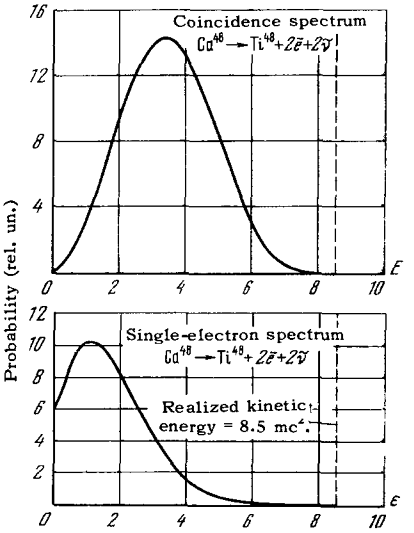

FIG. 3. Energy spectrum of two electrons (top) and of one of them (bottom) in the $\beta\beta$-decay $ca^{48} \rightarrow Ti^{48} + 2e^- + 2\tilde{\nu}$.

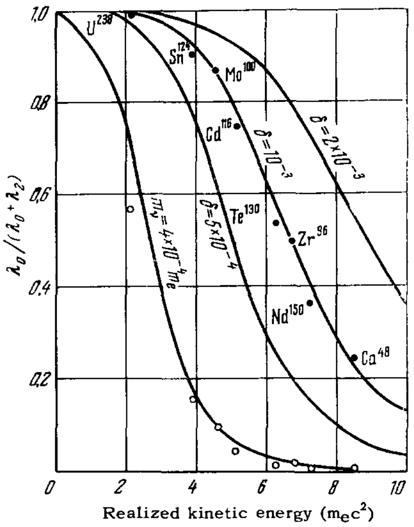

FIG. 4. Relative probability of neutrinoless $\beta\beta$ process vs. decay energy under different assumptions concerning the neutrino mass and the degree of their longitudinal polarization.

Thus, at the present stage of the development of the theory no changes have occurred with respect to the two-neutrino double beta decay. The situation is entirely different for the neutrinoless process. Greuling and Whitten[48] present an expression for the decay probability ratio in the case of a finite neutrino mass and parity-conservation violation:

$$\frac{\lambda_2}{\lambda_0} = 1.3\cdot 10^{-13} A^{2/3} m_\nu^{-2} (E_0 + 2)^7. \qquad (12)$$

Here λ_2 and λ_0 are the probabilities of the two neutrino and the neutrinoless processes, respectively, and m_ν and E_0 are the mass of the neutrino and the kinetic energy of the decay in m_ec^2 units. Figure 4 shows a plot of the ratio $\lambda_0/(\lambda_0 + \lambda_2)$, using the maximum value of the neutrino mass $m_\nu = 4 \times 10^{-4} m_e$. The same figure shows a plot of the same quantity for the case when $m_\nu = 0$, but with violation of the 100% longitudinal polarization. The ratio corresponding to this case is

$$\frac{\lambda_2}{\lambda_0} = 7.6\cdot 10^{-11} \delta^{-2} \left(\frac{A}{100}\right)^{2/3} \left(\frac{40}{z}\right)^{1/2} E_0^5, \qquad (13)$$

where δ is a quantity characterizing the degree of deviation of the neutrino from total longitudinal polarization. The authors note that, in accordance with the existing experimental data on longitudinal lepton polarization, values of $\delta > 0.1$ are feasible.

The spectra of the single-electron energies, calculated for neutrinoless double beta decay under the assumption that $m_\nu c^2 = 200$ eV and $\delta = 0$ (upper diagram) and $|\delta| = 10^{-3}$ and $m_\nu = 0$ (lower diagram) are shown in Fig. 5. It follows from these curves that the spectra of the single electron depend strongly on which of the initial assumptions actually holds. They differ from the spectrum obtained under parity-conservation assumption (Fig. 1) primarily by the large

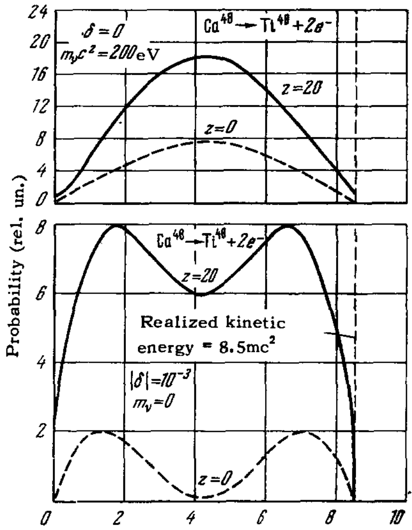

FIG. 5. Energy spectra of one of the coinciding electrons in the neutrinoless $\beta\beta$ decay $ca^{48} \to Ti^{48} + 2e^-$, in the case of a finite neutrino mass (top) and incomplete longitudinal neutrino polarization (bottom).

probability of emission of two electrons with equal energy.

Thus, within the framework of present-day notions, with account taken of parity nonconservation and of violation of the lepton charge conservation, one cannot exclude the feasibility of double beta decay without neutrino emission. It is necessary to realize in addition at least one of the following assumptions: presence of mixed transitions, finite neutrino mass, or, finally, departure from 100% longitudinal polarization of the virtual neutrino. All the possible variants lead to a strong decrease in the probability of the neutrinoless process, which becomes comparable in order of magnitude with the probability of the two neutrino double beta decay. In the case of simultaneous existence of both types of double beta decay, with comparable probabilities, the form of the coincidence spectrum will be approximately as follows: a broad maximum near half the decay energy, and a sharp peak at the upper limit of the spectrum, due to the neutrinoless process. The latter will lie much higher than the flat maximum, since the ratio of the areas of the spectra is a reflection of the relative probability of the processes.

3. INVERSE BETA PROCESSES

The problem of double beta decay is closely related to the general properties of the neutrino, a particle which is even now puzzling in many respects. The possible double beta decay processes depend strongly on whether the neutrino emitted from the nucleus during the beta decay is fully polarized, whether neutrinos of opposite polarization can be emitted in the beta decay, whether the lepton charge is conserved, and, finally, whether the neutrino and antineutrino are identical and whether the neutrino has a rest mass. To answer these questions we must investigate processes in which the neutrino participates. In particular, certain information can be obtained by investigating inverse beta processes. Let us examine briefly the situation with these experiments.

Besides the neutron and proton decay reactions (1)

$$n \to p + e^- + \tilde{\nu}; \quad p \to n + e^+ + \nu$$

there exist also the inverse reactions

$$\nu + n \to p + e^-, \tag{13}$$

$$\tilde{\nu} + p \to n + e^+. \tag{14}$$

These reactions can be readily obtained from the reactions (1) by recognizing, on the one hand, that the left side contains the annihilated particles and the right side the created ones, and on the other hand that creation of a particle is equivalent to annihilation of an antiparticle and vice versa. Processes (13) and (14) are beta decay processes induced by a flux of light leptons. If the neutrino and antineutrino are different particles, then the induced β^- decay (13) can occur only in a flux of neutron leptons obtained from positron decay, while the induced positron decay (14) can be obtained in a flux of neutron leptons created in β^- decay. By virtue of the extremely small effective cross section of the inverse beta reactions, powerful neutrino fluxes are necessary for their experimental investigation. Such fluxes are produced, in particular, by modern atomic reactors, in which numerous successive β^- transmutations of elements are produced during the decays of the fission fragments, which have great neutron excesses. A powerful source of a neutral-lepton flux is the sun, in which carbon-cycle processes connected with the positron decays of N^{13} and O^{15} occur continuously. The sun, however, is a very inconvenient source for experimental research of this type. The point is that we are unable to "switch off" the beta processes occurring in the sun, even for a short time, and the earth itself is not a sufficiently thick shield against the neutrino fluxes, so that it is impossible to control the background which may be due to processes other than inverse beta reactions.

Thus, if we assume that the neutrino has a antiparticle, then the only inverse beta process accessible so far to experimental study is (14). The first unsuccessful attempt to observe this reaction was undertaken in 1939 by Crane[51]. It was observed first by Cowan and Reines[52,53], who also measured in 1956 and 1959[54,55] the effective cross section of the process, $\sigma_{exp} = (11 \pm 2.6) \times 10^{-44}$ cm^2, which they found to agree with the calculated value.

If we assume that the neutrino and antineutrino are identical, then realization of reaction (13) becomes feasible in a flux of neutrinos from a nuclear reactor. An experimental investigation of this process is much more complicated than that of (14), owing to the difficulty in reducing the background, which could be overcome in the experiments of Cowan and Reines by using quadruple shifted coincidences (two γ quanta in the annihilation of the positron plus several quanta after slowing down the neutron by cadmium capture). A method of observing the reaction $\tilde{\nu} + n \rightarrow p + e^-$ was proposed by B. M. Pontecorvo[56]. If this reaction is actually realized, then it is possible to realize in an antineutrino flux the process $Cl^{37} + \tilde{\nu} \rightarrow Ar^{37} + e^-$. The produced Ar^{37} experiences K capture with a half-life of 34 days. The latter process can be registered with a Geiger counter after separating the argon from the irradiated substance. The separation can be effected by physical means. Such an experiment was carried out by Davis[57]. The result was negative: all that could be established was an upper limit for the cross section of this process, $\sigma_{exp} < 0.9 \times 10^{-45}$ cm^2, whereas the expected theoretical value was $\sigma_t = 2.6 \times 10^{-45}$ cm^2. This result is evidence in favor of a difference between the neutrino and the antineutrino, and confirms that only one perfectly definite type of neutrino (antineutrino) is produced in β^- decay.

4. METHODS OF INVESTIGATING DOUBLE BETA DECAY

In all the observable double beta decays, the parent (A, Z) and daughter (A, Z ± 2) nuclei are even-even. It is usually assumed that double beta transitions occur between the ground states of the parent and daughter nuclei. However, such transitions to the excited levels of the daughter nucleus are also possible. The intermediate nuclei (A, Z ± 1), which lie between the parent and the daughter, are inessential, for two reasons:

a) Single beta decay of the (A, Z) nucleus to any level of the (A, Z ± 1) nucleus is forbidden by energy considerations.

b) Such a decay may be energetically feasible, say, to the ground state of the (A, Z ± 1) nucleus, but the spin change associated with this is so large, that the double beta decay (A, Z) → (A, Z ± 2) is more probable by a large factor.

Case b) takes place, for example, in the triad $Ca^{48} - Sc^{48} - Ti^{48}$, where the double beta decay $Ca^{48} \rightarrow Ti^{48}$ should proceed at a much higher rate than the energetically feasible but sixfold forbidden single beta decay $Ca^{48} \rightarrow Sc^{48}$, the half-life of which is, according to Feenberg[58], of the order of $10^{24} - 10^{25}$ years. The energy level scheme for this triad is shown in Fig. 6.

The realizable energy of double beta decay is taken to be the maximum possible kinetic energy of any of the emitted beta particles, assuming that the neutrino mass is zero and that the recoil energy of the daughter nuclei is negligible. If energy is conserved, this quantity (divided by c^2) should be equal to the difference between the atomic masses of the parent and daughter nuclei in the case of $\beta^-\beta^-$ decay, or to the same difference reduced by four electron masses in the case of $\beta^+\beta^+$ decay. In double beta processes connected with emission of one positron and simultaneous K-capture of one orbital electron (which is bound to the K-shell of the atom with an energy η_K), the realizable energy of the process, which is identical with the maximum kinetic energy of the positron, is smaller than the mass difference of the parent and daughter nuclei ($\times c^2$) by $(2m_0c^2 + \eta_K)$; if this decay is neutrinoless, then the positrons are monoenergetic. Finally, in processes in which two orbital electrons are captured (KK capture), the realizable energy (which is equal to the maximum possible energy of any of the emitted neutrinos or, if the decay is neutinoless, to the energy of the internal bremsstrahlung photon emitted by the daughter nucleus) is smaller by $2\eta_K$ than the difference between the atomic masses of the nuclei.

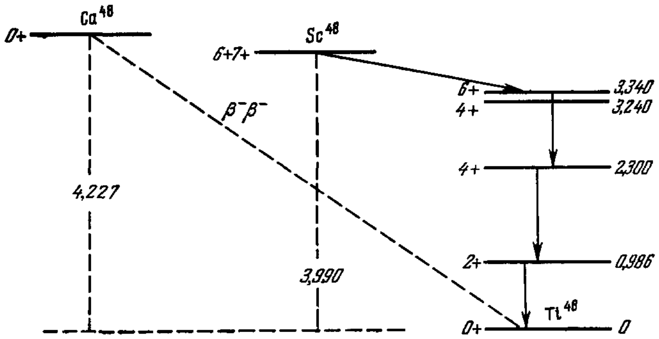

FIG. 6. Energy level scheme for the nuclei of the triad $Ca^{48} - Sc^{48} - Ti^{48}$.

Table III lists the possible $\beta^-\beta^-$ transitions and the percentage concentration of the initial substance in the natural isotope mixture, the mass difference in mass units, and the realizable energy in MeV. The next table, IV, gives the same values for double beta decays connected with double positron decay and KK capture. The realizable decay energy is calculated in this case for KK capture, and it is shown in parentheses for those cases when double positron decay is energetically feasible.

It is quite obvious that isotope pairs having a small mass difference are the most promising for attempts to observe double beta decay. In this case we have, besides a large realizable energy, also the maximum decay probability, owing to the large volume in phase space. It follows from the data of Tables III and IV that such pairs are $Ca^{48} - Ti^{48}$, $Nd^{150} - Sm^{150}$, $Zr^{96} - Mo^{96}$, and $Te^{130} - Xe^{130}$. Thus, the choice of isotopes similar to Sn^{124} for the experiment is presently not justified. Attempts to observe double positron decay and KK capture are apparently likewise quite lacking in promise.

Table III. Possible double electron decays[39]

Transition	Isotopic concentration, per cent [59]	Mass difference in mMU	Realizable decay energy (MeV)	
			Duckworth[60]	Other authors
${}_{20}Ca^{46} \to {}_{22}Ti^{46}$	0.0033	0,71±0,16	0.66±0,15	0.984±0.004
${}_{20}Ca^{48} \to {}_{22}Ti^{48}$	0.185	4,54±0.11	4.23±0,10	4.270±0.006
${}_{30}Zn^{70} \to {}_{32}Ge^{70}$	0,62	1,062±0.150	0.99±0.14	
${}_{32}Ge^{76} \to {}_{34}Se^{76}$	7,67	2,04±0.18	1.90±0.17	
${}_{34}Se^{80} \to {}_{36}Kr^{80}$	49.8	0.12±0.14	0.11±0.13	0,11±0,02
${}_{34}Se^{82} \to {}_{36}Kr^{82}$	9,2	3,20±0.21	2.98±0.20	
${}_{36}Kr^{86} \to {}_{38}Sr^{86}$	17,4	1,44±0.21	1.34±0.20	
${}_{40}Zr^{94} \to {}_{42}Mo^{94}$	17,4	1.22±0,60	1,14±0,56	
${}_{40}Zr^{96} \to {}_{42}Mo^{96}$	2.8	3,63±0.50	3.38±0,47	
${}_{42}Mo^{100} \to {}_{44}Ru^{100}$		9,62		2.3±0.2
${}_{44}Ru^{104} \to {}_{46}Pd^{104}$	18,5	1,21±0,32	1,13±0.30	
${}_{46}Pd^{110} \to {}_{48}Cd^{110}$	12.7±0,9	1.59±0.57	1,48±0.53	
${}_{48}Cd^{114} \to {}_{50}Sn^{114}$	28.9	0,61±0.50	0.57±0.47	0,56±0.03
${}_{48}Cd^{116} \to {}_{50}Sn^{116}$	7,6	2.80±0,46	2.61±0,43	
${}_{50}Sn^{122} \to {}_{52}Te^{122}$	4,7	0,42±0,43	0.39±0.40	0,42
${}_{50}Sn^{124} \to {}_{52}Te^{124}$	6.0	2.48±0.42	2.31±0.39	
${}_{52}Te^{128} \to {}_{54}Xe^{128}$	31,8	0.88±0.71	0.82±0.66	
${}_{52}Te^{130} \to {}_{54}Xe^{130}$	34.5	3,15±0.40	2,93±0.37	
${}_{54}Xe^{134} \to {}_{56}Ba^{134}$	10.4	1.01±0.14	0,94±0,13	1.08±0.09
${}_{54}Xe^{136} \to {}_{56}Ba^{136}$	8,9	2.870±0 093	2.67±0.09	2.64±0.09
${}_{58}Ce^{142} \to {}_{60}Nd^{142}$	11,1	1,71±0.12	1.59±0.11	1,69±0 07
${}_{60}Nd^{148} \to {}_{62}Sm^{148}$	5,71±0.05	2.04±0,21	1.90±0.20	
${}_{60}Nd^{150} \to {}_{62}Sm^{150}$	5.60±0.05	3.92±0.10	3.65±0.09	
${}_{62}Sm^{154} \to {}_{64}Gd^{154}$	22.61±0.37	0.97±0.38	0,90±0,35	
${}_{64}Gd^{160} \to {}_{66}Dy^{160}$	21,75±0.15	1.50±1.00	1 40±0,93	
${}_{92}U^{238} \to {}_{94}Pu^{238}$	99.3			1.0

Let us consider various methods used in experimental attempts to observe double beta decay. Besides original articles, numerous experiments in this field have been described many times in the literature[14,17,38,39], so that we can confine ourselves, without stopping to discuss each of them separately, only to the detailed summary table of experiments given at the end of this review.

Phenomena similar to double beta decay, which have extremely low probability, can be observed only if the background that makes the effect is suppressed to the maximum degree. Such a background is produced by cosmic radiation, by natural radioactivity of objects surrounding the installation (walls, ground), and also radioactive impurities in structural materials, such as K^{40} in glass. It is possible to reduce the background appreciably by surrounding the installation with a layer of heavy matter (lead, bismuth, iron, mercury) of sufficient thickness. Appreciable reduction in the cosmic-ray background is attained by burying the installation underground at a depth of several dozen and sometimes several hundred meters. The most modern experiments are carried out precisely under such conditions.

The background can be further reduced by special constructions that permit selection of events corresponding to specified parameters. These parameters include:

a) beta-particle identification,

b) emission of particles from one point of the sample,

c) simultaneity of emission of two particles,

d) registration of events contained in a limited energy interval,

e) elimination of events originating outside the installation.

It should be noted that in none of the published attempts to observe double beta decay were all these conditions satisfied completely.*

All the experiments for double beta decay can be divided into three groups:

a) Observation of daughter decay elements (A, Z ± 2) in investigations of a source containing the isotope (A, Z).

b) Observation, in a cloud chamber or in emulsion,

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*According to a report by Bardin, Ullman, and Wu for 1964-1965 [63], They are getting ready for an experiment on double beta decay in Ca^{48}, in which all the foregoing even-selection parameters will be used. Such an attempt, when using a large amount of matter (10.5 g of Ca^{48}) will probably yield in contestable data at the 10^{20} - 10^{21} yr level.

Table IV. Possible double electron captures and double positron decays[39]

Transition	Isotopic concentration, per cent [59]	Mass difference in mMU	Realizable decay energy (MeV)	
			Duckworth [60]	Other authors
${}_{18}Ar^{36} \to {}_{16}S^{36}$	0,34			0.486
${}_{20}Ca^{40} \to {}_{18}Ar^{40}$	97.0	0.242±0,030	0.23±0.03	0.17±0,01
${}_{24}Cr^{50} \to {}_{22}Ti^{50}$	4.3	1,15±0.11	1.07±0.10	1.175±0.003
${}_{26}Fe^{54} \to {}_{24}Cr^{54}$	5.8	0,680±0.076	0,63±0.07	
${}_{28}Ni^{58} \to {}_{26}Fe^{58}$	67.8	2,036±0,012	1.90±0.01	1.896±0.007
${}_{30}Zn^{64} \to {}_{28}Ni^{64}$	48.9	1,187±0.007	1.105±0.006	1.053±0.006
${}_{34}Se^{74} \to {}_{32}Ge^{74}$	0.87	1.31±0,18	1.22±0.17	1,19±0.02
${}_{36}Kr^{78} \to {}_{34}Se^{78}$	0.354	2.81±0.21	2.62±0,20 (0.57±020)	
${}_{38}Sr^{84} \to {}_{36}Kr^{84}$	0.555±0.005	1.74±0.21	1.62±0.20	1.74
${}_{42}Mo^{92} \to {}_{40}Zr^{92}$	15.9	1.72±0.57	1.60±0.53	
${}_{44}Ru^{96} \to {}_{42}Mo^{96}$	5.59±0.05	3.02±0.50	2.81±0.47 (0,77±0.47)	
${}_{46}Pd^{102} \to {}_{44}Ru^{102}$	0,88±0.08	1.30±0,32	1.21±0,30	1.11
${}_{48}Cd^{106} \to {}_{46}Pd^{106}$	1.22	2,86±0.50	2.66±0,47 (0,62±0,47)	
${}_{50}Sn^{112} \to {}_{48}Cd^{112}$	0.95	2.02±0.50	1.88±0.47	1,862±0.009
${}_{52}Te^{120} \to {}_{50}Sn^{120}$	0.089	1.97±0.42	1,83±0,39	
${}_{54}Xe^{124} \to {}_{52}Te^{124}$	0,096	2.92±0.42	2.72±0.39 (0.68±0.39)	
${}_{54}Xe^{126} \to {}_{52}Te^{126}$	0.090	0.96±0.42	0,89±0.39	0.97±0,02
${}_{56}Ba^{130} \to {}_{54}Xe^{130}$	0.115±0.015	2.74±0.05	2.55±0.05 (0.51±0.05)	2,53±0.09 (0.51±0.05)
${}_{56}Ba^{132} \to {}_{54}Xe^{132}$	0,144±0,046	0.89±0.13	0,83±0,12	
${}_{58}Ce^{136} \to {}_{56}Ba^{136}$	0,19	2,73±0.22	2.54±0,21 (0.50±0.21)	
${}_{58}Ce^{138} \to {}_{56}Ba^{138}$	0.250	1.140±0.215	1,06±0,20	1,19
${}_{62}Sm^{144} \to {}_{60}Nd^{144}$	3,11±0.04	1,95±0,14	1.82±0.13	1,72±0,13

of beta-particle tracks that start in a common point of the sample containing the investigated $\beta\beta$-active isotope.

c) Determination of the number of decays occurring in a sample containing the investigated isotope, using elementary-particle counters.

Method a) makes it possible to determine only the decay rate, whereas the remaining methods yield also the energy characteristics of the process. In this method a mixture of isotopes of the daughter element, which might have been produced as a result of double beta decay, is extracted from mineral rocks of known age and composition, containing the investigated isotope, or else from a pure isotope of known age. The daughter isotope is detected either by mass analysis or, if radioactive, by measuring the radioactivity. An advantage of this method is the possibility of increasing the "time of the experiment" to geological scales. However, the impossibility of proving that the observed daughter isotope is precisely a result of double beta decay, and is not a product of some other processes, makes affirmative results obtained by this method doubtful. Thus, for example, in the case of experiments with the $Te^{130} \to Xe^{130}$ transition[33,34], the probability of the successive process $Te^{130} \to I^{130} \to Xe^{130}$, as shown by Feenberg[58] and a few other workers, is comparable with the probability of the possible double beta decay.

Takaoka and Ogata[64] have proposed a method which can increase the reliability of operations performed by this method, consisting in the following. Mass spectrometry is used to determine the concentration of the daughter products of double beta decay of several elements, after which the dependence of the half-lives measured in this manner on the decay energy is compared with the theoretical predictions. Such a comparison can identify the nature of the observed activity.

The use of nuclear emulsions to observe double beta decay (method b)) is convenient because it makes it possible to investigate amounts of matter on the order of grams in an experiment time amounting to several months. This method, however, has serious shortcomings, such as lack of proof that two beta particles have been emitted from a single point, and the impossibility of excluding external causes of electron tracks (due to double Compton scattering, pair production, etc.). This method was used by Fremlin and Walters[24] to investigate a large number of isotopes, but in interpreting the photographic plates they counted only the total number of electron tracks per unit surface, without separating the double tracks emerging from a single point. This circumstance, by greatly deteriorating the quality of the results, casts very serious doubts on the positive results obtained by them for the transitions $Mo^{100} \rightarrow Ru^{100}$ and $Mo^{92} \rightarrow Zr^{92}$.

If a cloud chamber is used in the experiment, it becomes possible to exclude a large number of background events. This instrument makes it possible to identify beta particles, to determine with sufficient accuracy the point of their creation, and their energy. Comparing the "age" of the tracks, it is possible to establish time coincidence of two events with accuracy to 0.05 sec. The relatively strong limitations that arise when this perfect instrument is used to investigate such rare events as double beta decay are connected with the short sensitivity time. The latter circumstance can be well illustrated by the following examples. In his experiments with Sn^{124}, Lawson[29] obtained approximately 9000 photographs, and the total sensitivity time of the chamber amounted to only slightly more than one hour (4000 sec). In one of the experiments of Winter[25], 10 000 photographs corresponded to a total sensitivity time of 1400 sec.

Needless to say, it is possible to use cloud chambers which are triggered only by a signal produced by the appearance of two electrons in their fiducial volume, but this is frequently difficult to realize when an appreciable amount of matter is used. Such a chamber, triggered by two thin-walled Geiger counters placed on both sides of the sample, was used by Fireman and Schwartzer[31] in an experiment aimed at checking the positive result obtained by one of the authors with Sn^{124} in an experiment with gas counters. They believe that the use of a triggered chamber has made it possible to increase the effective measurement time by a factor of 1500. There are no published reports of experiments on double beta decay with a triggered cloud chamber protected against external radiation by a system of anticoincidences.

Going over to a consideration of the procedure in which elementary-particle counters are used, it should be noted that Geiger counters were used only in the first attempts at observing double beta decay. Scintillation counters are much more suitable for research of this type, since they make it possible also to register the decay-electron energy. Proportional counters can be used only in the investigation of such frequent modifications of the $\beta\beta$ process as double electron capture.

An important feature of experiments with scintillation counters is highly accurate registration of the simultaneity of emission of two electrons. Such a method of operating with coincidences results in a very strong reduction of the background. Further reduction of the background has been attained in modern investigations by immersing the counting apparatus in a liquid scintillation counter connected for anticoincidence with the "working" photomultipliers.

A highly important factor is a correct choice of the optimal thickness of the scintillator for the "working" photomultipliers. For example, the fact that Cowan et al.[35], experimenting with Nd^{150}, used a scintillator 7.5 cm thick (in place of the perfectly adequate 1.5—2 cm) has undoubtedly led to an appreciable increase in the background. Unfortunately, the counter method does not have the advantages inherent in the cloud-chamber and emulsion methods, which make it possible to localize in space the point of particle emission, and which also permit the particle charge and mass to be determined. In spite of this, most better investigations were those in which scintillation counters were used.

Mateosian and Goldhaber[65], in an experiment aimed at observing double beta decay, gave up the coincidence procedure, using as the scintillator a calcium fluoride crystal activated with europium, containing 11.4 g of Ca^{48} with isotopic concentration 96.59%. A similar crystal, containing calcium enriched with Ca^{40}, was used for comparison. Each of the crystals, which were placed in tandem, was serviced by a separate photomultiplier. Both scintillation counters were inside a cavity in a plastic scintillator, with the aid of which anticoincidence protection was afforded. The entire apparatus was placed inside the barrel of a naval gun with 14″ wall thickness.

Placement of the investigated isotope directly in the scintillator ensures a 4π geometry of the experiment, thus providing a gain in the counting efficiency by a factor not less than 2, and ensuring independence of the result of any possible angular correlation of the double beta decay electrons. At the same time, the lack of coincidences makes it impossible to distinguish between double decays and single processes, thus reducing to some extent the reliability of the experimental result.

Radioactive contamination of the crystal containing the Ca^{48} did not prevent the authors from carrying out an experiment on observation of the neutrinoless process, since the analysis of the obtained energy spectra was carried out in this case in a narrow region near 4.3 MeV, where the background is small. However, in an attempt to observe the double beta decay accompanied by production of two antineutrinos, the authors were forced to employ a coincidence method, after first preparing a sample of suitable thickness from the crystal material.

Unfortunately, the report by Mateosian and Goldhaber does not mention such important data as the energy resolution of the counters and the statistics of the experiment. This makes it impossible to evaluate fully the result of this experiment. The authors state that for the case of the neutrinoless process the

Table V. Experiments on double electron decay. Investigations in which a special study was made of the two neutrino double beta decay method are marked by $(\nu \not\equiv \tilde{\nu})$

Transition	Authors and experimental procedure*	Result of experiment	Obtained half-life (years)	Calculated half-life [39] (years)	
				Neutrinoless	Two-neutrino
${}_{20}\mathrm{Ca}^{48} \rightarrow {}_{22}\mathrm{Ti}^{48}$	[24] P.e.	Negative	$> 7 \cdot 10^{16}$	$2.6 \cdot 10^{15 \pm 2}$	$8 \cdot 10^{19 \pm 2}$
	18 S.c.	Affirmative?	$= 1{,}6 \cdot 10^{17}$		
	[20] S.c.	Negative	$> 2 \cdot 10^{18}$		
	[19] S.c.	Negative	$> 1 \cdot 10^{18}$		
	[21] S.c.	Negative	$> 7 \cdot 10^{18}$		
	[22] S.c.	Negative	$> 5 \cdot 10^{19}$		
	[22] S.c.	Negative	$> 3 \cdot 10^{18}$ $(\nu \not\equiv \tilde{\nu})$		
	[65] S.c.	Negative	$> 2 \cdot 10^{20}$		
	[65] S.c.	Negative	$> 5 \cdot 10^{18}$ $(\nu \not\equiv \tilde{\nu})$		
${}_{32}\mathrm{Ge}^{76} \rightarrow {}_{34}\mathrm{Se}^{76}$	[24] P.e.	Negative	$> 2{,}8 \cdot 10^{17}$	$1 \cdot 10^{17 \pm 2}$	$8.5 \cdot 10^{22 \pm 2}$
${}_{40}\mathrm{Zr}^{96} \rightarrow {}_{42}\mathrm{Mo}^{96}$	[23] S.c.	Affirmative	$= 6 \cdot 10^{16}$	$4{,}6 \cdot 10^{15 \pm 2}$	$2 \cdot 10^{20 \pm 2}$
	[20] S.c.	Negative	$> 5 \cdot 10^{17}$		
${}_{42}\mathrm{Mo}^{100} \rightarrow {}_{44}\mathrm{Ru}^{100}$	[24] P.e.	Affirmative?	$= 1{,}5 \cdot 10^{16}$	$3 \cdot 10^{16 \pm 2}$	$6 \cdot 10^{21 \pm 2}$
	[25] C.c.	Negative	$> 3 \cdot 10^{17}$		
${}_{46}\mathrm{Pd}^{110} \rightarrow {}_{48}\mathrm{Cd}^{110}$	[61] C.c.	Negative	$> 1{,}1 \cdot 10^{18}$	$2{,}6 \cdot 10^{17 \pm 2}$	$1 \cdot 10^{24 \pm 2}$
${}_{48}\mathrm{Cd}^{116} \rightarrow {}_{50}\mathrm{Sn}^{116}$	[24] P.e.	Negative	$> 1 \cdot 10^{17}$	$1.4 \cdot 10^{16 \pm 2}$	$3 \cdot 10^{21 \pm 2}$
	[26] S.c.	Negative	$> 6 \cdot 10^{16}$		
	[25] C.c.	Negative	$> 1 \cdot 10^{17}$		
${}_{50}\mathrm{Sn}^{124} \rightarrow {}_{52}\mathrm{Te}^{124}$	[6] G.M.c.	Affirmative?	$= 6.5 \cdot 10^{15}$	$2.5 \cdot 10^{16 \pm 2}$	$7 \cdot 10^{21 \pm 2}$
	[29] C.c.	Negative	$> 5 \cdot 10^{16}$		
	[30] G.M.c.	Negative	$> 2 \cdot 10^{17}$		
	[24] P.e.	Negative	$> 2 \cdot 10^{15}$		
	[31] C.c.	Negative	$> 1 \cdot 10^{17}$		
	[32] S.c.	Negative	$> 5 \cdot 10^{16}$		
	[23] S.c.	Negative	$> 1.5 \cdot 10^{17}$		
${}_{52}\mathrm{Te}^{128} \rightarrow {}_{54}\mathrm{Xe}^{128}$	[7] Chem.s.	Negative	$> 8 \cdot 10^{19}$	$4.4 \cdot 10^{18 \pm 2}$	$4 \cdot 10^{25 \pm 2}$
	[24] P.e.	Negative	$> 1.3\ 10^{16}$		
	[64] Chem.s.	Negative	$> 3 \cdot 10^{22}$		
${}_{52}\mathrm{Te}^{130} \rightarrow {}_{54}\mathrm{Xe}^{130}$	[33] Chem.s.	Affirmative?	$= 1.4 \cdot 10^{21}$	$7.4 \cdot 10^{15 \pm 2}$	$5 \cdot 10^{20 \pm 2}$
	[24] P.e.	Negative	$> 1.3 \cdot 10^{16}$		
	[34] Chem.s.	Affirmative?	$= 3.3 \cdot 10^{21}$		
	[64] Chem.s.	Affirmative?	$= (8.20 \pm 0.64) \cdot 10^{20}$		
${}_{60}\mathrm{Nd}^{150} \rightarrow {}_{62}\mathrm{Sm}^{150}$	[35] S.c.	Negative	$> 2 \cdot 10^{18}$	$2 \cdot 10^{15 \pm 2}$	$1{,}5 \cdot 10^{19 \pm 2}$
	[36] P.c.	Negative	$> 2 \cdot 10^{15}$		
${}_{92}\mathrm{U}^{238} \rightarrow {}_{94}\mathrm{Pu}^{238}$	[37] Chem.s.	Negative	$> 6 \cdot 10^{18}$	$8.5 \cdot 10^{17 \pm 2}$	$2 \cdot 10^{24 \pm 2}$

*P.e.—photo-emulsion method, S.c—scintillation counters, C.c.—cloud chamber; G.M.c.—Geiger-Muller counters, Chem.s.—chemical separation; P.c.—proportional counters.

Table VI. Experiments in double positron decay and double electron capture (for $Zn^{64} \rightarrow Ni^{64}$ only)

Transition	Authors and experimental procedure	Result of experiment	Obtained half-life (years)	Calculated half-life [39] (years)	
				безнейтринный	двухнейтринный
$_{24}Cr^{50} \rightarrow {}_{22}Ti^{50}$	[24] P.e.	Negative	$> 2.2 \cdot 10^{17}$	∞	∞
$_{26}Fe^{54} \rightarrow {}_{24}Cr^{54}$	[24] P.e.	Negative	$> 1.3 \cdot 10^{17}$	∞	∞
$_{28}Ni^{58} \rightarrow {}_{26}Fe^{58}$	[24] P.e.	Negative	$> 3\ 2 \cdot 10^{17}$	∞	∞
$_{30}Zn^{64} \rightarrow {}_{28}Ni^{64}$	[24] P.e.	Negative	$> 2\ 10^{17}$	∞	∞
$_{30}Zn^{64} \rightarrow {}_{28}Ni^{64}$ (*KK*-capture)	[62] P.c.	Negative	$> 8 \cdot 10^{17}$	$1.6\ 10^{26 \pm 2}$	$2 \cdot 10^{28 \pm 2}$
$_{38}Sr^{84} \rightarrow {}_{36}Kr^{84}$	[24] P.e.	Negative	$> 3\ 4 \cdot 10^{17}$	∞	∞
$_{42}Mo^{92} \rightarrow {}_{40}Zr^{92}$	[24] P.e. [25] C.c.	Affirmative? Negative	$= 1.5 \cdot 10^{16}$ $> 4 \cdot 10^{18}$	∞	∞
$_{48}Cd^{106} \rightarrow {}_{46}Pd^{106}$	[24] P.e. [25] C.c.	Negative Negative	$> 1 \cdot 10^{17}$ $> 6 \cdot 10^{16}$	$2 \cdot 10^{20 \pm 2}$	$1 \cdot 10^{28 \pm 2}$
$_{56}Ba^{130} \rightarrow {}_{54}Xe^{130}$	[24] P.e.	Negative	$> 1.8 \cdot 10^{15}$	$7 \cdot 10^{20 \pm 2}$	$1 \cdot 10^{29 \pm 2}$
$_{56}Ba^{132} \rightarrow {}_{54}Xe^{132}$	[24] P.e.	Negative	$> 1.8 \cdot 10^{15}$	∞	∞

half-life of the Ca^{48} exceeds 2×10^{20} years, and is larger than 5×10^{18} years for the process accompanied by creation of two antineutrinos.

In concluding the review we present in Tables V and VI a total list of experiments on double beta decay. All the affirmative results are marked in the tables with a question mark and are doubtful, for reasons considered in the text, or else have been refuted by later experiments.

CONCLUSION

The fact that the neutrinoless variant of the double beta decay was not observed, in spite of all efforts on the part of the experimental physicists, who were able to exceed by tens and hundreds of times the limits within which, according to theoretical predictions, this process should exist, is convincing evidence that the neutrino has an antiparticle. The same is confirmed also by results of very difficult experiments aimed at observing the inverse beta processes, carried out by Cowan and Reines and by Davis. At the present time, the simultaneous existence of neutrinos and antineutrinos is beyond any doubt.

It is possible that new attempts at observing double beta decay will lead to a further refinement of the properties of the neutrino, in connection with the proposed existence of the superweak interaction, but this phenomenon has not yet been observed. The gradually decreasing rate of experimentation is due only to the ever increasing limit for the lifetime of the nucleus capable of double decay.

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