Double β decay and conservation of lepton charge

Yu. G. Zdesenko

Institute of Nuclear Research, Ukrainian Academy of Sciences, Kiev
Fiz. Elem. Chastits At. Yadra **11**, 1369–1420 (November–December 1980)

The present state, tendencies, and prospects for the investigation of double β decay are described. The basic properties and most widely accepted schemes for classifying leptons are considered briefly, and also the methods for investigating possible nonconservation of the lepton charge. The fundamentals of the theory of double β decay are presented, and estimates of the lepton nonconservation parameter based on investigations of 2β decay are given. The experimental data are discussed extensively. The main attention is devoted to recent experiments. The possibility and prospects of further investigations of double β decay in direct experiments are considered.

PACS numbers: 23.40.Bw

INTRODUCTION

The part played by the law of conservation of the lepton charge in elementary-particle physics,[1] cosmology, astrophysics, and nuclear physics[2-3] is well known. So too is the fact that the results of investigation of 2β decay depend sensitively on even a very weak possible violation of this law.[2-5]

The possibility of realizing 2β decay was pointed out for the first time by Goeppert-Mayer[6] as a process in which "... a metastable isobar can change into a more stable one by simultaneous emission of two electrons." This work was published in 1935, i.e., only a year after the appearance of Fermi's theory of β decay.[7] Thus, the problem of 2β decay is as "ancient" as the problem of weak interactions. Nevertheless, despite an immense number of sometimes extremely subtle and complex experiments so far made, 2β decay has not been observed directly in any of them. It is only recently that indirect "geological" methods have shown that ^{130}Te and ^{82}Se may undergo 2β decay.[7-18]

The problem of 2β decay has been the subject of several excellent reviews[19-24] of varied length and differing in the particular emphasis. Since the study of 2β decay involves an exceptionally large number of questions, the present review is an attempt at a comparatively complete consideration of all the most important theoretical and experimental results bearing on this problem.

In addition, recent successes in the development of experimental techniques make it possible to plan experiments with a sensitivity that appeared unattainable even a few years ago. It has therefore become very necessary to review the achievements and tendencies in the development of facilities for studying 2β decay in order to estimate the possibilities and prospects of further progress in this field.

1. CONSERVATION OF LEPTON CHARGE

Properties and classification of leptons. It is well known that in nature there are four charged $(e^{\pm}, \mu^{\pm})$ and four neutral $(\nu_e, \tilde{\nu}_e, \nu_\mu, \tilde{\nu}_\mu)$ leptons[1)] and that these particles are subject to only the weak and electromagnetic interactions. The main properties of the leptons are given in Table I.

The limit on the mass of the electron antineutrino is established in experiments which measure the profile of the β-decay spectrum of tritium: $m_{\nu_e} \leq 35$ eV.[26] For the electron neutrino, $m_{\nu_e} \leq 6$ keV.[27] An upper limit for the mass of the muon neutrino is given in Ref. 28: $m_{\nu_\mu} \leq 0.65$ MeV.

All decays and processes with the participation of leptons are conveniently systematized by the introduction of a lepton charge, which is assumed to be conserved universally.[29]

There exist several different schemes by means of which leptons are classified. We shall consider the ones that are most widely used: the additive scheme, the multiplicative scheme, and the Konopinski–Mahmoud–Zel'dovich scheme.

The additive scheme[30] is usually employed in the theory of weak interactions and appears to be in the best agreement with the totality of the experimental data. In this scheme, one introduces two lepton charges, the electron L_e and muon L_μ, which are conserved separately and have the values

$$L_e = \begin{cases} +1 - e^-, \nu_e; \\ -1 - e^+, \tilde{\nu}_e; \end{cases} \quad L_\mu = \begin{cases} +1 - \mu^-, \nu_\mu; \\ -1 - \mu^+, \tilde{\nu}_\mu. \end{cases}$$

The particles e^-, ν_e, μ^-, ν_μ are leptons, while e^+, ν_e, μ^+, ν_μ are antileptons. The neutrinos ν_e and ν_μ have helicity -1, and the antineutrinos $\tilde{\nu}_e$ and $\tilde{\nu}_\mu$ have helicity $+1$.

In the multiplicative scheme,[31,32] it is not the charges L_e and L_μ separately that are conserved but their sum $\sum(L_e + L_\mu)$ and the sign of $(-1)^{L_\mu}$. Leptons have the same values of the charges as in the additive scheme.

TABLE I. Basic properties of leptons.

Lepton	Mass	Electric Charge	Spin	Mean lifetime	S, B
$e^{\mp}$	0.511 MeV	∓ 1	$1/2\pm$	Stable	0
$\tilde{\nu}_e$, ν_e	35 eV, 6 keV	0	1/2	Stable	0
$\mu^{\pm}$	105.650 MeV	± 1	$1/2^{\mp}$	2.2×10^{-6} sec	0
ν_μ, $\tilde{\nu}_\mu$	0.65 MeV	0	1/2	Stable	0

[1)] In this review, we shall not consider the properties of the heavy lepton $\tau^{\pm}$ with mass of about 1.9 GeV.[25]

 0090-4759/80/060542-22$02.80

Methods have frequently been proposed for determining which of the schemes—the multiplicative or the additive—holds in reality.[1,33-35] However, the obtained experimental results do not permit an unambiguous choice. These questions are considered in more detail in the reviews (for example, Ref. 3). We mention only one of the more recent studies,[36] which considered the possibility of investigating the reactions a) $\tilde{\nu}_\mu + e^- \to \mu^- + \tilde{\nu}_e$ and b) $\nu_\mu + e^- \to \mu^- + \nu_e$; both of these are allowed by the multiplicative law, in contrast to the additive law, which allows only reactions of type b).

The Konopinski–Mahmoud–Zel'dovich scheme[37,38] is the most economic, since in it one introduces only a single lepton number L, which has the value +1 for the leptons $e^-, \nu_e, \mu^+, \tilde{\nu}_\mu$ and −1 for the antileptons $e^+, \tilde{\nu}_e, \mu^-, \nu_\mu$. A four-component theory is used to describe the neutrinos, and both antineutrinos ν_e and $\tilde{\nu}_\mu$ are ascribed the helicity −1.

The Konopinski–Mahmoud–Zel'dovich scheme can be tested by studying μ capture[39,40] and also reactions with the participation of high-energy neutrinos and antineutrinos.[41]

Investigations into the nonconservation of lepton charge. It is well known[42] that the weak interaction is responsible for a) purely leptonic processes, for example, μ decay, b) semileptonic decays which may or may not change the strangeness (β decay; $\pi^- \to \mu^- + \tilde{\nu}_\mu$, $\Lambda^0 \to p + e^- + \tilde{\nu}_e$, $K^+ \to \mu^+ + \nu_\mu$), and c) nonleptonic decays ($\Lambda^0 \to p + \pi^-$, $K^+ \to \pi^+ + \pi^0$, etc.).

A satisfactory description of all the listed processes is achieved by introducing a weak interaction of two vector currents[43] with Hamiltonian of the form

$$H_W = (-G/2\sqrt{2})\,[g_\lambda g_\lambda^* + g_\lambda^* g_\lambda]. \tag{1}$$

In this expression, G is the coupling constant of the weak interaction, and g_λ is the vector current, which can be decomposed into the components

$$g_\lambda = J_\lambda \cos\theta + I_\lambda \sin\theta + l_\lambda,$$

where θ is the Cabibbo angle,[44] and J_λ and I_λ are, respectively, the strangeness-conserving and strangeness-changing hadronic currents, which can be expressed as sums of vector and axial-vector parts:

$$J_\lambda = J_\lambda^{(V)} + J_\lambda^{(A)}; \quad I_\lambda = I_\lambda^{(V)} + I_\lambda^{(A)}.$$

The lepton current l_λ consists of two terms:

$$l_\lambda = l_\lambda^{(e)} + l_\lambda^{(\mu)} = -i\Psi_{\nu_e}\gamma_\lambda(1+\gamma_5)\Psi_e - i\Psi_{\nu_\mu}\gamma_\lambda(1+\gamma_5)\Psi_\mu, \tag{2}$$

where Ψ is the field operator for the given species of lepton. Such a formalism corresponds to the additive scheme, i.e., the separate conservation of the lepton and muon charges.

There is a large class of experiments in high-energy physics that can be used to test the law of conservation of the lepton numbers. We shall not consider them here in detail but give only Table II (Ref. 45), which indicates the latest results of a number of experiments.[46-50]

Information about the nonconservation of the electron lepton charge can also be obtained in studies of parity in β decay and in inverse and double β decay.

To this aim, let us consider the form of the weak-interaction Hamiltonian for β decay.

The part of the Hamiltonian (1) responsible for the semileptonic processes consists of two terms:

$$H_W^{(\Delta S=0)} = -(G/\sqrt{2})\cos\theta\,[J_\lambda l_\lambda^* + \text{h.c.}]; \quad H_W^{(\Delta S=\pm 1)} = -(G/\sqrt{2})\sin\theta\,[I_\lambda l_\lambda^* + \text{h.c.}]. \tag{3}$$

The term (3) describes the semileptonic processes in which strangeness is conserved (nuclear β decay, μ capture, etc.). The Hamiltonian for β decay has the form

$$H_\beta = -(G/\sqrt{2})\cos\theta\,[J_\lambda l_\lambda^{(e)*} + \text{h.c.}];$$

where $l_\lambda^{(e)}$ is the electron part of the lepton current (2), i.e.,

$$l_\lambda^{(e)*} = -i\overline{\Psi}_e\gamma_\lambda(1+\gamma_5)\Psi_{\nu_e}. \tag{4}$$

If it is assumed that the hadron current contains only vector and axial parts, then the assumption that the electron part of the hadron current has the form (4) will be to a certain degree restrictive.[42] It is usually assumed that the form (4) is approximately correct or, at least, does not contradict the experimental data, though small deviations from it are possible. To this end, one introduces a more general form for $l_\lambda^{(e)}$:

$$l_\lambda^{(e)*} = -iN\overline{\Psi}_e\gamma_\lambda\{[(1+\gamma_5)+\eta(1-\gamma_5)]\Psi_{\nu_e} + [\xi(1+\gamma_5)+\delta(1-\gamma_5)]\Psi_{\tilde{\nu}_e}\}, \tag{5}$$

where $N = (1+\eta^2+\xi^2+\delta^2)^{-1/2}$, and $\Psi_{\tilde{\nu}_e}$ is the charge-conjugate field operator for the antineutrino. In Eq. (5), η, ξ, and δ are real (if T invariance is assumed) parameters which characterize the deviation of $l_\lambda^{(e)}$ from the form (4).

If the parameter ξ or δ is nonzero, the lepton number is not conserved, and if η or $\delta \neq 0$ then the neutrinos in β decay must have helicities differing from the values ±1.

TABLE II. Probability ratio $W(\text{I})/W(\text{II})$ of processes forbidden (I) and allowed (II) by the conservation law of lepton charges.[45]

Process forbidden by lepton conservation (I)	Observed process allowed by lepton conservation (II)	$\frac{W(\text{I})}{W(\text{II})}$	Confidence limit, %	Reference
a) Possible nonconservation of L_μ				
$\nu_\mu + N \to \mu^+ + \cdots$	$\nu_\mu + N \to \mu^- + \cdots$	$< 5\cdot10^{-3}$	95	[46]
b) Possible nonconservation of L_e and L_μ with conserved $\Sigma(L_e+L_\mu)$				
$\mu^+ \to e^+ + \gamma$	$\mu^+ \to e^+ + \nu_e + \tilde{\nu}_\mu$	$< 2.2\cdot10^{-8}$	90	[47]
$\mu^+ \to e^+ + e^- + e^+$	$\mu^+ \to e^+ + \nu_e + \tilde{\nu}_\mu$	$< 1.9\cdot10^{-9}$	90	[48]
$\mu^- + \text{Cu} \to e^- + \cdots$	$\mu^- + \text{Cu} \to \tilde{\nu}_\mu + \cdots$	$< 1.6\cdot10^{-8}$	90	[49]
$\nu_\mu + \text{N} \to e^- + \cdots$	$\nu_\mu + \text{N} \to \mu^- + \cdots$	$< 3\cdot10^{-3}$	95	[50]
c) Possible nonconservation of L_e and L_μ				
$\mu^- + \text{Cu} \to e^+ + \cdots$	$\mu^- + \text{Cu} \to \nu_\mu + \cdots$	$< 2.6\cdot10^{-8}$	90	[49]

In the special case when $\xi=1$ and $\eta=\delta=\eta'$, the electron current can be written in the form

$$l_\lambda^{(e)*}=(-i\Psi_e/\sqrt{1-\eta'^2})\,[\gamma_\lambda(1+\gamma_5)+\eta'\gamma_\lambda(1-\gamma_5)]\,\Psi'_{\nu_e},$$

where $\Psi'_{\nu_e}=(1/\sqrt{2})[\Psi_{\nu_e}+\Psi_{\tilde{\nu}_e}]$. It follows from the expression for $\Psi_{\tilde{\nu}_e}$ that $\Psi'_{\nu_e}=\Psi'_{\tilde{\nu}_e}$, i.e., that the particle ν_e is identical to the antiparticle $\tilde{\nu}_e$. This corresponds to the case of a Majorana neutrino.[51]

We now consider the restrictions on the possible deviations of the parameters η, ξ, and δ from zero that follow from the experiments on parity violation in β decay and also from the experiments on double and inverse β decay.

Information about violation of the lepton-number conservation law in β decay can be obtained from measurements of the following:

1) the angular distributions of the electrons and positrons produced by the decay of polarized nuclei;

2) the longitudinal polarizations of the electrons and positrons observed in the decay of unpolarized nuclei;

3) $\beta-\gamma$ correlations with determination of the circular polarization.

On the basis of (5), we can express the parameters characterizing the asymmetry in the above experiments in terms of η, ξ, and δ (Ref. 42):

$$A_i=A_i^{(0)}(1-\eta^2+\xi^2-\delta^2)/(1+\eta^2+\xi^2+\delta^2).$$

Here, $A_i, i=1,2,3$, is the corresponding asymmetry parameter, and $A_i^{(0)}$ is the value of A_i for $\eta=\xi=\delta=0$. In Ref. 42 (on p. 125 of the Russian translation) there is an extensive list of experimental values of $\Gamma_i=(A_i)_{exp}/A_i^{(0)}$ according to the data of different authors, and it is shown that on the basis of the accuracy achieved in the determination of $(A_i)_{exp}$ it is possible to establish the following limits for η, ξ, and δ:

$$2|\eta^2+\delta^2|\leqslant 0.012;\quad |\eta|\leqslant 0.1;\quad |\delta|\leqslant 0.1.$$

In Davis's experiment[52,53] unsuccessful attempts were made to observe the inverse K capture reaction $\tilde{\nu}_e+{}^{37}\mathrm{Cl}\to{}^{37}\mathrm{Ar}+e^-$, which is forbidden in the ordinary theory of β decay for $\eta=\xi=\delta=0$. The experiment established the limit $\sigma_{exp}=(0.1\pm0.6)\times10^{-45}$ cm^2 on the reaction cross section, and this was used to calculate the limiting value $\delta\leqslant 0.2$.[42] Experiments on inverse β decay are considered in more detail in the review of Ref. 23.

Much stronger restrictions on the parameter which characterizes the nonconservation of lepton charge can be obtained by studying neutrinoless 2β decay, which changes L_e by two units. This involves comparing the theoretical value of the half-life with the value measured experimentally. Thus, Rosen and Primakoff,[4] using their own theoretical calculations and the experimental data of Ref. 10 on the 2β decay of ^{130}Te, established a limit on the parameter η at the level 10^{-3}–10^{-4}.

In the following section, we shall return to a careful comparison of the estimates of the nonconservation parameter made by different authors, and we note here the correctness of the frequently made assertion (see, for example, Refs. 2–4, 23, and 24) to the effect that 2β decay is an extremely sensitive indicator of possible violation of the lepton conservation law.

There is one other way of testing this law, which is to search for neutrino oscillations, the existence of which was conjectured for the first time by Pontecorvo.[29] The problem of neutrino oscillations is so extensive and fundamental that even a superficial treatment would go beyond the scope of the present paper. The interested reader is recommended to the magnificent review in Ref. 45, which considers exhaustively the present state of the problem of neutrino oscillations.

2. ELEMENTS OF THE THEORY OF 2β DECAY

Probabilities of neutrinoless and two-neutrino processes. In the 2β-decay process a nucleus with charge Z and mass number A changes its charge by two units, emitting two electrons or two positrons. Instead of the emission of positrons, it is possible to have the capture of two orbital electrons or the capture of one K electron with the emission of one positron.

The energy ε_0 released in $\beta^\pm\beta^\pm$ decay in each of these cases is determined as follows:

a) $\varepsilon_0=\Delta M$, emission of two electrons;

b) $\varepsilon_0=\Delta M-4m_e$, emission of two positrons;

c) $\varepsilon_0=\Delta M-2\varepsilon_{bd}$, double K capture;

d) $\varepsilon_0=\Delta M-2m_e-\varepsilon_{bd}$, emission of a positron and capture of an orbital electron.

Here, ΔM is the difference between the masses of the parent and daughter nuclei, m_e is the electron mass, and ε_{bd} is the binding energy of the orbital electron.

These expressions show that the experimental study of the cases b), c), and d) is much more complicated than for a). For this reason, in the present paper we shall consider only double electron capture. Double positron capture, double K capture, or K capture with emission of a positron are considered in detail in, for example, Ref. 2.

If 2β decay is to occur, the transition must be energetically advantageous, i.e., the mass of the nucleus (A,Z) must be greater than the mass of the nucleus $(A,Z+2)$. In addition, the ordinary β decay $(A,Z)\to(A,Z+1)$ must be impossible energetically or strongly suppressed due to significant change in the spin and parity.

Analysis of nuclear stability shows that the most probable candidates for the parent (A,Z) and daughter $(A,Z+2)$ nuclei are pairs of even–even stable isobars. There are 62 known pairs of this kind, and we have listed them in Table III, in which we also give the isotope concentrations of the original elements and the mass differences between the parent and daughter atoms in keV (according to the 1977 data of Ref. 54).

TABLE III. List of stable–even isobar pairs.

№	Transition $(A,Z)\to(A,Z+2)$	A	Z	Isotope abundance, %	Mass difference, keV	Energy of β transition $(A,Z)\to(A,Z+1)$, keV	№	Transition $(A,Z)\to(A,Z-2)$	A	Z	Isotope abundance, %	Mass difference, keV	Energy of β^+ transition $(A,Z)\to(A,Z-1)$
1	Ca—Ti	46	20	0.0033	984.5±5.1	−1382.6±3.7	1	Ar—Se	36	18	0.337	434.58±1.78	−709.55±0.30
2	Ca—Ti	48	20	0.185	4271.7±5.4	+281±6	2	Ca—Ar	40	20	96.97	193.4±1.5	−1311.6±0.5
3	Zn—Ge	70	30	0.62	1001.5±5.2	−654.8±1.6	3	Cr—Ti	50	24	4.31	1174.1±4	−1038.7±1.4
4	Ge—Se	76	32	7.67	2045.7±5	−922.9±2.7	4	Fe—Cr	54	26	5.84	679.9±3	−697.4±1.7
5	Se—Kr	80	34	49.82	135.7±14.5	−1870.3±2	5	Ni—Fe	58	28	67.76	1927.5±3.1	−380.2±1.2
6	Se—Kr	82	34	9.19	3005±16	−88±12	6	Zn—Ni	64	30	48.89	1096.7±3.5	−578.2±1.5
7	Kr—Sr	86	36	17.37	1249.1±7.8	−526±5	7	Se—Ge	74	34	0.87	1209.4±4.5	−1353.1±2.6
8	Zr—Mo	94	40	2.80	1148.4±6.5	−896.8±2.6	8	Sr—Kr	84	38	0.56	1790.3±7.6	−890.0±3.5
9	Zr—Mo	96	40	17.40	3350.2±6.1	+163.0±5	9	Mo—Zr	92	42	15.86	1649.1±6.8	−359±4
10	Mo—Ru	98	42	23.75	110.6±8.4	−1682±5	10	Ru—Mo	96	44	5.7	2749.9±11.4	−254±10
11	Mo—Ru	100	42	9.62	3032.6±8.6	−170±6	11	Pd—Ru	102	46	0.8	1175.5±11.9	−1148±6
12	Ru—Pd	104	44	18.5	1301±11	−1147±7	12	Cd—Pd	106	48	1.215	2782±11	−202±9
13	Pd—Cd	110	46	12.7	2014±24	−879±20	13	Cd—Pd	108	48	0.875	272±11	−1649±8
14	Cd—Sn	114	48	28.86	540.4±7.3	−1444±5	14	Sn—Cd	112	50	0.95	1919.9±9.4	−658±6
15	Cd—Sn	116	48	7.58	2838.5±7.3	−464±8	15	Te—Sn	120	52	0.089	1697.8±24.5	−983±22
16	Sn—Te	122	50	4.71	358±8	−1622.7±3.6	16	Xe—Te	124	54	0.096	3068.3±143.8	−90±140
17	Sn—Te	124	50	5.98	2278.3±8.8	−627±5	17	Xe—Te	126	54	0.090	904±12	−1251±5
18	Te—Xe	128	52	31.79	868.9±5.5	−1258±5	18	Ba—Xe	130	56	0.101	2578.1±13.6	−440.9±3.9
19	Te—Xe	130	52	34.49	2533.1±6.6	−451±11	19	Ba—Xe	132	56	0.097	833±15	−1279±24
20	Xe—Ba	134	54	10.44	843±15	−1215±11	20	Ce—Ba	138	58	0.250	708±20	−1041±12
21	Xe—Ba	136	54	8.87	2481±15	−67±11	21	Gd—Sm	152	64	0.20	58±14	−1819.2±3.3
22	Ce—Nd	142	58	11.07	1414±11	−745.1±3.5	22	Dy—Gd	156	66	0.0524	2009±14	−428±8
23	Nd—Sm	148	60	5.71	1928±10	−536±9	23	Dy—Gd	158	66	0.0902	281±11	−935.4±3.6
24	Nd—Sm	150	60	5.60	3367±11	−130±80	24	Er—Dy	162	68	0.136	1846±12	−288±5
25	Sm—Gd	154	62	22.61	1250±10	−728±5	25	Er—Dy	164	68	1.56	27±12	−1002±4
26	Gd—Dy	160	64	21.75	1731±11	−102.3±1.4	26	Yb—Er	168	70	0.140	1420±13	−259±4
27	Yb—Hf	176	70	12.23	1077±12	−109.6±2.1	27	Yb—Er	170	70	3.03	655±12	−967.9±0.9
28	W—Os	186	74	28.41	489±14	−587.8±2.6	28	Hf—Yb	174	72	0.18	1110±14	−268.0±6
29	Pt—Hg	198	78	7.23	1043±26	−330±19	29	Os—W	184	76	0.018	1454±14	−42±6
30	Hg—Pb	204	80	6.85	414±12	−349±5	30	Pt—Os	192	78	0.78	408±14	−1456.9±3.8
31	U—Pu	238	92	99.275	1146.2±4.6	−145.6±1.3	31	Hg—Pt	196	80	0.146	806±16	−684±3.9

Nucleons in a nucleus can decay in accordance with the schemes

$$p\to n+e^{+}+\nu_e;\qquad n\to p+e^{-}+\tilde{\nu}_e. \tag{6}$$

From (6), using the rule for replacing a particle by an antiparticle in going from one side to the other, one can obtain the reaction

$$\nu_e+n\to p+e^{-}. \tag{7}$$

In the case of identity of ν_e and $\tilde{\nu}_e$, the antineutrino produced in the reaction (6) may stimulate the reaction (7). As a result, the nucleus (A,Z) is transformed into the nucleus $(A,Z+2)$ with the emission of two electrons:

$$(A,Z)\to(A,Z+2)+2e^{-}. \tag{8}$$

In the final state there are no neutrinos, and the total lepton charge has changed by two units, i.e., in this case the 2β decay occurs as a second-order process with the exchange of a virtual neutrino. But if ν_e and $\tilde{\nu}_e$ are not identical, the antineutrino from the reaction (6) cannot induce the reaction (7) and the 2β decay takes place as a process of second order in the weak interaction with the emission of two neutrinos and conservation of the total lepton number:

$$(A,Z)\to(A,Z+2)+2e^{-}+2\tilde{\nu}_e. \tag{9}$$

Figure 1 shows the corresponding diagrams of second-order weak interaction for neutrinoless (see Fig. 1a) and two-neutrino (see Fig. 1b) double β decay.

The following remark must be made about the diagram in Fig. 1a. If the virtual neutrino emitted by the neutron in the first β decay were absorbed again by the same neutron, there would not exist a limitation on the neutrino energy, since the nucleon can be assumed to be pointlike. Therefore, the nuclear matrix element of second order for neutrinoless 2β decay would be divergent. But since the isospin of nucleons is 1/2, the virtual neutrino cannot be absorbed by the same nucleon that emitted it. Therefore, the considered matrix element will be finite, and the reciprocal of the mean distance between the neutrons is a measure of the limiting energy of the neutrino. The diagrams in Figs. 1a and 1b correspond to the two-nucleon mechanism of 2β decay introduced by Furry.[55]

There has also been proposed one further mechanism for this process, the so-called resonance mechanism.[4] It is known that the deuteron contains with 1% probability an admixture of the nucleon resonance $J^{(P)}=5/2^{+}, I=1/2, m=1688$ MeV.[56–58] If this result is extended to other nuclei and other nucleon resonances, it can be assumed that the parent and daughter nuclei participating in 2β decay contain about 1% of the re-

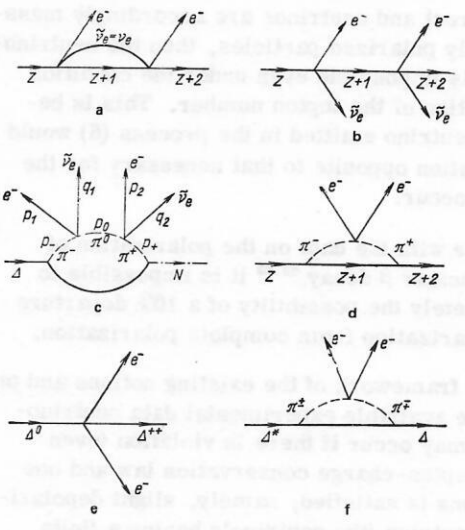

FIG. 1. Possible diagrams of 2β decay.

sonance $J^{(P)}=3/2^+, I=3/2, m=1232$ MeV, namely $\Delta(1232)$. Since $\Delta(1232)$ has isospin 3/2, it can emit and reabsorb a virtual neutrino with simultaneous emission of two electrons:

$$\Delta^-(1232)\to p+e^-+e^-;\quad n\to\Delta^{++}(1232)+e^-+e^-.$$

To overcome the problem of the divergence of the matrix element which arises when the nucleons and resonances are treated as point particles, it was suggested in Ref. 4 that the neutrino is emitted and absorbed by different quarks of the baryon state. The mean distance between the points at which the neutrino is emitted and absorbed is then of the order of the radius of one nucleon, and the probability of the neutrinoless process is considerably raised.

In Fig. 1c we show the diagram of two-neutrino 2β decay based on the pion core model[59] of the resonance $\Delta(1232)$.

Neutrinoless 2β decay could also occur without the participating of an intermediate neutrino and could therefore be independent of the properties of this particle if there is some superweak interaction for which this decay is a first-order process. The superweak interaction of Pontecorvo[60] with $\Delta S=0, \Delta L_e=2$ is in principle symmetric to the well-known interaction of Wolfenstein[61] with $\Delta S=2, \Delta L_e=0$, which violates CP invariance. Possible diagrams of neutrinoless 2β decay as a first-order process in the superweak interaction are shown in Figs. 1d–1f.

Originally, 2β decay was regarded as a method of distinguishing the Dirac neutrino (9) from the Majorana neutrino (8). This point of view was significantly modified after the discovery of parity nonconservation in weak interactions and the development of the theory of the two-component neutrino, in which neutrinos and antineutrinos are massless particles with 100% polarization. For the two-neutrino 2β decay, no important changes occurred. Two-neutrino 2β decay is always possible, irrespective of whether or not the lepton charge is conserved. But for neutrinoless 2β decay the situation is much more complicated. If the contemporary $V-A$ theory of the weak interactions is rigorously correct and neutrinos are accordingly massless, completely polarized particles, then the neutrinoless decay (8) is impossible even under the condition of nonconservation of the lepton number. This is because the antineutrino emitted in the process (6) would have a polarization opposite to that necessary for the process (7) to occur.

In accordance with the data on the polarization of electrons in nuclear β decay,[42,62] it is impossible to rule out completely the possibility of a 10% departure of neutrino polarization from complete polarization.

Thus, in the framework of the existing notions and on the basis of the available experimental data neutrinoless 2β decay may occur if there is violation (even slight) of the lepton-charge conservation law and one of two conditions is satisfied, namely, slight depolarization of the neutrino (the neutrino's having a finite mass could be one of the reasons for depolarization) or the existence of the hypothetical superweak interaction.

The first calculations of the probabilities of 2β decay were made by Goeppert-Mayer,[6] Furry,[55] Sliv,[63] Zel'dovich, Luk'yanov, and Smorodinskii,[19] Konopinski,[64] and Primakoff.[65] We shall consider the later calculations of Rosen and Primakoff[4] and Konopinski,[66] who treated 2β decay as a process of second order in the weak interaction.

In the case of the two-nucleon mechanism, we can write the matrix element of the transition in the form

$$\mathrm{ME}=\sum_{\nu}\frac{\langle\chi_f\Psi_f\mid H_\beta\mid\Psi_\nu\chi_\nu\rangle\langle\chi_\nu\Psi_\nu\mid H_\beta\mid\Psi_i\chi_i\rangle}{E_\nu-E_i},$$

where Ψ_i, Ψ_f, and Ψ_ν are the wave functions of the initial (A,Z), final $(A,Z\pm2)$, and intermediate $(A,Z\pm1)$ states of the nucleus, and χ_i, χ_f, and χ_ν are the wave functions of the lepton field. The symbol χ_i refers to the initial state, in which there are no leptons; χ_f, to the final state with two charged leptons; and χ_ν, to the intermediate state with two charged leptons together with two neutral leptons or without them; H_β is the usual Hamiltonian of the weak interaction with lepton current (5) of somewhat modified form[5]:

$$l_\lambda=\overline{\Psi}_e\gamma_\lambda\frac{[(1+\gamma_5)+\eta(1-\gamma_5)](\Psi_{\nu_e}+\xi\Psi_{\overline{\nu}_e})}{(1+\eta^2)^{1/2}(1+\xi^2)^{1/2}}.$$

It is easy to show that the amplitude of neutrinoless decay is proportional to the product $\xi\eta$ or, for the case of the Majorana neutrino ($\xi=1$), simply η^2.

With these assumptions, Rosen and Primakoff[2,4] obtained for the considered two-nucleon mechanism of 2β decay the following approximate expressions for the dependence of the half-lives on the nuclear matrix elements (ME) of the transition:

$$T^{0\nu}_{1/2}=(f_2/\eta^2)(1/|\mathrm{ME}|^2); \tag{10}$$

$$T^{2\nu}_{1/2}=f_4/|\mathrm{ME}|^2, \tag{10'}$$

where f_2 and f_4 are the values of the effective phase spaces for the final states with two and four leptons:

$$f_2=\frac{10^{19.9}}{f(\varepsilon_0)}\left(\frac{137}{2\pi Z}\right)^2\left[1-\exp\left(-\frac{2\pi Z}{137}\right)\right]^2\left(\frac{A}{130}\right)^{2/3}\text{years}; \tag{11}$$

$$f_4=6\cdot10^{18}\left(\frac{\overline{\Delta E}+(1/2)\varepsilon_0+1}{10}\right)^2\left(\frac{60}{Z}\right)^2\times\left[1-\exp\left(-\frac{2\pi Z}{137}\right)\right]^2\left(\frac{8}{\varepsilon_0}\right)^{10}\text{years}, \tag{12}$$

where $\overline{\Delta E}$ is the mean difference between the energies of the initial and intermediate states of the nucleus, ε_0 is the energy released in units of m_ec^2, and

$$f(\varepsilon_0)=(\varepsilon_0^3+13\varepsilon_0^2+77\varepsilon_0+70)\varepsilon_0^4.$$

The half-lives for the most interesting transitions were calculated by means of these expressions in Ref. 3; the results are given in Table IV. The values of $T_{1/2}$ for neutrinoless decay through the two-nucleon mechanism were determined in two ways. In the eighth column of Table IV, we give the results of the calculations in accordance with Eq. (10) for $\eta=1$, and in the ninth column in accordance with the expression

$$T^{0\nu}_{1/2}\approx1.55\cdot10^{29}\frac{A^{2/3}[1-\exp(-2\pi Z/137)]^2}{Z^2f(\varepsilon_0)},$$

TABLE IV. Theoretical values of $T_{1/2}$ against 2β decay.

Transition	A	Z	Isotope abundance, %	Energy of 2β transition $(A, Z)\to(A, Z+2)$, keV	Energy of β transition $(A, Z)\to(A, Z+1)$, keV	$T_{1/2}$ for the two-neutrino channel, year	$T_{1/2}$ for the neutrinoless channel, year: Two-nucleon mechanism, $\eta=1$	Two-nucleon mechanism, $T_{1/2}(^{130}\text{Te})=2.2\times10^{21}$ years	Resonance mechanism, $\eta=1$	Resonance mechanism, $T_{1/2}(^{130}\text{Te})=2.2\times10^{21}$ years
Ca—Ti	46	20	0,0033	984.5±5.1	−1382.6±3.7	$7.4\cdot10^{26\pm2}$	$4.5\cdot10^{17\pm2}$	$4.7\cdot10^{23}$	$1.7\cdot10^{16\pm2}$	$5.4\cdot10^{23}$
Ca—Ti	48	20	0.185	4271.7±5.4	+281.0±6.0	$4.0\cdot10^{20\pm2}$	$1.6\cdot10^{14\pm2}$	$1.7\cdot10^{20}$	$1.2\cdot10^{13\pm2}$	$3.8\cdot10^{20}$
Zn—Ge	70	30	0,62	1001.5±5.2	−654.8±1.6	$2.8\cdot10^{26\pm2}$	$3.7\cdot10^{17\pm2}$	$3.8\cdot10^{23}$	$1.1\cdot10^{16\pm2}$	$3.4\cdot10^{23}$
Ge—Se	76	32	7.67	2045.7±5.0	−922.9±2.7	$3.3\cdot10^{23\pm2}$	$9.2\cdot10^{15\pm2}$	$1.0\cdot10^{22}$	$4.1\cdot10^{14\pm2}$	$1.3\cdot10^{22}$
Se—Kr	80	34	49.82	135.7±14.5	−1870.3±2.0	$1.6\cdot10^{35\pm2}$	$3.0\cdot10^{21\pm2}$	$3.2\cdot10^{27}$	$5.2\cdot10^{18\pm2}$	$1.6\cdot10^{26}$
Se—Kr	82	34	9.19	3005.0±16.0	−88.0±12.0	$5.6\cdot10^{21\pm2}$	$1.1\cdot10^{15\pm2}$	$1.1\cdot10^{21}$	$5.3\cdot10^{13\pm2}$	$1.6\cdot10^{21}$
Kr—Sr	86	36	17.37	1249.1±7.8	−526.0±5.0	$2.9\cdot10^{25\pm2}$	$1.2\cdot10^{17\pm2}$	$1.3\cdot10^{23}$	$3.7\cdot10^{15\pm2}$	$1.1\cdot10^{23}$
Zr—Mo	94	40	2.80	1148.4±6.5	−896.8±2.6	$3.3\cdot10^{25\pm2}$	$1.2\cdot10^{17\pm2}$	$1.2\cdot10^{23}$	$3.4\cdot10^{15\pm2}$	$1.0\cdot10^{23}$
Zr—Mo	96	40	17.40	3350.2±6.1	+163.0±5.0	$1.7\cdot10^{21\pm2}$	$5.1\cdot10^{14\pm2}$	$5.4\cdot10^{20}$	$2.3\cdot10^{13\pm2}$	$7.1\cdot10^{20}$
Mo—Ru	100	42	9.62	3032.6±8.6	−170.0±6.0	$4.3\cdot10^{21\pm2}$	$8.8\cdot10^{14\pm2}$	$0.9\cdot10^{21}$	$3.8\cdot10^{13\pm2}$	$1.1\cdot10^{21}$
Ru—Pd	104	44	18.5	1301.0±11.0	−1147.0±7.0	$1.6\cdot10^{25\pm2}$	$7.6\cdot10^{16\pm2}$	$8.0\cdot10^{22}$	$2.2\cdot10^{15\pm2}$	$6.6\cdot10^{22}$
Pd—Cd	110	46	12.7	2014.0±24.0	−879.0±20.0	$2.5\cdot10^{23\pm2}$	$8.2\cdot10^{15\pm2}$	$8.7\cdot10^{21}$	$2.9\cdot10^{14\pm2}$	$8.9\cdot10^{21}$
Cd—Sn	114	48	28.86	540.4±7.3	−1444.0±5.0	$9.4\cdot10^{28\pm2}$	$5.4\cdot10^{18\pm2}$	$5.6\cdot10^{24}$	$6.1\cdot10^{16\pm2}$	$1.9\cdot10^{24}$
Cd—Sn	116	48	7.58	2808.5±7.3	−464.0±8.0	$8.0\cdot10^{21\pm2}$	$1.2\cdot10^{15\pm2}$	$1.3\cdot10^{21}$	$4.8\cdot10^{13\pm2}$	$1.5\cdot10^{21}$
Sn—Te	122	50	4,71	358.0±8.0	−1622.7±3.6	$8.2\cdot10^{30\pm2}$	$4.2\cdot10^{19\pm2}$	$4.4\cdot10^{25}$	$2.5\cdot10^{17\pm2}$	$7.6\cdot10^{24}$
Sn—Te	124	50	5,98	2278.3±8.8	−627.0±5.0	$6.8\cdot10^{22\pm2}$	$4.1\cdot10^{15\pm2}$	$4.3\cdot10^{21}$	$1.4\cdot10^{14\pm2}$	$4.3\cdot10^{21}$
Te—Xe	128	52	31.79	868.9±5.5	−1258.0±5.0	$7.8\cdot10^{24\pm2}$	$5.5\cdot10^{17\pm2}$	$5.8\cdot10^{23}$	$9.7\cdot10^{15\pm2}$	$3.0\cdot10^{23}$
Te—Xe	130	52	34.49	2533.1±6.6	−451.0±11.0	$1.7\cdot10^{22\pm2}$	$2.1\cdot10^{15\pm2}$	$2.2\cdot10^{21}$	$7.2\cdot10^{13\pm2}$	$2.2\cdot10^{21}$
Xe—Ba	134	54	10.44	843.0±15.0	−1215.0±11.0	$4.3\cdot10^{27\pm2}$	$1.3\cdot10^{18\pm2}$	$1.3\cdot10^{24}$	$1.8\cdot10^{16\pm2}$	$5.5\cdot10^{23}$
Xe—Ba	136	54	8.87	2481.0±15.0	−67.0±11.0	$7.6\cdot10^{21\pm3}$	$1.4\cdot10^{15\pm2}$	$1.5\cdot10^{21}$	$4.8\cdot10^{13\pm2}$	$1.5\cdot10^{21}$
Ce—Nd	142	58	11.07	1414.0±11.0	−745.1±3.5	$6.1\cdot10^{24\pm2}$	$5.0\cdot10^{16\pm2}$	$5.2\cdot10^{22}$	$1.2\cdot10^{15\pm2}$	$3.6\cdot10^{22}$
Nd—Sm	148	60	5.71	1928.0±10.0	−536.0±9.0	$1.9\cdot10^{23\pm2}$	$8.1\cdot10^{15\pm2}$	$8.5\cdot10^{21}$	$2.3\cdot10^{14\pm2}$	$7.0\cdot10^{21}$
Nd—Sm	150	60	5.60	3367.0±11.0	−130.0±80.0	$8.0\cdot10^{20\pm2}$	$3.6\cdot10^{14\pm2}$	$3.8\cdot10^{20}$	$1.2\cdot10^{13\pm2}$	$3.8\cdot10^{20}$
Sm—Gd	154	62	22.61	1250.0±10.0	−728.0±5.0	$1.3\cdot10^{23\pm2}$	$7.5\cdot10^{15\pm2}$	$7.8\cdot10^{22}$	$1.6\cdot10^{15\pm2}$	$4.9\cdot10^{22}$
Gd—Dy	160	64	21.75	1731.0±11.0	−102.3±1.4	$2.9\cdot10^{23\pm2}$	$1.2\cdot10^{16\pm2}$	$1.2\cdot10^{22}$	$3.1\cdot10^{14\pm2}$	$9.4\cdot10^{21}$
U—Pu	238	92	99.275	1146.2±4.6	−145.6±1.3	$8.9\cdot10^{24\pm2}$	$7.1\cdot10^{16\pm2}$	$7.5\cdot10^{22}$	$1.1\cdot10^{15\pm2}$	$3.3\cdot10^{22}$

which can be obtained from (10) under the following assumptions: a) the matrix elements for all transitions are approximately equal; b) the measured value $T_{1/2}=2.2\times10^{21}$ years for ^{130}Te corresponds to the neutrinoless channel. In the seventh column of Table IV, we give the half-lives for the two-neutrino decay channel calculated in accordance with Eq. (10′).

We now consider calculations of the half-lives made with allowance for the "resonance" mechanism. On the basis of the quark model of the $\Delta(1232)$ resonance, Rosen and Primakoff[4] obtained the following expression for 2β decay without neutrino emission:

$$T_{1/2}^{0\nu}\approx\frac{10^{17.5}}{\eta^2 g(\varepsilon_0)}\left(\frac{137}{2\pi Z}\right)^2\times\left[1-\exp\left(-\frac{2\pi Z}{137}\right)\right]^2\frac{(\langle r_{nm}\rangle)^2}{(0.7\cdot10^{-13}\text{ cm})^2 P(\Delta)\,|\langle\Phi_f|\Phi_i\rangle|^2}\text{ years},\quad(13)$$

where $g(\varepsilon_0)=\varepsilon_0^2(\varepsilon_0^5+14\varepsilon_0^4+81\varepsilon_0^3+221\varepsilon_0^2+228\varepsilon_0+140)$, $\langle r_{nm}\rangle$ is the mean distance between any quarks in the nucleon and $\Delta(1232)$, $P(\Delta)$ is the probability of finding the resonance $\Delta(1232)$ in the nucleus, and $\langle\Phi_f|\Phi_i\rangle$ is the overlap factor of the wave functions of the initial and final states of the nucleus.

In the tenth column of Table IV, we give the values of $T_{1/2}$ calculated in Ref. 3 on the basis of (13) and the approximations

$$\langle r_{nm}\rangle\approx0.7\cdot10^{-13}\text{ cm},\quad P(\Delta)\approx0.01;\quad\langle\Phi_f|\Phi_i\rangle\approx0.3.$$

Further, assuming that the matrix elements are equal for all triplets, and taking for $T_{1/2}(^{130}\text{Te})$ the measured value 2.2×10^{21} years, we obtain from (13)

$$T_{1/2}^{0\nu}(A,Z)\approx5.15\cdot10^{30}\frac{[1-\exp(-2\pi Z/137)]^2}{Z^2 g(\varepsilon_0)}\text{ years}.$$

The corresponding values of $T_{1/2}$ are given in the final column of Table IV.

The pion-core model for the $\Delta(1232)$ resonance was used by Smith, Picciotto, and Bryman[67] to estimate the probability of neutrinoless 2β decay as a process of first order in the superweak interaction (the diagram in Fig. 1f). A Lagrangian analogous to the one that describes β decay of the pion ($\pi^-\to\pi^0+e^-+\tilde\nu_e$) was used to calculate the decay constant:

$$\lambda_{0\nu}=7.2\cdot10^{-6}\left(\frac{G'}{G}\right)^2\left(\frac{2\pi Z}{137}\right)^2\left[1-\exp\left(-\frac{2\pi Z}{137}\right)\right]^{-2}\times P(\Delta)\,|\langle\Phi_f|\Phi_i\rangle|^2\,\varepsilon_0(\varepsilon_0^4+6\varepsilon_0^3+25\varepsilon_0^2+40\varepsilon_0+48)\text{ year}^{-1},$$

where G' is the coupling constant of the superweak interaction. With the values $P(\Delta)$ and $\langle\Phi_f|\Phi_i\rangle$ given above, $T_{1/2}(^{130}\text{Te})=3\times10^{-5}(G/G')^2$ years was obtained. Comparison with the experimental value[10] of $T_{1/2}(^{130}\text{Te})$ made it possible to establish that $G'=10^{-12.9}G$. Further, using this value of G', the authors calculated the half-lives for ^{48}Ca($10^{20.9}$ years), ^{76}Ge($10^{21.9}$ years), ^{82}Se($10^{21.3}$ years), and ^{128}Te($10^{22.7}$ years), which agree reasonably with the experimental limits and the calculations of other authors.

The same authors[68] calculated the rate of two-neutrino 2β decay through the resonance mechanism (the diagram of the process is in Fig. 1c):

$$\lambda=\ln2\left[2.22\cdot10^{25}\left(1-\exp\left(-\frac{2\pi Z}{137}\right)\right)^2\left(\frac{137}{2\pi Z}\right)^2\times\frac{1}{|\langle\Phi_f|\Phi_i\rangle|^2 P(\Delta)\,\bar K f_0(\varepsilon_0)}\right]^{-1}\text{year}^{-1},$$

where $f_0(\varepsilon_0)=\varepsilon_0^7(1+\varepsilon_0/2+\varepsilon_0^2/9+\varepsilon_0^3/90+\varepsilon_0^4/1980)$, and $\bar K$ is the mean value of the function

$$K=[(E_1+\varepsilon_1)^{-1}+(E_2+\varepsilon_2)^{-1}]\{2[(E_1+\varepsilon_1)^{-1}+(E_2+\varepsilon_2)^{-1}]-[(E_1+\varepsilon_2)^{-1}+(E_2+\varepsilon_1)^{-1}]\}+(E_1\leftrightarrow E_2)$$

($E_1, E_2, \varepsilon_1, \varepsilon_2$ are the energies of the electrons and neutrinos, respectively).

Under the assumption that $|\langle\Phi_f|\Phi_i\rangle|\approx10^{-1}$, it was found that

$$T_{1/2}(^{130}\text{Te})=10^{19.5}[P(\Delta)]^{-1}\text{years}.$$

Comparison with the experimental value $T_{1/2}(^{130}\text{Te})=10^{21.34}$ years yielded $P(\Delta)\approx1.4\%$. This value of $P(\Delta)$ was taken as the basis of calculations of the half-lives of ^{48}Ca, ^{82}Se, and ^{128}Te.

TABLE V.

Transition	Transition energy, $m_e c^2$	Theoretical values of $T_{1/2}$, year: Weak interaciton: 2ν (Ref. 66) 2-nucl.	Weak interaciton: 2ν (Ref. 68) Δ-mech.	Weak interaciton: 0ν (Ref. 4) 2-nucl.	Weak interaciton: 0ν (Ref. 4) Δ-mech.	Superweak: Ref. 67 Δ-mech.	Experimental values of $T_{1/2}$, year
$^{48}Ca \rightarrow {}^{48}Ti$	8.4	$10^{20.3}$	$10^{19.9}$	$10^{20.6}$	$10^{20.5}$	$10^{20.9}$	$> 10^{21.3}$ —0ν [69] $> 10^{19.56}$—2ν [69]
$^{76}Ge \rightarrow {}^{76}Se$	4.0	$10^{22.3}$	$10^{22.4}$	$10^{22.0}$	$10^{22.1}$	$10^{21.9}$	$> 10^{21.7}$ —0ν [70] $> 10^{21.49}$—0ν [71]
$^{82}Se \rightarrow {}^{82}Kr$	5.9	$10^{20.9}$	$10^{21.0}$	10^{21}	$10^{21.2}$	$10^{21.3}$	$10^{20.42}$— [18]
$^{128}Te \rightarrow {}^{128}Xe$	1.7	$10^{25.1}$	$10^{24.9}$	$10^{23.7}$	$10^{23.5}$	$10^{22.7}$	$10^{24.54\pm12}$ [15]
$^{130}Te \rightarrow {}^{130}Xe$	5.0	$10^{21.3}$	$10^{21.3}$	$10^{21.3}$	$10^{21.3}$	$10^{21.3}$	$10^{21.34\pm0.12}$ [10]

The results of the calculations of Refs. 67 and 68 are given in Table V, which is taken from Ref. 24. These calculations show that the presence of resonances with a probability of only about 1% can play a very important part in the problem of 2β decay.

We note that the results of the calculations of Ref. 3 contain the factor $10^{\pm 2}$, which arises because of the appreciable uncertainty in the values of the nuclear matrix elements, which have been calculated with allowance for nuclear structure for only a few nuclei.

Calculations of nuclear matrix elements and estimates of the lepton nonconservation parameter. The matrix elements of two-neutrino decay of ^{130}Te are calculated in Ref. 72. It is shown that the contribution of the Fermi interaction to the decay probability can be ignored, and the Gamow–Teller matrix element is calculated on the basis of a pairing model in which the value of the Gamow–Teller force is chosen so as to obtain the correct value of the rate of ordinary β decay. The obtained ^{130}Te half-life (1.2×10^{20} years) is two orders of magnitude smaller than the value given in Table IV and an order of magnitude smaller than the experimental value.

It was established by Khodel' in Ref. 73 that the nuclear matrix element of neutrinoless double β decay of ^{48}Ca has a maximal value if the single-particle quantum numbers of the pair of nucleons which decays are close to those of the pair which is formed. The fluctuations of the nuclear matrix elements of the decay were investigated and it was shown that these fluctuations can be large even for neighboring nuclei because of the possible interference of the matrix elements of different components of the quasiparticle wave functions of the initial state and the final state. Khodel' later calculated[74] the nuclear matrix elements for two-neutrino decay of ^{48}Ca by means of a method based on the principle of diagram selection used in quantum electrodynamics to derive the low-energy theorem for bremsstrahlung. He obtained equations for calculating the matrix elements in terms of the constants introduced in the theory of finite Fermi systems. The calculated value of $T_{1/2}$ is approximately 10^{20} years, which agrees reasonably with the experimental limit $T_{1/2} \geq 3.6\times10^{19}$ years for this transition.[69]

In Ref. 75, the wave functions of the nuclear shell model were used to calculate the nuclear matrix elements of the 2β decay of ^{48}Ca, ^{128}Te, and ^{130}Te, treated as a Gamow–Teller transition of second order. Vergados[75] confirmed the smallness of the matrix elements of ^{48}Ca($|ME|^2 \approx 1.2\times10^{-2}$) calculated earlier by Khodel',[73] and concluded that the ^{48}Ca nucleus is probably not the best candidate for studying lepton nonconservation because of the impossibility of exact calculation of the matrix elements and possible hindrance of the 2β decay. For ^{128}Te and ^{130}Te, the matrix elements were calculated by means of the approximate shell model and the following assumptions:

1) the ground states are products of the proton and neutron wave functions;

2) the neutron wave functions have the form $1h^n_{11/2}$. The values obtained for the matrix elements were -0.568 and -0.496 for $A = 128$ and 130, which confirms the assumption of the approximate equality of the matrix elements of these nuclei made earlier by Pontecorvo[60] and also Rosen and Primakoff.[4]

Finally, in their recent paper of Ref. 76 Fayans and Khodel' recalculated the matrix elements of the neutrinoless decay of ^{48}Ca using the theory of finite Fermi systems. For the matrix elements, they obtained the values $M_V = -0.221$, $M_S = 0.591$, and $M_T = -0.030$.

We now turn to estimates of the lepton-charge nonconservation parameter, which can be obtained directly from the expression (10) using the calculated matrix element and the measured lifetime for neutrinoless 2β decay.

The results of indirect mass-spectroscopy experiments can also be used to determine the extent to which the lepton-number conservation law is violated. But since in this case the neutrinoless and two-neutrino decay channels are not distinguished experimentally, the estimate of η can be written on the basis of (10) and (10′) in the form

$$\eta^2 = f_2 [(T_{1/2} | ME|^2)^{-1} - f_4^{-1}]. \qquad (14)$$

Rosen and Primakoff[4] assumed that the half-life of ^{130}Te($10^{21.34}$ years) measured by Kirsten[10] in an indirect experiment is completely due to neutrinoless 2β decay, and from (10) they obtained $\eta \approx 10^{-4} ME^{-1}$. However, if $ME \approx 0.1$, then $\eta \approx 10^{-3}$. The same authors[4] estimated the parameter η for the same experimental value of Ref. 10 on the basis of the expression (13) obtained under the assumption of the resonance mechanism of the neutrinoless decay. They found

$$\eta \approx 10^{5.3} [P(\Delta)]^{1/2} |\langle \Phi_f | \Phi_i \rangle|^{-1},$$

which for $P(\Delta) \approx 0.01$ and $|\langle \Phi_f | \Phi_i \rangle| \approx 0.3$ imposes a more stringent limit on the value of η: $\eta \approx 1.7\times10^{-4}$.

Khodel',[73] who used the early results[77] of the Columbia group in their study of the neutrinoless decay of ^{48}Ca($T_{1/2} \geq 1.6\times10^{21}$ years) and its own calculations of the nuclear matrix elements of this transition, established that $\eta \leq 3\times10^{-4}$. In the later experiments of Ref. 69 with ^{48}Ca, the experimental half-life was determined more accurately ($T_{1/2} \geq 2\times10^{21}$ years). This enabled Fayans and Khodel',[76] who made fairly complicated theoretical calculations, to conclude that the nonconservation parameter does not exceed 0.6×10^{-4},

and that the mass of the electron antineutrino satisfies $m_{\bar{\nu}_e} \leq 50$ eV.

Recently, the 2β decay of ^{48}Ca was again carefully studied in Ref. 78, in which the nuclear matrix elements of neutrinoless and two-neutrino transitions were calculated. The following values were calculated for the half-lives:

$$T_{1/2}^{0\nu} = (0.32 \pm 0.1) \cdot 10^{11} [(1+\delta_0)/(1-\delta_0)]^2 \text{ years},$$
$$T_{1/2}^{2\nu} = 6 \cdot 10^{19 \pm 0.5} \text{ years},$$

where δ_0 is a parameter whose departure from unity characterizes the nonconservation of the leptons. Comparison of the theoretical value of $T_{1/2}$ with the experimental[69] showed that $|1 - \delta_0| \leq 3 \times 10^{-6}$.

In the opinion of the Columbia group,[71] they made the first and most accurate estimate of η without explicit allowance for the matrix elements of the investigated transition ^{82}Se → ^{82}Kr. The nonconservation parameter was calculated on the basis of the results of this group, which determined a limit on the lifetime for neutrinoless decay of ^{82}Se(3.1×10^{21} years), the data of Srinivasan *et al.*[18] on the total half-life of ^{82}Se(2.76×10^{20} years), and also the following assumptions:

1) the nuclear matrix elements for the neutrinoless and two-neutrino channels are comparable;

2) the ratio of the phase spaces for the 0ν and 2ν decay channels is approximately 10^6. It then follows from (9) and (10) that $T_{1/2}^{2\nu}/T_{1/2}^{0\nu} \approx 10^6 \eta^2$. Using the relation $T_{1/2}^{2\nu}/T_{1/2}^{0\nu} = R_0/(1-R_0)$, where the branching ratio R_0 is equal to the ratio of the probability of neutrinoless decay to the total probability of 2β decay, one obtains $R_0/(1-R_0) \approx 10^6 \eta^2$. The value of R_0 determined from the data of Refs. 18 and 71 is 0.09, so that $\eta \approx 3 \times 10^{-4}$.

In Ref. 14, the half-life ratio $T_{1/2}(^{128}\text{Te})/T_{1/2}(^{130}\text{Te}) \approx 1.59 \times 10^3$ measured by the mass-spectroscopy method was used in conjunction with the assumption of equality of the matrix elements to find $\eta \leq 0.8 \times 10^{-4}$.

To determine the lepton nonconservation parameter, Vergados[75] used the experimental data of Refs. 10, 14, and 69 in addition to the calculated matrix elements. The corresponding values of the effective phase spaces in the expression (14) were calculated on the basis of Eqs. (11) and (12) (the unit of measurement is a year): $f_2(48) = 4.0 \times 10^{12}$, $f_4(48) = 7.94 \times 10^{18}$, $f_2(128) = 4 \times 10^{15}$, $f_4(128) = 4.10 \times 10^{24}$, $f_2(130) = 3.16 \times 10^{13}$, and $f_4(130) = 6.64 \times 10^{20}$.

The upshot was $\eta(48) = 4 \times 10^{-4}$, $\eta(128) = 0.86 \times 10^{-4}$, and $\eta(130) = 2.8 \times 10^{-4}$. Assuming that $|ME(128)/ME(130)|^2 = 1.3$, this ratio and the half-life ratio of ^{128}Te and ^{130}Te were used to make an even more accurate and reliable estimate: $\eta = 0.45 \times 10^{-4}$. In the opinion of the author, this result agrees excellently with the values previously found, which confirms the reliability of the calculations of the matrix elements.

The longest limiting lifetime against neutrinoless 2β decay (5×10^{21} years) was determined in an experimental study of the transition ^{76}Ge → ^{76}Se.[70] On the basis of this result and approximating assumptions analogous to those made by Primakoff and Rosen,[4] Fiorini[3] calculated bounds for the parameter η: $10^{-2.6 \pm 1}$ and $10^{-3 \pm 1}$ for the two-nucleon and resonance mechanisms of 2β decay, respectively.

Table VI gathers together all the most important data on nonconservation of lepton charge in 2β decay processes.

Energy spectra and angular correlation of electrons. In the case of decay through the neutrinoless channel, the transition energy is distributed effectively between the two electrons, since the recoil of the nucleus can be ignored. In this case, the profile of the energy spectrum of a single electron completely determines the law of the distribution of the energy between the two electrons.

If ε_1, ε_2, and W_0 are, respectively, the total energy of the first and second electron and the total energy released by the decay (measured in units of $m_e c^2$), then the probability of finding an electron with energy in the range $(\varepsilon_1, \varepsilon_1 + d\varepsilon_1)$ is determined by the expression[22]

$$\omega(\varepsilon_1)\, d\varepsilon_1 = \text{const}\, F(\varepsilon_1)\, F(\varepsilon_2) \times [(\varepsilon_1 - 1)^{1/2} (\varepsilon_2 - 1)^{1/2}]\, (\varepsilon_1 \varepsilon_2 - 1)\, (\varepsilon_1 - \varepsilon_2)^2\, d\varepsilon_1,$$

where $F(\varepsilon) = 2\pi Z e^2 / [1 - \exp(2\pi Z e^2/\hbar v)]\hbar v$, $\varepsilon_2 = W_0 - \varepsilon_1$, and v and e are the velocity and charge of the electron. Ignoring the exponential in the denominator of $F(\varepsilon_1)$ for sufficiently heavy nuclei, and restricting the total energy of the electrons to the range $2 \leq \varepsilon_1 \leq W_0 - 2$, i.e., considering electrons with velocity $\approx c$, we obtain

TABLE VI. Estimates of the lepton nonconservation parameter on the basis of 2β-decay experiments.

Transition	Experimental values of $T_{1/2}$, year	Values of matrix elements	Additional assumptions	Values of the parameter η	Reference
^{48}Ca → ^{48}Ti	$\geq 1.6 \cdot 10^{21}$ 0ν – [77]	$\lvert ME \rvert \approx 0.17$	–	$\leq 3 \cdot 10^{-4}$	[73]
	$\geq 2 \cdot 10^{21}$ 0ν – [69]	$M_V = -0.221$ $M_S = 0.591$ $M_T = 0.030$	–	$\leq 0.6 \cdot 10^{-4}$	[76]
		$\lvert ME \rvert^2 = 1.2 \cdot 10^{-2}$	$f_2 = 4 \cdot 10^{12}$ years $f_4 = 7.94 \cdot 10^{18}$ years	$\leq 4 \cdot 10^{-4}$	[75]
^{76}Ge → ^{76}Se	$\geq 5 \cdot 10^{21}$ 0ν – [70]	$\lvert ME \rvert \approx 0.1$	$\lvert ME \rvert \approx 0.1$	$10^{-2.6 \pm 1}$	[3]
			$P(\Delta) \approx 0.01$ $\lvert \langle \Phi_f \rvert \Phi_i \rangle \rvert^2 \approx 0.01$	$10^{-3 \pm 1}$ Δ mechanism	
^{82}Se → ^{82}Kr	$\geq 3.1 \cdot 10^{21}$ 0ν – [71] $2.76 \cdot 10^{20}$ $0\nu + 2\nu$ – [18]	$\lvert ME \rvert_{0\nu} \approx \lvert ME \rvert_{2\nu}$ $R_0 = \frac{\lambda_{0\nu}}{\lambda_{0\nu} + \lambda_{2\nu}} \approx 0.09$	$\lvert ME \rvert_{0\nu} \approx \lvert ME \rvert_{2\nu}$ $f_4/f_2 \approx 10^6$	$\leq 3 \cdot 10^{-4}$	[71]
^{128}Te → ^{128}Xe	$1.5 \cdot 10^{24}$ $0\nu + 2\nu$ – [14]	$\lvert ME \rvert^2 = 0.32$	$f_2 = 4 \cdot 10^{15}$ years $f_4 = 4.1 \cdot 10^{24}$ years	$0.9 \cdot 10^{-4}$	[75]
^{130}Te → ^{130}Xe	$2.2 \cdot 10^{21}$ $0\nu + 2\nu$ – [10]	$\lvert ME \rvert^2 = 0.25$	$f_2 = 3.16 \cdot 10^{13}$ years $f_4 = 6.64 \cdot 10^{20}$ years	$2.8 \cdot 10^{-4}$	[75]
		$\lvert ME \rvert \approx 0.1$	$\lvert ME \rvert \approx 0.1$	10^{-3}	[4]
			$P(\Delta) \approx 0.01$ $\lvert \langle \Phi_f \rvert \Phi_i \rangle \rvert^2 \approx 0.01$	$1.7 \cdot 10^{-4}$ Δ mechanism	
^{128}Te → ^{128}Xe ^{130}Te → ^{130}Xe	$\frac{T_{1/2}(128)}{T_{1/2}(130)} = 1.59 \cdot 10^3$ [14]	$\lvert ME \rvert_{128} \approx \lvert ME \rvert_{130}$	$\lvert ME \rvert_{128} \approx \lvert ME \rvert_{130}$	$(6 - 10) \cdot 10^{-4}$	[14]
		$\frac{\lvert ME \rvert^2_{128}}{\lvert ME \rvert^2_{130}} \approx 1.28$		$(0.5 - 0.7) \times 10^{-4}$	[75]

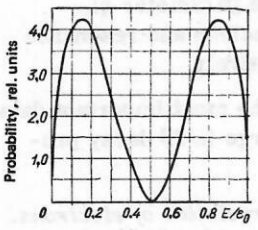

FIG. 2. Energy spectrum for one of the electrons in the case of neutrinoless 2β decay.

$F(\varepsilon_1) \approx 2\pi Ze^2/\hbar c = \text{const}$. If we now go over from the total energies to the kinetic energies $\varepsilon_0 = W_0 - 2$ and $E = \varepsilon - 1$, we can derive the following expression for the spectrum of single electrons:

$$\omega(x)\,dx = \text{const}\,(2x-1)^2\,(x/\varepsilon_0 + x - x^2)\,(x-x^2)^{1/2},$$

where $x = E/\varepsilon_0$ and $1 \leq E \leq \varepsilon_0 - 1$.

Figure 2 shows the graph of this dependence for the 2β decay of ^{48}Ca. It can be seen that in the most probable division one electron will have an energy of about $0.85\varepsilon_0$, and the second will have $0.15\varepsilon_0$. Emission of electrons with energies $0.5\varepsilon_0$ or ε_0 is virtually impossible. These characteristic features of the distribution are still obtained with initial assumptions different from those adopted above.[78,80]

The profiles of the single and total energy spectra for two-neutrino 2β decay were calculated in Refs. 78 and 81. In Fig. 3, the spectra are shown for the 2β decay of ^{48}Ca.[81]

In Ref. 79, the form of the angular correlation function of the electrons in neutrinoless 2β decay was also established:

$$F(\theta) = 1 + f(E_1;\ E_2)\cos\theta, \tag{15}$$

where f is a complicated function of the energy of the electrons and depends on the chosen variant of the β interaction. In a rough approximation, $f(E_1; E_2) \approx 1$ for first-forbidden nuclear 2β transitions and

$$F(\theta) \approx 1 + \cos\theta.$$

For such a dependence, $-\pi/2 \leq \theta \leq \pi/2$ is the most probable angular correlation, which significantly reduces the efficiency of coincidence detection.

Rosen and Primakoff[4] showed that the angular correlation function for the resonance mechanism of neutrinoless 2β decay differs significantly from (15) and has the form

$$F(\mathbf{P}_1\mathbf{P}_2) \approx \left\{1 - \left(\frac{\mathbf{P}_1}{|\mathbf{P}_1|}\cdot\frac{\mathbf{P}_2}{|\mathbf{P}|_2}\right)\right\}\left\{1 - \frac{1}{3}\left(\frac{\mathbf{P}_1}{|\mathbf{P}_1|}\cdot\frac{\mathbf{P}_2}{|\mathbf{P}_2|}\right)\right\},$$

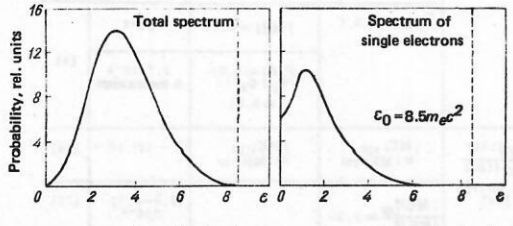

FIG. 3. Total and single energy spectra of electrons for two-neutrino 2β decay of ^{48}Ca.

where $\mathbf{P}_1$ and $\mathbf{P}_2$ are the electron momenta.

At the same time, a calculation based on the resonance mechanism of 2β decay as a first-order effect in the superweak interaction[67] leads to a result analogous to (15):

$$F(\theta) = 1 + v_1 v_2 \cos\theta + m_e^2/(E_1 - E_2),$$

where v_1, v_2 and $E_1 E_2$ are the velocities and energies of the electrons.

Thus, if the form of the angular correlation is to be used to choose between the two-nucleon and resonance mechanism of 2β decay, it is necessary to determine first which interaction (weak or superweak) is responsible for this process.

For completeness, we also give the result of Konopinski[66] obtained for two-neutrino decay in accordance with the two-nucleon mechanism:

$$F(\mathbf{P}_1\cdot\mathbf{P}_2) \approx 1 - (\mathbf{P}_1\cdot\mathbf{P}_2)/(\varepsilon_1+1)\,(\varepsilon_2+1),$$

where ε_1 and ε_2 are the kinetic energies of the electrons in units of the electron mass.

3. REVIEW OF EXPERIMENTAL RESULTS

In this section, the main attention will be devoted to experiments made in recent years.

There are two fundamentally different groups of experiments in which 2β decay is studied—the direct and the indirect. In the former, the problem consists of detecting the simultaneous emission of two electrons and studying the probability distribution of the sum of the kinetic energies of the electrons. However, the extremely low probability of the 2β process makes it extremely hard to observe decay events directly, since the intensity of the background exceeds by many orders the vanishingly small intensity of the effect which must be distinguished. For example, in a gram of sample there is about one decay per year at a half-life of 10^{21} years.

The difficulties of the direct detection of 2β decay stimulated the development of indirect methods of studying this phenomenon in which one looks for daughter nuclei $(A, Z+2)$ in samples with high initial concentration of nuclei of the parent element (A, Z). The advantage of the indirect experiments is the huge length of time, equal to the age of the sample and reaching several billion years, during which products of the 2β decay are accumulated. But this is simultaneously the shortcoming of the method, since ignorance of the "history" of the sample unfortunately imposes serious limitations on the reliability of the results obtained.

Indirect experiments. In the overwhelming majority of the experiments hitherto made, the samples chosen for investigation were minerals containing selenium and tellurium, which are transformed by 2β decay into inert gases—krypton and xenon.

The investigation consists of several stages.

1. The determination of the age of the sample by several methods if possible.

2. The determination of the tellurium and selenium concentrations in the sample.

3. The extraction of xenon and krypton from the sample.

4. A mass-spectroscopy isotope analysis of the extracted gases and determination of the absolute concentrations of the Xe and Kr isotopes.

5. The determination of the coefficient of retention of the xenon and krypton in the sample during the time of its existence.

6. A comprehensive and careful allowance for the contribution of the various background reactions to the formation of the isotopes ^{128}Xe, ^{130}Xe, and ^{82}Se.

7. Calculations on the basis of the obtained data of the half-life in accordance with the formula

$$T_{1/2} = \ln(2)\, M_m t S / M_t,$$

where t is the age of the mineral, M_m is the amount of the parent element, M_t is the amount of the daughter product formed by the 2β decay, and S is the coefficient of retention of the daughter element during time t.

In the first experiments of this kind, Leviene *et al.*[82] established the lower limit 6×10^{18} years for the transition $^{238}U \to {}^{238}Pu$, and Inghram and Reynolds[82] found $T_{1/2} = 1.4\times10^{21}$ years for the decay $^{130}Te \to {}^{130}Xe$. The result 3.3×10^{21} years was obtained for this transition in Ref. 83. In the later experiments of Ref. 84, the value of $T_{1/2}$ for ^{130}Te was found to be $(8^{+0.4}_{-0.9})\times10^{20}$ years and for ^{128}Te to be 3×10^{22} years.

The investigations of Refs. 82–84 did not take into account the contribution from background reactions and the possible loss of some of the xenon during the time of existence of the sample, which reduces to some extent the value of the obtained results.

In Ref. 8, to determine the amount of xenon formed by 2β decay, a number of corrections were introduced to make allowance for the fact that, in the opinion of the authors, the xenon released from the mineral consisted of three components: atmospheric xenon, xenon from the spontaneous fission of uranium, and xenon formed in nuclear reactions. To determine the coefficient of retention of xenon in the sample, it was assumed that the rates of diffusion of ^{128}Xe and ^{130}Xe differ little from the rate of diffusion of ^{136}Xe when the mineral is heated (this was confirmed by special experiments). Since ^{136}Xe is basically produced by the spontaneous fission of uranium present in the sample, the uranium concentration could be used to calculate the amount of ^{136}Xe produced during the time of existence of the sample. Then, measuring the actual amount of ^{136}Xe and comparing it with the calculated value, the authors found a coefficient of retention of ^{136}Xe equal to 0.07 and took this value for ^{128}Xe and ^{130}Xe. This then yielded $T_{1/2}(^{130}\text{Te}) = (3.0\pm0.4)\times10^{20}$ years and $T_{1/2}(^{128}\text{Te}) > 7.7\times10^{20}$ years.

In an ore sample from the Good Hope mine in Colorado with a tellurium content of $99.4\pm0.6\%$ Kirsten *et al.*[9,10] found an excess of ^{130}Xe (70% of the total Xe content) that exceeded by 50 times the atmospheric concentration of Xe.

The absence of other anomalies with regard to the xenon rules out all processes except 2β decay that could be responsible for the production of the excess ^{130}Xe. For example, spontaneous fission of uranium cannot be the source of the ^{130}Xe, since in such a case the amount of ^{136}Xe would be about 10^5 times greater than the amount of ^{130}Xe. (The uranium concentration in the sample was determined by the neutron-activation method and was $(21\pm2)\times10^{-7}\%$, which is four orders of magnitude less than in the samples used in the previous investigations of Refs. 8 and 82–84.) Reactions induced by neutrons could produce ^{129}Xe and ^{131}Xe, but neither of these anomalies was observed in the sample, which establishes a limiting value for the maximal internal flux of neutrons. On the basis of this limit, the influence of the reaction $^{133}\text{Cs}(n,\alpha)^{130}\text{I}^{\beta-} \to {}^{130}$Xe can be ignored. Spallation reactions induced by cosmic rays would lead to the formation of much greater amounts of ^{124}Xe and ^{126}Xe compared with ^{130}Xe. Natural α radiation could be responsible for producing ^{128}Xe, ^{129}Xe, and ^{131}Xe, but not ^{130}Xe, since the energy of the α particles is insufficient for the reaction $^{128}\text{Te}(\alpha,2n)^{130}$Xe to take place. Thus, the only reasonable explanation for the observed ^{130}Xe excess is the 2β decay of ^{130}Te.

The age of the sample was dated by the potassium–argon method at $(1.31\pm0.14)\times10^9$ years, which is in reasonable agreement with the geological situation of the ore sample. On the other hand, the age calculated from the helium and uranium content was $(2.05\pm0.55)\times10^8$ years. On the basis of this difference, Kirsten *et al.* ignored the xenon losses; for although a partial depletion by helium did occur, the amount of argon was not reduced. The high retention of ^{130}Xe was also confirmed in experiments with heating by stages. With the above assumption, the half-life for ^{130}Te was found to be $10^{21.34\pm0.12}$ years. For ^{128}Te, the results obtained in the previous investigations were not confirmed, and only the limit $T_{1/2} \geq 10^{23.3}$ years was established.

In the investigation of Ref. 9, studies were also made of selenium-bearing minerals with a view to detecting the transition $^{82}\text{Se} \to {}^{82}$Kr. Krypton was extracted from the samples and the isotope ratios $^{82}\text{Kr} : {}^{83}\text{Kr} : {}^{84}\text{Kr} : {}^{86}\text{Kr} = 0.3 : 16.5 : 1.0 : 0.3$ determined. Atmospheric krypton has the ratios $^{82}\text{Kr} : {}^{83}\text{Kr} : {}^{84}\text{Kr} : {}^{86}\text{Kr} = 0.2 : 0.2 : 1.0 : 0.35$. Thus, an appreciable ^{83}Kr excess was found. The reactions $^{80}\text{Se}(\alpha,n)^{83}$Kr and $^{82}\text{Se}(n,\gamma)^{83}\text{Se}^{\beta-} \to {}^{83}\text{Br}^{\beta-} \to {}^{83}$Kr give a good and complete explanation of the anomaly in the ^{83}Kr abundance. The isotope ^{82}Kr could be formed as follows:

1) $^{78}\text{Se}(n,\gamma)^{79}\text{Se}(\alpha,n)^{82}\text{Kr}$; 2) $^{80}\text{Se}(\alpha,2n)^{82}\text{Kr}$;
3) $^{85}\text{Rb}(n,\alpha)^{82}\text{Br} \xrightarrow{\beta^-} {}^{82}\text{Kr}$; 4) $^{81}\text{Br}(n,\gamma)^{82}\text{Br} \xrightarrow{\beta^-} {}^{82}\text{Kr}$;
5) $^{82}\text{Se} \xrightarrow{2\beta^-} {}^{82}\text{Kr}$.

Since $T_{1/2} = 7\times10^4$ years for ^{79}Se, the formation of an appreciable amount of ^{82}Kr through the process 1) is impossible. The reaction 2) takes place at $E_\alpha \geq 11$ MeV, and, bearing in mind the cross section for production of ^{83}Kr in (α,n) reactions, can ensure a very

slight excess of ^{82}Kr. For the processes 3) and 4) exact estimates were not made, but it was shown that a small amount of ^{82}Kr can be formed in them. The age of the mineral was determined with low accuracy at $(6-23)\times10^7$ years. Therefore, $T_{1/2}=(3-10)\times10^{19}$ years. The mean value $T_{1/2}(^{82}\text{Se})=6\times10^{19\pm0.3}$ years is obtained.

In Ref. 13, more reliable determinations of the ^{82}Se half-life were obtained. For six selenium-bearing samples an excess concentration (relative to the atmospheric) of ^{82}Kr was found. A selenium–kobellite sample with the largest ^{82}Kr excess had the ratio $^{82}\text{Kr} : {}^{83}\text{Kr}\approx4.7$. The isotopic composition of the krypton extracted from this sample clearly revealed that the concentration of all the krypton isotopes except ^{82}Kr corresponded to the atmospheric values. This last fact makes it possible to rule out extraneous reactions as the possible explanation for the ^{82}Kr excess (the arguments made in Ref. 9 are repeated).

Since the accumulation of ^{82}Kr as a result of 2β decay and of ^{86}Kr as a result of fission of uranium is almost linear over a time interval equal to the age of the sample [$(250-350)\times10^6$ years], the ^{82}Se half-life was calculated solely on the basis of the ratios of the krypton isotopes, which thus eliminated the uncertainty due to allowance for the diffusion of the gases. The result was $T_{1/2}=(1.37\pm0.28)\times10^{20}$ years.

In the series of investigations of Refs. 16–18, the half-lives of ^{130}Te and ^{82}Se were determined with a careful analysis of all the possible channels for the production of ^{130}Xe and ^{82}Kr. To take into account the influence of reactions induced by neutrons on the isotope composition of the krypton and xenon, the samples were irradiated with reactor neutrons and an isotope analysis was then made.

For a 2.46×10^9-year tellurium ore from Kalgoorlie (Australia) $T_{1/2}(^{130}\text{Te})=(2.83\pm0.30)\times10^{21}$ years was obtained.[16]

Investigating then[17] the tellurobismuthite sample No. 25 IB (Boliden, Sweden), the authors found $T_{1/2}(^{130}\text{Te})=(2.69\pm0.27)\times10^{21}$ years, which agrees excellently with their previous result.

In the following investigation of Ref. 18 on the same sample (No. 25 IB), the isotope composition of Se and Kr was determined, which made it possible to establish $T_{1/2}(^{130}\text{Te})/T_{1/2}(^{82}\text{Se})=10\pm2$. On the basis of this ratio and the previously determined $T_{1/2}(^{130}\text{Te})$, Srinivasan *et al.* calculated two values for $T_{1/2}(^{82}\text{Se})$: $(2.69\pm0.60)\times10^{20}$ years and $(2.83\pm0.64)\times10^{20}$ years. The mean value is $(2.76\pm0.88)\times10^{20}$ years. This result is almost twice the values obtained by Kirsten *et al.*[13] In an attempt to understand the discrepancy between the data, a study was made of the isotopic composition of Se and Kr in an umangite sample from Harbi (Western Moravia), i.e., from the same region as the sample of Kirsten *et al.* A much lower ratio $^{82}\text{Kr}/^{82}\text{Se}$ was found than in Ref. 13. Using $T_{1/2}(^{82}\text{Se})=(2.76\pm0.88)\times10^{20}$ years, Srinivasan *et al.* determined the age of this sample at $(1.6\pm0.5)\times10^8$ years, which is near the lower limit of the assumed geological age of this deposit.

In the investigation of Ref. 14, a sample of gold telluride from the Kalgoorlie deposits in Australia was studied. The age of the mineralized gold in this region is $(2.460\pm0.080)\times10^9$ years according to the data of rubidium–strontium dating. From 10 g of the telluride, one sample of mass 3.791 g was investigated on a mass spectrometer, and from the remaining mass of the mineral, which was divided into 50 parts, two aliquots (0.210 and 0.307 g) were prepared. The aliquots, together with tellurium and iodine monitors, were irradiated with an integrated neutron flux 2×10^{13} neutrons/cm^2 from a reactor, after which an isotope analysis was made. All analyses were made carefully to avoid contamination of the sample by atmospheric xenon. Xenon was released in four stages, at 250, 350, 600, and 750°C.

For the isotopes ^{128}Xe, ^{130}Xe, and ^{131}Xe, the first sample had the following excesses (compared with the atmospheric composition): 2.9, 5090, and 26. The $^{128}\text{Xe}/^{130}\text{Xe}$ excess ratio was $(5.8-0.2)\times10^{-4}$ and 50 times smaller than the preceding result of Takaoka and Ogata.[84] At the same time, this value agrees reasonably with the earlier results of the authors, which gave upper limits for this ratio of 9.3×10^{-3} and 3.2×10^{-3}; it also agrees with unpublished data of Kirsten, who investigated samples of natural tellurium from the Good Hope mine in Colorado and determined the limit 4.6×10^{-4} for this ratio. The agreement is particularly gratifying in that the xenon in Kirsten's sample had only a tenfold enrichment of ^{130}Xe, whereas the xenon from the Kalgoorlie telluride was enriched by more than 700 times. The calculation based on this ratio gave $T_{1/2}(^{128}\text{Te})/T_{1/2}(^{130}\text{Te})=(1.59\pm0.05)\times10^3$. In addition, $T_{1/2}(^{130}\text{Te})=(1.05\pm0.04)\times10^{21}$ years and $(0.89\pm0.11)\times10^{21}$ years were found for the two samples. The mean $T_{1/2}(^{130}\text{Te})=1.0\times10^{21}$ years and the half-life ratio were used to calculate $T_{1/2}(^{128}\text{Te})=(1.54\pm0.17)\times10^{24}$ years.

Subsequently, the half-life ratio of ^{128}Te and ^{130}Te was again measured[15] in an analysis of an altaite sample (PbTe) from Mattagami Lake (Quebec). The obtained value $(1.57\pm0.10)\times10^3$ is in excellent agreement with the previous result of Ref. 14. It should be noted that these half-life ratios are obviously the most reliable of the results established in the mass-spectroscopy experiments, since systematic errors in the determination of the age of the sample and the loss of gases do not affect the values of these ratios. Nevertheless, there are fairly serious grounds for questioning the data of independent experiments.

For example, study of the natural nuclear reactor in Oklo[85] showed that in the "core" all the heavy and rare-earth elements, and also the lighter fission products, were almost completely preserved. All these elements remained in the same uranite grains as the burnt uranium despite the two billion years that have elapsed since the time the reaction occurred. It was only the inert gases xenon and krypton that had almost completely disappeared from the region of the reactor, and, judging from the shortage of their decay products, this occurred already at the time the reactor was active.[85]

Thus, the experiment set up by nature itself shows that xenon and krypton are obviously not the most ideal objects for retention during billions of years.

Direct experiments. The direct observation of two electrons emitted simultaneously in 2β decay would be the most convincing proof that this process exists. Unfortunately, despite the tremendous number of studies so far made, a positive result has not yet been obtained. The most varied detectors (photographic emulsions, Wilson chambers, magnetic spectrometers, streamer chambers, and scintillation and semiconductor detectors) have been used to detect the electrons. Numerous reports of the observation of 2β decay have failed to be confirmed in subsequent experiments, which, naturally, is due to the exceptional weakness of the effect to be detected.

Let us consider the earliest investigations. Using Wilson chambers, Lawson[86] determined a lower limit of 10^{16} years for $T_{1/2}$ for the transition $^{124}Sn \rightarrow {}^{124}Te$. In another experiment in which a Wilson chamber was used the limit $\geq 10^{17}$ years was established for this decay.[87] Using the method of coincidences, McCarthy[88] investigated the transitions $^{124}Sn \rightarrow {}^{124}Te$ and $^{96}Zr \rightarrow {}^{96}Mo$ and found that the half-lives are greater than 1.5×10^{17} and 2×10^{16} years, respectively. In experiments with a Wilson chamber, Winter[89] determined half-lives of 1×10^{17} years for $^{116}Cd \rightarrow {}^{116}Sn$, 3×10^{17} years for ^{100}Mo, and 6×10^{16} years for $^{106}Cd \rightarrow {}^{106}Pd$. The transition $^{124}Sn \rightarrow {}^{124}Te$ was also studied in Refs. 90 and 91, in which the limits 2×10^{17} and 5×10^{16} years, respectively, were established. In Ref. 92, $T_{1/2}=6\times10^{16}$ years was established for the 2β decay of cadmium ($^{116}Cd \rightarrow {}^{116}Sn$). Numerous experiments have searched for the 2β decay $^{48}Ca \rightarrow {}^{48}Ti$. For example, in the probability distribution for the sum of the kinetic energies of two electrons McCarthy[88] found a maximum in the high-energy part of the spectrum. The excess above the background was significant, and this was the basis of an interpretation of it as due to neutrinoless 2β decay with $T_{1/2}=2\times10^{17}$ years. However, experiments made by Awschalom[93] using similar equipment but with a lower background level did not confirm these results. Only lower limits were established: $T_{1/2}(^{48}Ca) \geq 2\times10^{18}$ years and $T_{1/2}(^{96}Zr) \geq 5\times10^{17}$ years. Dobrokhotov *et al.*[94] and Goldhaber[95] also obtained $T_{1/2} \geq 2\times10^{18}$ years for ^{48}Ca. In Ref. 96, the limit $T_{1/2} \geq 4\times10^{18}$ years was established for the 2β decay $^{150}Nd \rightarrow {}^{150}Sm$. It is also necessary to mention the experiments of Fremlin and Walter,[97] who studied 2β decay be means of photographic emulsions. All results were negative, except for the transition $^{100}Mo \rightarrow {}^{100}Ru$, but the estimate $T_{1/2}=2\times10^{16}$ years contradicts the results of Ref. 89.

In Ref. 98, which was published in 1971, the results are given of searches for the 2β decay of ^{150}Nd by means of a magnetic spectrometer. To reduce the background, the spectrometer was placed in a salt mine at a depth of 585 m below ground level. The experiment, including two series of background measurements, lasted 750 h. From the observed counting rate, limits were determined for the half-lives of the neutrinoless and two-neutrino decay channels: 7×10^{18} years and 5×10^{18} years, respectively.

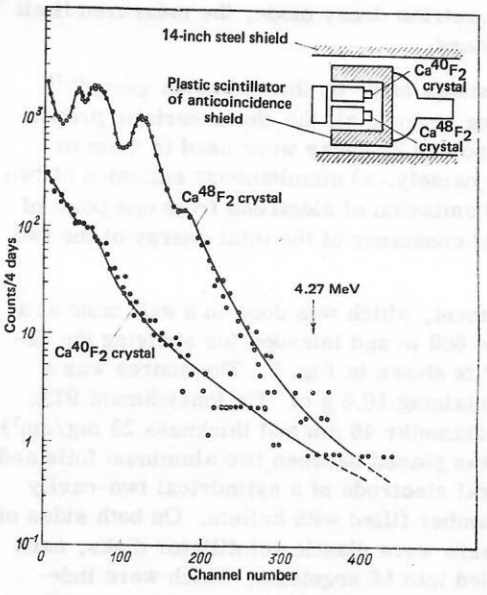

FIG. 4. Background spectra obtained in the experiment of Mateosian and Goldhaber.[99]

We now consider the experiments made recently at a fairly high level, which have made it possible to raise the limits on the half-lives for some transitions by several orders of magnitude.

Mateosian and Goldhaber[99] investigated the transition $^{48}Ca \rightarrow {}^{48}Ti$. To detect the electrons, they used a specially grown calcium fluoride crystal containing about 11 g of ^{48}Ca. The background was estimated relative to another crystal enriched with ^{40}Ca. The arrangement of the experiment is shown in Fig. 4. Both scintillation detectors were placed in the cavity of a shielding plastic scintillator, which was scanned by a photoelectric multiplier and connected in anticoincidence with the inner detectors. The complete detecting system with the shielding scintillator was placed inside the barrel of a ship's cannon, which provided additional shielding from the local radioactivity. Figure 4 shows the spectrum measured in the experiment. It can be seen that in the region of 4.27 MeV, i.e., in the region of the neutrinoless 2β decay of ^{48}Ca, there is no peak and virtually no excess above the background. For the neutrinoless 2β decay of ^{48}Ca this therefore established the limit $T_{1/2} \geq 2\times10^{20}$ years.

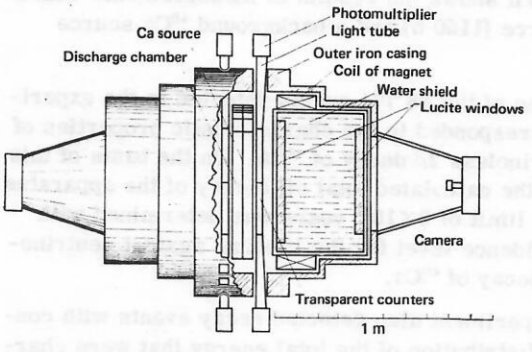

FIG. 5. Experiment of the Columbia group.[69]

For the two-neutrino decay mode, the measured limit was 5×10^{18} years.

The experiments made by the Columbia group[69,71] are interesting because all the characteristic properties of neutrinoless 2β decay were used in them to select events namely, a) simultaneous emission of two electrons, b) emission of electrons from one point of the source, c) constancy of the total energy of the two particles.

The experiment, which was done in a salt mine at a depth of about 600 m and intended for studying the decay of ^{48}Ca,[69] is shown in Fig. 5. The source was a CaF_2 disk containing 10.6 g of ^{48}Ca (enrichment 97%; the disk had diameter 46 cm and thickness 20 mg/cm^2). The source was placed between two aluminum foils and was the central electrode of a cylindrical two-cavity streamer chamber filled with helium. On both sides of the source there were plastic scintillator disks, each of them divided into 16 segments, which were independently scanned by photoelectric multipliers. The scintillators were covered by a transparent nickel mesh, which served as the outer electrode of the streamer chamber. The plastic scintillator gave information about the simultaneity of the emission of two electrons and about their energy.

The tracks in the chamber were photographed through shielding spaces containing water and through the scintillation disks. It was found that a satisfactory spatial reconstruction of the electron trajectories could be achieved with only one camera set up on each side, provided use was made of both the direct and the reflected (in the mirror plane of the central electrode) images of the tracks. The use of the streamer chamber in a magnetic field of 385 ± 10 Oe made it possible to reduce the background from the equipment very effectively by selecting tracks on the basis of criteria that required a common point of origin, correct sign of the curvature, and agreement between the curvature and the energy of the electron measured by the scintillator. It was estimated by the authors that the use of these additional conditions reduces the background by 6000 times compared with an experiment using only scintillation counters. The electronic logic circuit triggered the chamber on coincidence of signals from the two scintillators; the energy deposited in each of them had to exceed 250 keV, and the total energy had to be within given limits.

Table VII shows the results of measurements with a ^{48}Ca source (1150 h) and a background ^{40}Ca source (597 h).

Only one of the 48 774 events detected in the experiment corresponded to the characteristic properties of the neutrinoless 2β decay of ^{48}Ca. On the basis of this fact and the calculated total efficiency of the apparatus ($\approx57\%$) a limit of 2×10^{21} years was determined with 80% confidence level for the lifetime against neutrinoless 2β decay of ^{48}Ca.

The experiment also detected decay events with continuous distribution of the total energy that were characteristic of two-neutrino 2β decay. But comparison

TABLE VII. Results of searches for neutrinoless 2β events.[69]

№	Conditions of measurement	^{40}Ca	^{48}Ca
1	Live time, h	597	1 150
2	Total number of events	18 485	48 774
3	Frames with $E_s \geq 3$ MeV	467	687
4	After accepting only those with a two-prong vertex on the source and $E_s < 7$ MeV	163	197
5	The same as in No. 4 but within the adopted solid angle	89	118
6	After selection of events for which the track curvature agrees with the energy (according to scintillator)	17	23
7	The same as in No 6 but for opening angle less than 155°	1	4
8	Within two standard deviations (525 keV) in the region of 4.24 MeV	0	1

with the spectrum obtained with the background ^{40}Ca source showed that the ^{48}Ca source was slightly contaminated by radium with activity of about 0.037 pCi. Therefore, restricting their attention to events with total energy greater than 2.2 MeV, Bardin *et al.* could establish only the bound 3.6×10^{19} years for the half-life against the two-neutrino process.

Later, the equipment of the Columbia group was used to study the transition $^{82}Se \rightarrow {}^{82}Kr$.[71] The source consisted of 46 g of metallic selenium enriched with ^{82}Se by 56.5%. The selenium was purified by being passed repeatedly through ion-exchange columns. (The measured activity did not exceed 3.5 decays/min for ^{40}K and 0.25 decays/min for the remaining impurities.) The total thickness of the source was 58 mg/cm^2 Al equivalent with an rms deviation of order 8%. To take into account the energy loss by the electrons in a source of such thickness, a Monte Carlo calculation was made, and this, with allowance for the resolution of the scintillation detector, led to the conclusion that the energy distribution for neutrinoless 2β decay has a maximum at 2.75 MeV with a width of 0.3 MeV.

Possible 2β decay events were selected by visual examination of photographic film with a view to finding frames in which two and only two electron tracks having a common vertex leave the source. During 1300 h of measurement, 201 events of this kind were detected. The results of the observations are given in Table VIII. The analysis of the tracks is hardest in the cases when the electron is emitted with a high energy or at a small angle to the axis of the chamber. A reliable determination of the curvature of such tracks was virtually impossible. Therefore, only those events were selected in which both tracks made angles of more than 21° to the axis of the chamber (as can be seen in Table

TABLE VIII. Results of searches for neutrinoless decays of ^{82}Se (Ref. 71).

Total number of events	65 550
Events with two tracks corresponding to 2β decay	201
Events with lengths of both tracks greater than 1 cm	183
Number of events with both track saggitas greater than 0.5 mm	148
Number of events in which the energy of the scintillation detector agrees with the energy determined from the track curvature	96
Number of events in the range from 2.53 to 3.17 MeV	0

VIII, this corresponds to a track length longer than 1 cm). A second restriction was imposed on the height of the track segment, this being due to the comparatively low intensity of the magnetic field (370 G), which is insufficient for unambiguous interpretation of the tracks of high-energy electrons. The threshold was taken equal to 0.5 mm. With allowance for these restrictions, the calculated value of the geometrical efficiency did not exceed 28.5%. The efficiency of the film examination did not fall below 90%. The energy range in which the search for neutrinoless 2β decay was made was restricted to 2.4–3.2 MeV, which amounts to 75% of the total area under the curve of the expected energy distribution.

The absence of events in this region and the resulting efficiency (19%) of the equipment were used to estimate (at the 68% confidence level) a lower limit for the half-life against neutrinoless 2β decay of ^{82}Se: $T_{1/2} \geq 3.1 \times 10^{21}$ years.

In their experiments, the Milan group[70,100,101] used a semiconductor detector made of natural germanium (containing 7.67% of ^{76}Ge), which served simultaneously as a source and detector of 2β decay events; only one property of neutrinoless 2β decay—constancy of the total energy of the electrons—was used to select the events. Three series of experiments with different detectors were made.

The first experiment, at sea level, with a detector of volume 17 cm^3, lasted 712 h.[100] The result was $T_{1/2} \geq 3 \times 10^{20}$ years (confidence level 68%).

The second experiment was made with a detector of volume 24 cm^3 in the low background at the Monte dei Capuccini cosmic-ray laboratory at a depth of 70 m water equivalent.[101] The detector was shielded by several layers: 5 cm of mercury, 4 cm of copper, 20 cm of lead, 2 mm of cadmium, and 10 cm of paraffin. In addition, a plastic scintillator was placed above the detector as an anticoincidence shield. All these measures made it possible to reduce the background in the working region to $(5.3 \pm 0.5) \times 10^{-3}$ h^{-1} · keV^{-1}. As before, no peak was noted in the region of the transition energy (the experiment lasted 2800 h). The limit on the neutrinoless half-life was shifted to 1.2×10^{21} years (68% confidence level).

In the third experiment, a detector with volume 68 cm^3 was used.[70]

The experiment was set up in the International Cosmic-Ray Laboratory of the Italian C.N.R. in the Mont Blanc Tunnel. The rocks (4200 m.w.e.) above the tunnel provide an alternation factor of about 10^6 of the cosmic-ray component. The screen for shielding the detector from the local radioactivity is shown in Fig. 6. The cover of the cryostat of the detector was surrounded by a nylon container filled with twice distilled mercury. The thickness of the mercury layer was 5 cm. The nylon vessel was covered by a layer of electrolytic copper 4-cm thick. Then followed a layer of low-radioactive lead 10-cm thick (with activity three times lower than the usual value) and a screen of ordinary lead 10-cm thick. The resulting cube,

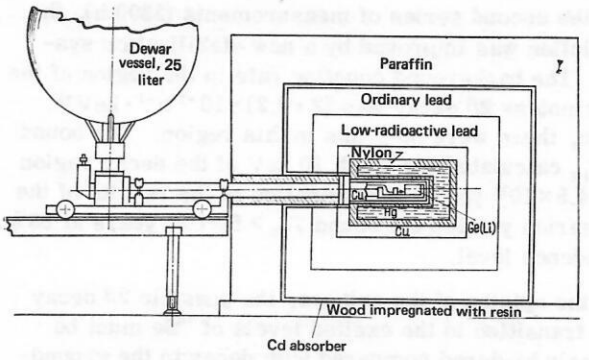

FIG. 6. Arrangement of the Milan group's experiment.[70]

with edge 70 cm, was wrapped in a sheet of cadmium 2-mm thick and placed on a wooden stand impregnated with resin. The cube was also shielded by a layer of paraffin 20-cm thick to slow down and absorb the neutrons produced by the spontaneous fission of uranium in the walls of the laboratory. The experiment was made in two stages. In the first series of measurements, the cover of the cryostat of the detector was made of electrolytic copper and the holder of the Ge(Li) diode out of Al 1100 aluminum. In the second series, both the cover and the holder were made of oxygen-free high-conductivity copper (OFHC). The remaining parts of the cryostat were made of stainless steel. The Ge(Li) diode was insulated electrically from the holder by a layer of boron nitride. The overall energy resolution (FWHM) was 6 keV for energy 2.615 MeV. The pulses from the free amplifier were analyzed by a 4096-channel analyzer, which had a system for stabilizing the spectrum that prevented a displacement of the zero level and a change of the conversion coefficient.

The equipment was tested every three days and the spectrum put on punched tape. If small displacements of the spectrum were observed, a correction was made by means of a PDP-8 computer. In the second series of experiments, a correction was not needed, since an improved stabilization system reduced the displacement of the spectrum to less than one channel (0.7 keV). To eliminate pulses due to external induction and electrical disturbances, the screen was surrounded by an antenna, a signal from this stopping the recording of information from the main detector. The frequency of anticoincidence signals did not exceed 0.1 sec^{-1}.

When the spectrum obtained in the first series of measurements, which lasted 2100 h, was studied, it was found that in the region of the neutrinoless decay, where the background was $(4.3 \pm 0.2) \times 10^{-3}$ h^{-1} · keV^{-1}, peaks were absent. To obtain a bound for the half-life, it was assumed that the background spectrum was continuous and the putative peak in the relevant region of width 15 keV was distributed in accordance with Poisson's law. Allowance was made for "edge" effects in the determination of the "effective" volume of the detector (63 cm^3). The bound $T_{1/2} \geq 2.5 \times 10^{21}$ years was obtained at the confidence level 68%.

In the second series of measurements (2300 h), the resolution was improved by a new stabilization system. The background counting rate in the region of the neutrinoless 2β decay was $(2\pm0.2)\times10^{-3}$ h$^{-1}\cdot$keV^{-1}. Again, there were no peaks in this region. The bound on $T_{1/2}$ calculated for width 10 keV of the decay region was 4.5×10^{21} years. Combination of the results of the two series yielded the bound $T_{1/2}\geq5\times10^{21}$ years at 68% confidence level.

In the opinion of the authors, the possible 2β decay with transition to the excited levels of ^{76}Se must be strongly hindered compared with decay to the ground-state level because of the lower transition energy and the change in the parity and the spin. Peaks corresponding to neutrinoless transition to the levels 0.559 and 1.216 MeV were absent. The bounds (2×10^{21} and 1.5×10^{21} years, respectively) are lower than for the ground state because of the higher level of the background in this energy range (based on the results of a 2300-h series). Subsequently,[102] the limit for the transition to the level at 0.559 MeV in ^{76}Se was increased to 3×10^{21} years by combination of the data of the first and second series.

An interesting method was developed by a group from the University of California at Irvine.[103,104] Their experiment (Fig. 7) used a Wilson chamber (diameter 46 cm and height 20 cm) controlled by a system consisting of a multiwire proportional counter and a plastic scintillator 1-cm thick. The chamber was triggered every time that a two-electron event was detected in the proportional counter and the total energy deposited in the scintillator exceeded 1 MeV. The sensitivity time of the chamber was sufficient to detect delayed α particles from decay of ^{212}Bi or ^{214}Bi, which made it possible to eliminate the background from these most probable and very dangerous radioactive impurities in the sample. The chamber was in a magnetic field of

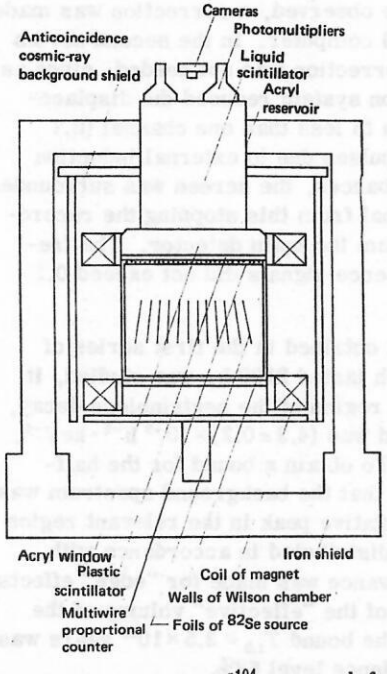

FIG. 7. Apparatus used[104] to search for 2β decay of ^{82}Se.

1000 Oe, which was produced by two Helmholtz coils. The tracks were photographed stereoscopically through a transparent scintillator, a plastic window, and liquid scintillator used as an "active" shield.

A massive steel screen 36-cm thick surrounding the equipment reduced the background from cosmic rays and the radioactivity of the surroundings.

Preliminary measurements were made with 14 g of ^{82}Se (enriched to 97%) placed in the form of thin foils of thickness 6.5 mg/cm^2 within the Wilson chamber. The equipment was situated on the surface of the Earth. During 37 days of "live" time, 20 two-electron events corresponding to 2β decay of ^{82}Se with the participation of neutrinos were recorded. The half-life calculated on the basis of the measured counting rate was 2×10^{19} years. It is intended to improve the equipment with a view to raising the energy resolution.

In Table IX, we give all relevant results of the experiments as at May 1979.

4. POSSIBILITIES AND PROSPECTS FOR NEW EXPERIMENTS

On the basis of the level that has been achieved, we now attempt to estimate the possibilities and prospects for further investigations of 2β decay in direct experiments. As we have noted above, the most significant recent results have been obtained by means of two different methods.

TABLE IX. Main experimental results.

Transition; isotope abundance of parent nucleus; transition energy	Apparatus, method	Results	Reference, year
Direct experiments			
^{48}Ca → ^{48}Ti: 0.185%;	Streamer chamber and scintillator in 370-Oe magnetic field	$T^{0\nu}_{1/2}\geq2\cdot10^{21}$ years (80% confidence level) $T^{2\nu}_{1/2}\geq3.6\cdot10^{19}$ years	[69], 1970
4271.7 keV	Salt mine at depth 600 m 10.6 g of ^{48}Ca; 1103 h 26 g of ^{82}Se; 1300 h	$T^{0\nu}_{1/2}\geq3.1\cdot10^{21}$ years (68% confidence level)	[71], 1975
^{82}Se → ^{82}Kr: 9.19%; 3005 keV	Wilson chamber in 1000-Oe field 14 g of ^{82}Se (6.5 mg/cm^2); 890 h	$T^{2\nu}_{1/2}\approx2\cdot10^{19}$ years	[104], 1977
^{76}Ge → ^{76}Se; 7.67%; 2045.7 keV	Ge (Li) detector: 68 cm^3; resolution 6 keV at $E=2615$ keV; 4400 h; tunnel at depth 4200 m w.e.	$T^{0\nu}_{1/2}\geq5\cdot10^{21}$ years (68% confidence level) $T^{0\nu}_{1/2}\geq3\cdot10^{21}$ years (to excited level) 0.559 keV ^{76}Se	[70] 1973
Indirect experiments			
^{82}Se → ^{82}Kr: 9.19%; 3005 keV	Mass spectrometer; $T_{sample}=(3\pm0.5)\times10^8$ years	$T_{1/2}=(1.37\pm0.28)\times10^{20}$ years	[13], 1969
	Mass spectrometer; irradiation of sample with reactor neutrons	$T_{1/2}=(2.76\pm0.88)\cdot10^{20}$ years $T_{1/2}(130)/T_{1/2}(82)=10\pm2$ years	[18], 1973
^{128}Te → ^{128}Xe; 31.79%; 868.9 keV	Mass spectrometer; $T_{sample}=1.3\times10^9$ years	$T_{1/2}\geq10^{23.3}$ years	[10], 1968
	Mass spectrometer; irradiation of sample with reactor neutron $T_{sample}=2.46\times10^9$ years	$T_{1/2}=(1.57\pm0.17)\times10^{24}$ years $T_{1/2}(128)/T_{1/2}(130)=(1.59\pm0.17)\cdot10^3$ years	[14], 1975 [15], 1978
^{130}Te → ^{130}Xe; 34.49%; 2533.1 keV	Mass spectrometer; $T_{sample}=1.3\times10^9$ years	$T_{1/2}=10^{21.34\pm0.12}$ years	[10], 1968
	Mass spectrometer; irradiation of sample with reactor neutron	$T_{1/2}=(2.76\pm0.3)\times10^{21}$ years	[16,17], 1972
	Mass spectrometer; irradiation of sample with reactor neutrons; $T_{sample}=2.4\times10^9$ years	$T_{1/2}=(1.05\pm0.15)\times10^{21}$ years	[14], 1975

The first is the method of the Milan group,[70] in which the required effect is distinguished on the basis of only one property of the neutrinoless process—the constancy of the total energy of the electrons. The second is the method of the Columbia group,[69,71] in which events are selected on the basis of all the properties of 2β decay. This is achieved by the use of a streamer chamber placed in a magnetic field and controlled by coincidences from scintillation detectors on either side of it.

In accordance with these methods, the direct experiments can be nominally divided into two classes—identification experiments and complete experiments.

Identification experiments. In these experiments, it is customary to use a detector containing within it a certain number of putative 2β-active nuclei. If these nuclei decay through the neutrinoless channel, the background spectrum in the region of the energy of the 2β decay will reveal a peak with width determined by the energy resolution of the detector. Unfortunately, the usual result is the absence of a peak. In such a case, a limit can be established for the probability of the neutrinoless process from the level of the background in the region of the transition energy. To do this, one takes the mean number N_b of background pulses in the investigated interval,[2)] and calculates the maximal number N_e of events in a putative 2β peak which has the profile of the instrumental line of the detector and escapes observation at the given level of the continuously distributed background. From N_e one must then calculate a bound for the half-life corresponding to the neutrinoless 2β process.

To solve this problem, we consider the statistical fluctuations in the background activity A_b calculated from N_b. Such an analysis is made rigorously in Ref. 105 using the binomial distribution to determine the probability of decay of the nuclei. For low-background measurements, this is the most correct procedure. In accordance with Eqs. (29) and (30) of Ref. 105, the probable decay rate A_b and the standard deviation $\sigma(A_b)$ for N_b decays observed during time t is

$$A_b = (1/\Omega t)\,[\exp(-\lambda_b t)]/t + N_b/\Omega t; \tag{16}$$

$$\sigma(A_b) = \sqrt{[(N_b+1)/t^2]\,[\exp(-\lambda_b t)/\Omega + 1/\Omega^2 - 1/\Omega]}, \tag{17}$$

where Ω is the efficiency of the detector and λ_b is the decay constant of the background. We simplify the expressions (16) and (17) by assuming that $\lambda_b t \to 0$, and $\Omega \approx 1$, and we obtain

$$A_b = (N_b+1)/t; \quad \sigma(A_b) = \sqrt{N_b+1}/t. \tag{18}$$

The maximal rate of neutrinoless 2β decay lies in the interval

$$0 \leqslant A_e \leqslant K_a \sigma(A_b),$$

where K_a is a coefficient associated with the confidence level for finding A_e in this interval. Then one can assert that the limiting value for the half-life is

$$T_{1/2} \geqslant \ln 2 N_a \alpha \delta \rho v t / M K_a \sqrt{N_b+1}, \tag{19}$$

where N_a is Avogadro's number, M is the atomic weight, ρ is the density of the detector, v is the sensitive volume of the detector, δ is the relative volume concentration of 2β-active nuclei, and α is a coefficient which measures the effective use of the detector volume and, for example, takes into account the effect of a boundary layer. In addition, N_b can be represented in the form

$$N_b = f \Delta E v t, \tag{20}$$

where f is the index of the background, i.e., the background in unit energy interval normalized to the time of measurement and the volume of the detector, and ΔE is the width of the chosen energy region. Using (20), we write Eq. (19) in the form

$$T_{1/2} \geqslant 1.51\,(\alpha\delta\rho/MK_a)\sqrt{tv/f\Delta E} \tag{21}$$

with the following units of measurement: 10^{21} years for $T_{1/2}$, 10^3 h for t, $\text{keV}^{-1}\cdot\text{h}^{-1}\cdot\text{cm}^{-3}$ for f, keV for ΔE, g/cm^3 for ρ, and cm^3 for v. Finally, transforming (21) to a form which indicates what parameters the detector must have to establish a given limit on the half-life at the 68% confidence level[3)] ($K_a = 1$):

$$R/v \leqslant 0.895\,(t/f)\,(\alpha\delta\rho/MT_{1/2})^2. \tag{22}$$

In deriving (22), we have assumed that $\Delta E = 2.55R$, where R is the resolution of the detector. This corresponds to finding in the interval ΔE not less than 99% of the area of the peak of the expected neutrinoless 2β decay under the assumption that the profile of the instrumental line of the detector can be approximated by a normal distribution.

We now use (22) to estimate the possibilities of some detectors.

In a semiconductor detector made of cadmium telluride one can investigate the four transitions $^{130}\text{Te} \to {}^{130}\text{Xe}$ (2543 keV), $^{128}\text{Te} \to {}^{128}\text{Xe}$ (872 keV), $^{114}\text{Cd} \to {}^{114}\text{Sn}$ (547 keV), and $^{116}\text{Cd} \to {}^{116}\text{Sn}$ (2811 keV). If natural tellurium and cadmium are used, then to establish the limit $T_{1/2}(^{130}\text{Te}) \approx 10^{21}$ years, a detector with $R/v \leqslant 8.3$ keV/cm^3 is needed. Here, the index of the background is taken equal to the value obtained in Ref. 70. Bearing in mind the very modest contemporary achievements in the development of TeCd detectors,[106] an acceptable variant could be a block of 8–10 detectors, each having a volume of 1 cm^3 and a resolution of about 80 keV at 2.5 MeV. For the three remaining transitions, this same detector could establish limits on the half-life at the level 4×10^{20} years.

If the detector is made of tellurium enriched with ^{130}Te to 95%, then for $R/v = 8$ keV/cm^3 we obtain the bound $T_{1/2}(^{130}\text{Te}) = 2.7\times10^{21}$ years, which exceeds the maximal theoretical estimate for the transition $^{130}\text{Te} \to {}^{130}\text{Xe}$ (see Table IV). The main problem in the preparation of a detector made of enriched Te consists

[2)] The width of the interval in which the background is taken into account depends on the energy resolution and the profile of the instrumental line of the detector for monoenergetic radiation.

[3)] We have here used the connection between a and K_a for the normal law, since it is a good approximation to the binomial distribution if there is an appreciable number of samplings and a low probability of an individual decay.

of purifying the ^{130}Te from possible radioactive contamination.

At the present time, many laboratories are conducting studies on the development of detectors in the proportional or ionization regime based on condensed noble gases.[107-109] In Ref. 108, there is a description of a proportional counter filled with liquid xenon with 15% resolution at 1 MeV for volume 1 cm^3. Let us estimate the parameters of such a detector on the basis of natural xenon in order to study the transition ^{136}Xe → ^{136}Ba (2718 keV) at given limit $T_{1/2} = 10^{21}$ years. Assuming that the index of the background does not exceed the value achieved in Ref. 70, we find that we need a detector with $R/v \leq 0.5$ keV/cm^3. At the moment, the difference between the required and actual parameters of the detectors is too great to plan an experiment. One must, however, take into account the possibility of progress, since theoretically a liquid-xenon ionization chamber should achieve a resolution only slightly inferior to that of a Ge(Li) detector.

Let us also consider the possibility of raising the $T_{1/2}$ limit for ^{76}Ge compared with the result 5×10^{21} years obtained by the Milan group; we want to aim at the maximal theoretical estimate, which is 1.3×10^{22} years (see Table IV). If we use a detector with resolution 3 keV and volume about 100 cm^3, and also reduce the index of the background by 1.5–2 times, the limit then becomes 1.4×10^{22} years. Obviously, it is worth repeating the experiment with the germanium detector at such a level.

Analysis of the expression (21) shows that the possible ways of raising the limiting $T_{1/2}$ are to increase the useful volume, decrease the index of the background, and improve the resolution of the detector.

Because the energy resolution of the majority of modern detectors is close to the theoretical limit, in designing experiments one must attempt to maximize the detector volume and adopt all existing methods to reduce the background.

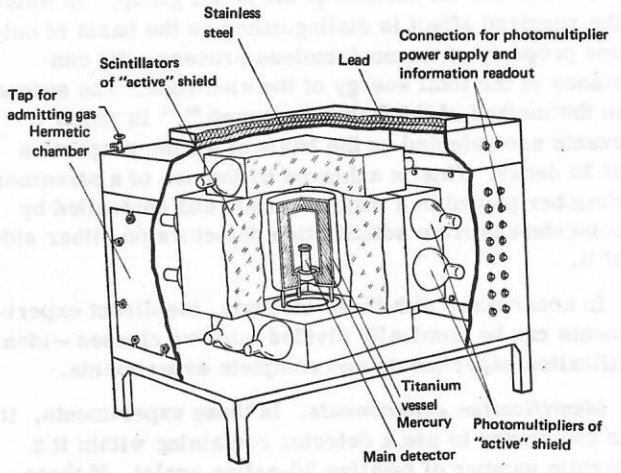

FIG. 8. Arrangement of low-background experiment for studying 2β decay.[110]

In Ref. 110 there is a description of a low-background experiment designed with allowance for these requirements and intended for the investigation of 2β decay by means of semiconductor and scintillation detectors. For the effective elimination of the background due to cosmic rays and natural radioactivity of the surroundings, a complex system of "passive" and "active" shields is used.

The general arrangement is shown in Fig. 8. The main detector (semiconductor or scintillation) is shielded by an 8-cm layer of high-purity (ROD grade) mercury, which is situated in a reservoir of titanium (VT-1-00). The detector and the mercury shield are placed in a closed space (300×300×500 mm) formed by six plastic scintillators, which each measure 500×500×200 mm. The scintillators are scanned by

TABLE X. Background levels of the apparatus (keV$^{-1}\cdot$h$^{-1}\cdot$cm^{-3}).

Energy interval, keV	350—500	500—850	850—1200	1200—1550	1550—1900	1900—2250	2250—2600	2600—2950	2950—3300	3300—4000
In building, A	$6\cdot10^{-1}$	$2\cdot10^{-1}$	$1\cdot10^{-1}$	$7\cdot10^{-2}$	$3\cdot10^{-2}$	$2\cdot10^{-2}$	$1.5\cdot10^{-2}$	$1\cdot10^{-2}$	$7\cdot10^{-3}$	$4\cdot10^{-3}$
Mounted with mercury shield, B	$7\cdot10^{-2}$	$7\cdot10^{-3}$	$3.3\cdot10^{-3}$	$1.6\cdot10^{-3}$	$9\cdot10^{-4}$	$5.5\cdot10^{-4}$	$4\cdot10^{-4}$	$2.8\cdot10^{-4}$	$2.5\cdot10^{-4}$	$2\cdot10^{-4}$
Mounted with mercury shield and anticoincidence shield, Γ	$2\cdot10^{-2}$	$2\cdot10^{-3}$	$8.8\cdot10^{-4}$	$4\cdot10^{-4}$	$1.6\cdot10^{-4}$	$6.9\cdot10^{-5}$	$3.6\cdot10^{-5}$	$1.6\cdot10^{-5}$	$3.6\cdot10^{-6}$	$2\cdot10^{-6}$
Background suppression coefficient, A/Γ	30	100	110	175	187	290	416	625	1900	2000
Background suppression coefficient, B/Γ	3.5	3.5	3.7	4	5.6	8	11	17.5	70	100
According to the data of Ref. 70	$1.5\cdot10^{-3}$	$5.9\cdot10^{-4}$	$3\cdot10^{-4}$	$1.5\cdot10^{-4}$	$7\cdot10^{-5}$	$3\cdot10^{-5}$	$1\cdot10^{-5}$			

16 photoelectric multipliers of the FÉU-49B type with diameter 170 mm of the photocathode. The main detector is connected in anticoincidence with the scintillation shield, which has a minimal thickness of 10 cm where the upper and lower scintillators adjoin the central scintillators and 20 cm in all other directions. Polystyrene scintillators, which have a high light yield and sufficient transparency, are used.

To eliminate the influence of the radioactivity of air, the active shield is placed in a hermetic chamber filled with a purified gas. The chamber is covered at the top by a 3-cm layer of stainless steel and a 5-cm layer of lead.

The cavity within the mercury shield containing the main detector has a useful volume of about 7 dm^3 (diameter 150 mm and height 400 mm).

To test the efficiency of the active and passive shields, preliminary measurements were made of the background in the working cavity by placing there a polystyrene scintillation detector of diameter 145 mm and height 160 mm. The detector was joined to a FÉU-49B photomultiplier by a light tube of polymethyl methacrylate of height 50 mm. The equipment was placed in an ordinary building on the surface of the Earth.

In Table X, we give the background indices ($keV^{-1} \cdot h^{-1} \cdot cm^{-3}$) measured by the detector under various conditions and also the background suppression coefficients, namely, the total coefficient A/Γ and that for the active shield B/Γ.

For comparison, in the last row of Table X we give the values of the background index obtained in Ref. 70 in the study of 2β decay.

We estimate the possibilities of such an arrangement on the basis of the expression (21). The maximal volume of scintillator that can be used is 4–5 dm^3.[4)] If about 2% of a putative 2β-active isotope with transition energy 3 MeV (for example, ^{100}Mo or ^{96}Zr) is introduced into this volume, then for the obtained background index ($f = 5 \times 10^{-6}$ $keV^{-1} \cdot h^{-1} \cdot cm^{-3}$) it is possible to establish a limit for $T_{1/2}$ at the level $(2-5) \times 10^{21}$ years. For example, taking $K_a = 1$, $\delta = 0.02$, $\Delta E = 500$ keV, $\alpha = 0.9$, and $t = 2400$ h, we obtain in accordance with (21) half-lives of 5×10^{21} and 3×10^{21} years for molybdenum and zirconium, respectively.

Complete experiments. Although the apparatus needed for complete study of 2β decay is much more complicated than that needed in identification experiments, it has the advantage of obtaining more complete physical information. The point is that one measures both the total and the individual energy spectra of the electrons and also the angular correlation function.

[4)] By April 1980, one experiment on ^{130}Te had been made by means of this apparatus.[116,117] The main detector consists of 13 polystyrene scintillation plates, which are each 10-mm thick. The mass of the ^{130}Te distributed in a uniform layer (160 mg/cm^2) between the plates is 342.82 g. The experiment, which lasted 3300 h, established a limit on the half-life of ^{130}Te against neutrinoless 2β decay equal to 1.2×10^{21} years at 68% confidence level.

It has frequently been pointed out[2,3,24] that this information is needed to deepen our knowledge about the nature of the weak interaction and to determine more precisely the mechanism of neutrinoless 2β decay.

The complexity and specific features of the problem of detecting 2β decay impose very stringent requirements on the technical characteristics of the apparatus, the most important of which are the sensitivity, i.e., the possibility of detecting a given level of 2β activity, and reliability and stability of operation over several thousand hours.

The sensitivity can be raised by improving the signal-to-background ratio, which requires:

1) maximal reduction in the level of the background;

2) the use of all properties of 2β decay to select events;

3) an increase in the mass of the sample;

4) an increase in the efficiency of detection of the investigated events.

Let us consider these points in order.

To reduce the background, the following measures are usually employed:

a) the selection of constructional materials free of radioactive contamination;

b) a thick passive shield (subterranean chamber) to suppress the cosmic-ray background;

c) an efficient "active" anticoincidence shield;

d) an additional passive shield made of radioactivity "pure" materials;

e) sealing of the measuring apparatus to eliminate an influence of the radioactivity of air.

To select the investigated events, one also uses features of the 2β decay such as the simultaneity of the emission and the common origin of the electrons, the angular distribution, and the distribution of the sum of the kinetic energies of the two electrons. These properties can be used only if the experiment includes equipment for detecting electron trajectories. Further, by placing the track detectors in a magnetic field, whose optimal intensity is in the region of 1000 Oe,[103,111] it is possible to achieve an additional reduction of the background by a discrimination of the tracks according to the sign of the curvature and also the correspondence between the curvature and the electron energy measured by the main detector.

This leads us to the arrangement of the Columbia group.[69,71] Careful analysis[69] shows that in such experiments the overwhelming majority of background events can be distinguished from 2β decay events. There remain only three processes that can simulate 2β decay in such an experiment:

a) double Compton scattering of a γ ray in the source;

b) Compton scattering of a γ ray in the source and Møller scattering of the recoil electron in the same

source;

c) Compton or Møller scattering in the source of either a γ ray or electron from a $\beta\gamma$ cascade of a radioactive impurity in the source itself.

It is easy to show that the intensity of the background events in cases a) and b) is proportional to the square of the thickness of the source; in case c), it is proportional to the thickness of the source. Thus, decreasing the thickness of the source is the most effective method for reducing the residual background in such experiments. In addition, a thin source is also needed to preserve the initial angular correlation of the electrons.

At the same time, the need to reduce the source thickness conflicts with the need to increase the mass of the sample to a value at which statistically reliable information can be accumulated during a reasonable duration of the experiment ($1-5\times10^3$ h).

In the two experiments[69,71] of the Columbia group, 10.6 g of ^{48}Ca and 26 g of ^{82}Se (area of the source 1000 cm^2) were exposed for 1103 and 1300 h, respectively. During this time, not more than seven or eight decays could occur in each sample at a half-life of 2×10^{21} years. With allowance for the total efficiency of the apparatus (20–50%), this number must be reduced by at least a factor 2; but this means that even in experiments with no background at all a statistically inadequate volume of information may be obtained.

A way out is to increase the area of the source. If it is increased by ten times (1 m^2) compared with the case described in Ref. 69, this would make it possible to increase the mass of a sample of thickness 5–6 mg/cm^2 to 50–60 g, which is a reasonable compromise between the statistical and background requirements.

Thus, the ideal modern experiment for studying 2β decay on the basis of these principles must use all methods of background reduction, must have a sample area of not less than 1 m^2, and, in addition, must operate reliably and stably, preferably automatically, for several thousand hours.

The straightforward way of achieving such an aim is to improve an experiment of the type described in Ref. 69 and increase the sizes appropriately. But, of course, this is not the most economic or most readily implemented method, though it does warrant consideration.

In Ref. 111 there is a suggestion for solving the problem somewhat differently. The basic idea is to construct a Wilson chamber that operates with a mixture of helium and xenon vapor and is triggered by the electroluminescence of this mixture. The authors have made a careful thermodynamic analysis of the conditions of operation of such a chamber, and on the basis of this analysis prepared and tested an actual model with a useful volume of about 150 cm^3. The model functioned stably in the temperature range 150–185°K. They investigated the possibility of using such a chamber to study the 2β decay of ^{136}Xe filling the chamber and showed that the sensitivity with a chamber of volume 1 m^3 will be sufficient for the reliable identification of the two-neutrino 2β activity of ^{136}Xe at a half-life of 2×10^{21} years. According to the calculations, an experiment with 100% enrichment of the xenon by the isotope ^{136}Xe will detect about seven true events per day.

The practical realization of the project requires the solution of complicated problems in the construction of the Wilson chamber with appropriate servosystems and cryostat, a magnet with iron core or solenoid with magnetic-field volume of several cubic meters, the system for detecting the electroluminescence, etc; at the same time, it is necessary to bear in mind all the requirements with regard to the reduction of the background.

Although the complexity and cost of such a facility will make it comparable with large-scale facilities in high-energy physics, its use is limited, unfortunately, to the investigation of ^{136}Xe alone.

The author of the present review has proposed[112] a much simpler arrangement that meets almost completely the requirements and is suitable for studying all nuclei.

This uses two six-coordinate multiwire proportional chambers, each of which adjoins a plastic scintillator. The source is placed between the chambers. An electromagnet with iron core is used to produce a magnetic field of intensity 1–2 kOe. The scintillators are used to determine the energy (resolution 30–40%) and simultaneity of the emission of the electrons (accuracy 10–20 nsec). The electron trajectories are reconstructed by means of the data from the proportional chambers. In addition, by means of the chambers one can measure the ionization energy losses, which makes possible an additional selection of the events on the basis of the magnitude of the ionization losses.

It will be noted that the proposal is very similar to the apparatus described in Ref. 69, except that multiwire proportional chambers are used instead of streamer chambers. It is found that this replacement permits a more complete and simpler realization of an experiment to look for 2β decay.

The point is that the absence of systems for photographic detection of tracks makes the apparatus extremely compact and allows one to use an electromagnet with an iron core to produce the magnetic field. No serious technical difficulties have to be overcome[113–115] in developing a construction with a source area of 1.5–2 m^2, and the small scale of the apparatus facilitates the successful application of combined measures to reduce the background.

In Ref. 112, the present author has given the results of computer calculations of the energy resolution of the system with the multiwire proportional chambers and with allowance for multiple Coulomb scattering of the electrons. These show that in a wide range of emission angles and energies of the electrons the resolution does not exceed 15–20%, and 10% for energies $\geq$0.7 MeV and angles $\geq$40°.

Further, the replacement of the streamer chambers by proportional chambers improves the operating characteristics, since, first, the proportional chambers work at constant voltages of order 5–6 kV, while the streamer chambers require a pulsed supply with amplitude 80–150 kV; second, electronic readout of the information from the proportional chambers is extremely convenient for automating the processes of measurement and accumulation and evaluation of the experimental data.

An apparatus constructed in accordance with the proposal will have a sensitivity (for source area 1–1.5 m^2 and thickness 5 mg/cm^2) that is at least an order of magnitude higher than for the apparatus described in Ref. 69 (an increase by 4–6 times in the event rate due to the increased mass of the sample and a reduction in the background by 4–5 times due to the decrease in the thickness of the source and the improvement in the energy resolution).

According to the calculations in Ref. 69, the sensitivity of the Columbia apparatus is sufficient to detect two-neutrino 2β activity with lifetime 10^{20} years. Then the experiment with proportional chambers can study 2β processes with expected half-lives at the level of 10^{21} years for two-neutrino decay and 10^{22} years for neutrinoless decay.

CONCLUSIONS

Detailed study of the problem of 2β decay inspires hope of a successful resolution to the problem in the not too distant future, despite the fact that three decades of strenuous work have not yet brought the expected proofs.

The optimism is due both to the successes in the development of the experimental techniques and to a number of recent results that may be regarded as positive in a certain sense.

In the first place, we have the indication in the indirect experiments of the possible existence of 2β decay and the measurement of two half-life ratios ($^{128}Te/^{130}Te$ and $^{130}Te/^{82}Se$).

Further positive achievements are the establishment in the direct experiments of fairly high limits on the lifetimes against neutrinoless 2β decay of ^{48}Ca, ^{76}Ge, and ^{82}Se; these limit the value of the parameter which measures nonconservation of the lepton charge to the range 10^{-3}–10^{-4}.

It would be very desirable to increase the number of nuclei investigated with this sensitivity. Of greatest interest among the possible candidates (^{96}Zr, ^{100}Mo, ^{116}Cd, ^{124}Sn, ^{130}Te, ^{136}Xe, ^{150}Nd) is undoubtedly ^{130}Te. The existing facilities and those under development are sufficient to obtain lifetime limits against neutrinoless 2β decay at the level 10^{21}–10^{22} years in identification experiments. Among the promising detectors, we must mention counters based on condensed noble gases, cadmium telluride semiconductor detectors, and large-volume scintillators.

The existing theoretical models of 2β decay predict the probabilities of this process with errors which do not make possible a final choice between the models on the basis of comparison with experimental data. More work by the theoreticians aimed at increasing the accuracy of the calculations will be very helpful, but it is a deep conviction of the present author that the desired success will be achieved only when the experiments have given a reliable positive result for at least one nucleus.

Since such a result can be obtained only in a direct experiment with direct detection of the decay events, it becomes particularly important to develop apparatus with sensitivity sufficient to detect two-neutrino 2β activity at a half-life of 10^{21} years. Two proposals have been made: one is based on a Wilson chamber and the other on proportional chambers. The realization of these proposals requires considerable effort and is a complicated but not insuperable problem; and the achievement of real progress in the study of 2β decay depends on the successful solution of this problem.

Concluding the review, we must emphasize once more the importance of the study of 2β decay, which was predicted theoretically 45 years ago but has still not yet been detected experimentally. The reasons that stimulate further searches for this elusive phenomenon are as follows:

1) investigations of 2β decay deepen and make more precise fundamental notions about the nature of the neutrino and the properties of the weak interaction;

2) the possible existence of a superweak interaction is related to the problem of 2β decay;

3) the study of neutrinoless 2β decay is one of the most sensitive ways of testing the conservation law of lepton charge.

I should like to express my sincere gratitude to B. M. Pontecorvo for lively interest and helpful discussion of the work, and also thank L. A. Mikaelyan and A. A. Borovoĭ for constructive criticism and valuable comments made during long and fruitful discussions of this problem.

[1]R. E. Marshak, Riazuddin, and C. P. Ryan, Theory of Weak Interactions in Particle Physics, Wiley–Interscience, New York (1969).
[2]S. P. Rosen and H. Primakoff, in: Alpha-, Beta-, and Gamma-Ray Spectroscopy (ed. K. Siegbahn), Amsterdam (1965) [the Russian reference is to p. 177 of the Russian translation published by Atomizdat, Moscow (1969)].
[3]E. Fiorini, Riv. Nuovo Cimento 2, 1 (1972).
[4]H. Primakoff and S. P. Rosen, Phys. Rev. 184, 1925 (1969).
[5]S. P. Rosen, in: Proc. of the 1975 Meeting of the Division of Particles and Fields of the American Physical Society, Baltay, New York (1975), p. 6.
[6]M. Goeppert-Mayer, Phys. Rev. 48, 512 (1935).
[7]E. Fermi, Nuovo Cimento 11, 1 (1934).
[8]E. K. Gerling, Yu. A. Shukolyukov, and G. Sh. Ashkinadze, Yad. Fiz. 6, 311 (1967) [Sov. J. Nucl. Phys. 6, 226 (1967)].
[9]T. Kirsten, W. Gentner, and O. A. Schaeffer, Z. Phys. 202, 273 (1967).
[10]T. Kirsten *et al.*, Phys. Rev. Lett. 20, 1300 (1968).

[11]T. Kirsten and H. W. Müller, Earth Planet. Sci. Lett. **6**, 271 (1969).
[12]T. Kirsten and H. W. Müller, Earth Planet, Sci. Lett. **7**, 300 (1969).
[13]T.Kirsten, H. W. Müller, and E. Norton, in: Proc. Intern. Conf. on Mass Spectroscopy, Kyoto 1969, Tokyo (1970), p. 501.
[14]E. W. Hennecke and O. K. Manuel, Phys. Rev. C **11**, 1378 (1975).
[15]E. W. Hennecke, Phys. Rev. C **17**, 1168 (1978).
[16]B. Srinivasan, E. C. Alexander, Jr., and O. K. Manuel, Econ. Geol. **67**, 592 (1972).
[17]B. Srinivasan, E. C. Alexander, Jr., and O. K. Manuel, J. Inorg. Nucl. Chem. **34**, 2381 (1972).
[18]B. Srinivasan, E. C. Alexander, Jr., and O. K. Manuel, Econ. Geol. **68**, 252 (1973).
[19]Ya. B. Zel'dovich, S. Yu. Luk'yanov, and Ya. A. Smorodinskiĭ, Usp. Fiz. Nauk **54**, 361 (1954).
[20]M. Deutsch and O. Kofoed-Hansen, in: Experimental Nuclear Physics, Vol. 3 (ed. E. Segrê), Wiley, New York (1959), p. 427 [the Russian reference is to p. 535 of the Russian translation published by Izd. Inostr. Lit. (1961)].
[21]K. L. Luke and T. S. Wu, Methods of Determining the Basic Characteristics of Nuclei and Elementary Particles: Measurement of Masses, Spins, Parities, Polarization, and Lifetimes (Russian translation published by Mir, Moscow).
[22]V. R. Lazarenko, Usp. Fiz. Nauk **90**, 601 (1966) [Sov. Phys. Usp. **9**, 860 (1967)].
[23]A. A. Borovoĭ, Yu. A. Plis, and V. A. Khodel', Fiz. Elem. Chastits At. Yadra **2**, No. 3, 691 (1972) [Sov. J. Part. Nucl. **2**, Part 3, 110 (1972)].
[24]D. Bryman and C. Picciotto, Rev. Mod. Phys. **50**, 11 (1978).
[25]M. L. Perl *et al.*, Phys. Lett. **B63**, 466 (1976).
[26]E. F. Tret'yakov *et al.*, Preprint No. 15 [in Russian], Institute of Theoretical and Experimental Physics, Moscow (1976).
[27]K. E. Bergkvist, in: Proc. Topical Conf. on Weak Interactions, CERN, Geneva (1969), p. 91.
[28]A. Clark *et al.*, Phys. Rev. D **9**, 533 (1974).
[29]B. M. Pontecorvo, Zh. Eksp. Teor. Fiz. **53**, 1717 (1967) [Sov. Phys. JETP **26**, 984 (1968)].
[30]T. D. Lee and C. S. Wu, Ann. Rev. Nucl. Sci. **15**, 381 (1965).
[31]G. Feinberg and S. Weinberg, Nuovo Cimento **14**, 571 (1959).
[32]G. Feinberg and S. Weinberg, Phys. Lett. **6**, 381 (1961).
[33]C. I. Chang, Phys. Rev. Lett. **24**, 79 (1970).
[34]K. Börer, Phys. Lett. **B29**, 614 (1969).
[35]G. R. Kalbfleisch, Preprint B. N. L. 14966 (quoted in Ref. 3).
[36]C. I. Chang and D. P. Rosen, Phys. Rev. Lett. **38**, 471 (1976).
[37]F. S. Konopinski and H. M. Mahmoud, Phys. Rev. **92**, 1045 (1953).
[38]Ya. B. Zel'dovich, Dokl. Akad. Nauk SSSR **91**, 1317 (1953).
[39]L. Kisslinger, Phys. Rev. Lett. **26**, 998 (1971).
[40]B. M. Pontecorvo, Zh. Eksp. Teor. Fiz. **53**, 1717 (1967) [Sov. Phys. JETP **26**, 984 (1968)].
[41]H. Pilkuhn, Lett. Nuovo Cimento **1**, 1055 (1971).
[42]R. J. Blin-Stoyle, Fundamental Interactions and the Nucleus, North-Holland, Amsterdam (1973) [Russian translation published by Mir, Moscow (1976)].
[43]H. Appel, Z. Phys. **155**, 580 (1959).
[44]N. Cabibbo, Phys. Rev. Lett. **10**, 531 (1963).
[45]S. M. Bilen'kiĭ and B. M. Pontecorvo, Usp. Fiz. Nauk **123**, 181 (1977) [Sov. Phys. Usp. **20**, 776 (1977)].
[46]K. Borer *et al.*, in: Proc. 14th Intern. Conf. on High Energy Physics, Vienna (1968).
[47]S. Parker, H. L. Anderson, and C. Rey, Phys. Rev. B **133**, 768 (1964); S. M. Korenchenko *et al.*, Yad. Fiz. **13**, 341 (1971) [Sov. J. Nucl. Phys. **13**, 190 (1971)].
[48]S. M. Korenchenko *et al.*, in: Tr. XVIII mezhdunar. konf. po fizike vysokikh énergiĭ, Tbilisi, 1976 (Proc. 18th Intern. Conf. on High Energy Physics, Tbilisi, 1976), Vol. 2, Dubna (1977).
[49]D. A. Bryman *et al.*, Phys. Rev. Lett. **28**, 1469 (1972).
[50]E. Belotti, Lett. Nuovo Cimento **17**, 553 (1976).
[51]E. Majorana, Nuovo Cimento **14**, 171 (1937).
[52]R. Davis, in: Proc. Intern. Conf. on Radioisotopes in Scientific Research, Pergamon Press, Paris–London (1958).
[53]R. Davis, Jr. and D. S. Harmer, Bull. Am. Phys. Soc. **4**, 217 (1959).
[54]A. H. Wapstra and K. Bos, At. Data Nucl. Data Tables **19**, 177 (1977).
[55]W. H. Furry, Phys. Rev. **58**, 1184 (1939).
[56]A. K. Kerman and L. S. Kisslinger, Phys. Rev. **180**, 1483 (1969).
[57]L. S. Kisslinger, Phys. Rev. B **29**, 211 (1969).
[58]H. Arenhövel, M. Danos, and H. T. Williams, Phys. Lett. **B31**, 109 (1970).
[59]B. T. Feld, Models of Elementary Particles, Blaisdell, Waltham, Mass. (1969).
[60]B. M. Pontecorvo, Phys. Lett. **B26**, 630 (1968).
[61]J. Wolfenstein, Phys. Rev. Lett. **13**, 562 (1964).
[62]J. C. Palathingol, Phys. Rev. Lett. **24**, 524 (1970).
[63]L. A. Sliv, Zh. Eksp. Teor. Fiz. **20**, 1035 (1950).
[64]E. J. Konopinski, Report LAMS-1949, Los Alamos.
[65]H. Primakoff, Phys. Rev. **85**, 888 (1952).
[66]E. J. Konopinski, Theory of Beta Radioactivity, Oxford University Press, London (1966).
[67]D. Smith, C. Picciotto, and D. Bryman, Nucl. Phys. **B64**, 525 (1973).
[68]D. Smith, C. Picciotto, and D. Bryman, Phys. Lett. **B46**, 157 (1973).
[69]R. K. Bardin *et al.*, Nucl. Phys. **A158**, 337 (1970).
[70]E. Fiorini *et al.*, Nuovo Cimento **A13**, 747 (1973).
[71]B. T. Clevelend *et al.*, Phys. Rev. Lett. **35**, 757 (1975).
[72]A. H. Huffman, Phys. Rev. C **2**, 743 (1970).
[73]V. A. Khodel', Yad. Fiz. **12**, 916 (1970) [Sov. J. Nucl. Phys. **12**, 499 (1971)].
[74]V. A. Khodel', Yad. Fiz. **20**, 317 (1974) [Sov. J. Nucl. Phys. **20**, 169 (1974)].
[75]J. D. Vergados, Phys. Rev. C **13**, 865 (1976).
[76]S. A. Fayans and V. A. Khodel, J. Phys. G **3**, 359 (1977).
[77]R. K. Bardin *et al.*, Phys. Lett. **B25**, 112 (1967).
[78]A. Molina and P. Pascual, Nuovo Cimento **A41**, 756 (1977).
[79]H. Primakoff, Phys. Rev. **85**, 888 (1952).
[80]E. Greuling and R. C. Whitten, Ann. Phys. (N.Y.) **4**, 510 (1960).
[81]S. P. Rosen, Proc. Phys. Soc. **A477**, 350 (1958).
[82]B. Leviene, A. Ghiorso, and G. T. Seaborg, Phys. Rev. **77**, 296 (1950); M. G. Inghram and J. H. Reynolds, Phys. Rev. **76**, 1265 (1949).
[83]R. I. Hayden and M. G. Inghram, Nat. Bur. Stand. Circ. **522**, 189 (1953).
[84]N. Takaoka and K. Ogata, Z. Naturforsch., Teil A **21**, 84 (1966).
[85]Yu. V. Petrov, Usp. Fiz. Nauk **123**, 473 (1977) [Sov. Phys. Usp. **20**, 937 (1977)].
[86]J. S. Lawson, Phys. Rev. **81**, 299 (1951).
[87]E. L. Fireman and D. Schwatzer, Phys. Rev. **86**, 451 (1952).
[88]J. A. McCarthy, Phys. Rev. **90**, 853 (1953); **97**, 1234 (1955).
[89]R. G. Winter, Phys. Rev. **99**, 88 (1955).
[90]M. J. Kalkstein and W. F. Libby, Phys. Rev. **85**, 368 (1952).
[91]R. M. Pearce and E. K. Darby, Phys. Rev. **86**, 1049 (1952).
[92]J. F. Detoef and R. J. Moch, Phys. Radium **16**, 897 (1955).
[93]M. Awschalom, Phys. Rev. **101**, 1041 (1956).
[94]E. I. Dobrokhotov, V. R. Lazarenko, and S. K. Luk'yanov, Dokl. Akad. Nauk SSSR **110**, 966 (1956) [Sov. Phys. Dokl. **1**, 600 (1957)].
[95]M. Goldhaber, Bull. Am. Phys. Soc. **8**, 46 (1963).
[96]C. L. Covan *et al.*, Nuovo Cimento **3**, 649 (1956).
[97]J. H. Fremlin and M. C. Walter, Proc. Phys. Soc. **A65**, 911 (1952).
[98]G. R. Smith, Phys. Rev. C **4**, 1344 (1971).
[99]E. Mateosian and M. Goldhaber, Phys. Rev. **146**, 810 (1966).

[100]E. Fiorini *et al.*, Phys. Lett. **B25**, 602 (1967).
[101]E. Fiorini *et al.*, Lett. Nuovo Cimento **3**, 149 (1970).
[102]E. Fiorini, in: Proc. Intern. Conf. on Neutrino Physics and Neutrino Astrophysics, Baksan Valley, 1977, Vol. 2, Moscow (1978), p. 315.
[103]M. Moe, D. Lowenthal, and F. Reines, in: Neutrino-72, Proc. Europhysics Conf., Balatonfured, 1972, Vol. 1, Budapest (1972), p. 121.
[104]M. Moe and D. D. Lowenthal, in: Proc. Intern. Neutrino Conf., Aachen, 1976, Braunschweig (1977), p. 672.
[105]T. Dimchev, Preprint 6-6011 [in Russian], JINR, Dubna (1971).
[106]P. Siffer, Nucl. Instrum. Methods **150**, 1 (1978).
[107]B. A. Dolgoshein, in: Mezhdunar. Soveshch. po metodam provolochnykh kamer (Intern. Symposium on Wire Chamber Methods), D13-9164, JINR, Dubna (1975).
[108]M. Miyajima *et al.*, Nucl. Instrum. Methods **134**, 403 (1976).
[109]V. G. Grebinnyk *et al.*, Preprint R13-11165 [in Russian], JINR, Dubna (1977).
[110]Yu. G. Zdesenko *et al.*, Prib. Tekh. Eksp. No. 5, 47 (1979).
[111]G. M. De'Munari and G. H. Mambriani, Nuovo Cimento **A33**, 299 (1976).
[112]Yu. G. Zdesenko, Prib. Tekh. Eksp. No. 5, 44 (1979).
[113]V. M. Golovatyuk, Yu. V. Zanevskiĭ, and V. D. Peshekhonov, Preprint RV-9914 [in Russian], JINR, Dubna (1977).
[114]G. D. Alekseev *et al.*, Preprint R13-10607 [in Russian], JINR, Dubna (1977).
[115]G. Charpak *et al.*, Nucl. Instrum. Methods **148**, 471 (1978).
[116]Yu. G. Zdesenko *et al.*, Report at the 30th All-Union Symposium on Nuclear Spectroscopy, Leningrad (1980).
[117]Yu. G. Zdesenko, Pis'ma Zh. Eksp. Teor. Fiz. **32**, 62 (1980) [JETP Lett. **32**, 58 (1980)].

Translated by Julian B. Barbour