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THE COMPLETE EXPERIMENT IN β DECAY

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THE existing theory of weak interactions describes the processes of β decay of neutrons, μ-e decay, μ-meson capture by protons, and others, using the principle of relativistic invariance and a number of additional hypotheses that generalize the experimental data.

The most common possible relativistically-invariant form of the weak-interaction Hamiltonian, in which account is taken of violation of spatial parity, is [1]

$$H_{\rm wk}=(G/\sqrt{2})\sum_{i=1}^{5}(\overline{\Psi}_4 O_i \Psi_3)(\overline{\Psi}_2 O_i (C_i+C_i'\gamma_5)\Psi_1)+c.c., \qquad (1)$$

where G is the absolute constant of the weak interaction of the process $O_i = 1$; γ_μ; $\sigma_{\mu\nu}$; $i\gamma_\mu\gamma_5$; γ_5 for i = 1–5, respectively.

The indices 1–4 of the wave functions have the following meaning:

$1=\nu_e$	$2=e$	$3=n$	$4=p$	β	decay
$1=\nu_e$	$2=e$	$3=\mu^-$	$4=\nu_\mu$	$\mu-e$	decay
$1=\mu^-$	$2=\nu_\mu$	$3=p$	$4=n$	μ	capture

The Hamiltonian (1) contains five variants of the interaction: scalar (S), vector (V), tensor (T), pseudovector (A), and pseudoscalar (PS).

An experimental investigation of the β decay of a neutron and of β transitions of nuclei shows that these variants enter in the β-decay Hamiltonian with different weights, so that what is actually realized is only a combination of the V and A variants. To interpret such a situation, a number of hypotheses are introduced in the theory of the weak interaction; these hypotheses establish the magnitude of the constant G and the relations observed in experiment between C_i and C_i'. In turn, an experimental investigation of the β decay may be constructed in such a way as to obtain complete information on all ten possible complex quantities C. Such a set of experiments is called the complete experiment.

1. BASIC EXPERIMENTAL DATA

An ideal realization of the complete experiment on β decay is an exhaustive investigation of the neutron decay—its lifetime, spectrum, and the entire aggregate of correlations of the decay products with allowance for their polarization. As we shall show, at the present time such a program has been realized only in part and the accuracy of such experiments is, as a rule, lower than the accuracy of analogous experiments on the β decay of nuclei.

Inasmuch as the existing theory of β-transitions of nuclei regards the β-decay process as the decay of one of its nucleons and does not make any distinctions, from the point of view of the weak interaction, between the β decays of the bound and free nucleons, it is possible in principle to extract information concerning the weak-interaction Hamiltonian from experiments on complex nuclei.

One of the possible real ways of realizing a complete experiment on complex nuclei is to investigate the spectra and the angular and polarization correlations of the β-decay products in allowed β transitions. Preference should be given here to such β transitions and to such types of experiments, where the number of experimental parameters that depend on the structure of the nucleus—the nuclear matrix elements—is minimal, and the accuracy of their independent determination is a few percent.

Such β transitions include the following:

a) 0^+-0^+ β transitions of the pure Fermi type,

b) β transitions with $|\Delta j| = 1$—of the pure Gamow-Teller type,

c) Mirror β transitions or β transitions between the analog states.

β transitions of the pure Fermi and the pure Gamow-Teller types depend on one matrix element, which can be determined from the lifetime of the nucleus or, equivalently, from experimental data on ft. As to the coefficients of all possible angular and polarization correlations, this matrix element does not enter in them at all, so that they are determined only by the constants of the weak-interaction Hamiltonian.

The β transitions between analog states are determined by two matrix elements (excluding 0^+-0^+). One of them—of the Fermi type—is uniquely determined by the isospin of these states, and the Coulomb corrections to it, due to the violation of the isospin conservation law, are less than several percent [2–4] and can be well estimated theoretically. Thus, the experimental data on ft turn out to be sufficient here also for the determination of both matrix elements, so that these transitions can also be used to determine the constants of the β-interaction Hamiltonian. It must be noted, however, that in spite of the fact that in principle we can determine the matrix elements of any such transition, actually to determine the constants of the β interaction one can use only a few of them, since the accuracy of the experimental determination of ft in most such transitions is insufficient (see Table I [4,5]).

The use of other types of allowed β transitions for the realization of the complete experiment, and also of β transitions of the forbidden type, is at present quite problematic, since in such experiments it is necessary to know the structure of the nucleus and to use model representations. The accuracy of theoretical concepts of this kind is at the present time never better than 10%. The only possible exceptions are 0^+-0^- transitions and transitions of the unique type (the former having two matrix elements each, and the latter one matrix element each), where these matrix elements can be determined

Table I. Experimental ratios of the Gamow–Teller and Fermi matrix elements

β transition	E_β	ft_{exp}	$\|M_F\|^2$	$\|G_{GT}M_{GT}/G_F M_F\|^2$	Reference
$n_0^1\,(\beta^-)\,p_1^1$	0.7829 ± 0.0004	1190 ± 33	1	4.20	13
$H_1^3\,(\beta^-)\,He_2^3$	0.0186 ± 0.0001	1132 ± 40	1	4.52 ± 0.020	30
$Be_4^7\,(K)\,Li_3^7$		2340 ± 100	1	1.67 ± 0.10	4
$C_6^{11}\,(\beta^+)\,B_5^{11}$	0.960 ± 0.003	3890 ± 50	1	0.607 ± 0.02	4
$N_7^{13}\,(\beta^+)\,C_6^{13}$	1.200 ± 0.002	4670 ± 50	1	0.357 ± 0.02	4
$O_8^{15}\,(\beta^+)\,N_7^{15}$	1.739 ± 0.002	4400 ± 100	1	0.421 ± 0.04	4
$F_9^{17}\,(\beta^+)\,O_8^{17}$	1.745 ± 0.006	2280 ± 100	1	1.74 ± 0.12	4
$Ne_{10}^{19}\,(\beta^+)\,F_9^{19}$	2.24 ± 0.01	1800 ± 100	1	2.48 ± 0.19	4
$Na_{11}^{21}\,(\beta^+)\,Ne_{10}^{21}$	2.51 ± 0.02	3910 ± 150	1	$0,60\pm0.06$	5
$Mg_{12}^{23}\,(\beta^+)\,Na_{11}^{23}$	3.09 ± 0.01	5490 ± 100	1	0.139 ± 0.021	5
$Al_{13}^{25}\,(\beta^+)\,Mg_{12}^{25}$	3.38 ± 0.03	4300 ± 190	1	0.455 ± 0.06	5
$Si_{14}^{27}\,(\beta^+)\,Al_{13}^{27}$	$3,85\pm0.02$	4410 ± 230	1	0.42 ± 0.04	5
$P_{15}^{29}\,(\beta^+)\,Si_{14}^{29}$	3.96 ± 0.02	4800 ± 200	1	0.30 ± 0.05	4
$S_{16}^{31}\,(\beta^+)\,P_{15}^{31}$	4.39 ± 0.03	5160 ± 100	1	0.212 ± 0.022	5
$Cl_{17}^{33}\,(\beta^+)\,S_{16}^{33}$	4.51 ± 0.05	5300 ± 500	1	$0,18\pm0.10$	4
$Ar_{18}^{35}\,(\beta^+)\,Cl_{17}^{35}$	4.93 ± 0.05	5600 ± 400	1	0.12 ± 0.08	4
$K_{19}^{37}\,(\beta^+)\,Ar_{18}^{37}$	5.15 ± 0.07	4600 ± 500	1	0.36 ± 0.14	4
$Ca_{20}^{39}\,(\beta^+)\,K_{19}^{39}$	5.490 ± 0.025	4330 ± 100	1	0.44 ± 0.03	5
$Sc_{21}^{41}\,(\beta^+)\,Ca_{20}^{41}$	4.94 ± 0.10	2200 ± 250	1	1.84 ± 0.30	4

from experiment. The experimental data on 0^+-0^- transitions are used at present to find the values of C_{PS}. The experimental data on the unique β transitions are so far very scanty.

Besides experimental convenience, it is necessary to note also one more convenience of allowed β transitions for the performance of the complete experiment. This is connected with the fact that allowed β transitions can receive contributions from only four types of β interactions (S, V, T, A), so that it is necessary to determine in the complete experiment eight out of the ten complex constants C, i.e., only 16 real parameters. The pseudoscalar variant of the interaction makes no contribution to allowed transitions. At the same time, it should be noted that there exists a natural lower limit of accuracy for the determination of the constants C from allowed β transitions; this limit is connected with the possible influence of second-forbidden matrix elements. According to most estimates this limit is always smaller than 1%.[6]

The simplest variant of the complete experiment is the one that occurs if we assume all the eight constants are real. As will be shown later, the assumption that the interaction constants are real is a direct consequence of L. D. Landau's hypothesis of CP parity conservation in weak interactions. Recently, in experiments with K mesons, CP-parity violation was observed. This fact raises again the question of investigating the CP conservation in β decay of nucleons, and consequently also the question of organizing the complete experiment without additional assumptions concerning the reality of the constants C_i and C_i'.

The organization of experiments for the realization of the complete experiment, which yields information on eight complex constants C, is a complicated problem. For its solution it is necessary to realize a set of experiments on the spectra and correlations of the β-decay products, such as to obtain 15 independent combinations of the constants C_i and C_i'. Table II lists all the β-decay experiments containing not more than three measured quantities, and the combinations of constants[7] for which information can be obtained from these experiments. As will be shown later, the experiments realized to date do not suffice to make up a complete set. They give in the best case 13 relations for the interaction constants, out of the 15 necessary, so that the realization of the complete experiment calls for at least two experiments of a new type.

Let us examine now the main results realized in β decay, and the information on the constants C_i and C_i' presently at our disposal.

a) Measurement of the constants G_F and G_{GT}/G_F

To measure the absolute value of the constant G, which is chosen to be a constant that specifies the magnitude of the Fermi β transition, G_F, it is customary to use 0^+-0^+ transitions between analog states in such nuclei as O^{14}, Al^{26}, Cl^{34}, etc., where the matrix element of the Fermi transition is well known. Experiment then yields the quantity

$$|G_F^{(\beta)}|^2 = 1/2\{|C_S|^2+|C_S'|^2+|C_V|^2 + |C_V'|^2 \pm m_e\gamma\langle E_e^{-1}\rangle\, 2\,\mathrm{Re}\,[C_S C_V^* + C_S' C_V'^*]\}, \quad (2)$$

where $\gamma = (1-\alpha^2 Z^2)^{1/2}$, which is connected with ft by the relation

$$2\,|G_F^{(\beta)}|^2\,(ft)_{0^+-0^+} = 2\pi^3\hbar^7 \ln 2/m_e^5 c^4 \quad (3)$$

(m_e is the electron mass).

In Table III are gathered experimental data on 0^+-0^+ transitions in nuclei of this type and the results of their theoretical reduction with allowance for the influence of the Coulomb field of the nucleus. As seen from the table, the results of different authors are in good agreement and give the following mean values of ft (in seconds)

$$\overline{ft} = \begin{cases} 3113 \pm 7 & [^8], \\ 3123 \pm 7 & [^9], \\ 3128 \pm 7 & [^{10}], \end{cases}$$

which yield for $G_F^{(\beta)}$ (in erg-cm³), respectively,

$$G_F^{(\beta)} = \begin{cases} (1{,}4057 \pm 0{,}0016)\cdot 10^{-49} & [^8], \\ (1{,}4034 \pm 0{,}0016)\cdot 10^{-49} & [^9], \\ (1{,}4016 \pm 0{,}0022)\cdot 10^{-49} & [^{10}], \end{cases} \quad (4)$$

with a total error in the calculation of the radiative corrections

$$\Delta G_F^{(\beta)} = (\pm\, 0{,}0070)\cdot 10^{-49}\ \text{erg-cm}^3.$$

Table II. Principal correlation experiments in allowed β transitions

Experiment	Measured correlation	Combination of constants
Spectrum	1	$\|C_S\|^2+\|C'_S\|^2+\|C_V\|^2+\|C'_V\|^2$ $\|C_T\|^2+\|C'_T\|^2+\|C_A\|^2+\|C'_A\|^2$
	m/E	$\mathrm{Re}\,(C_S C_V^* + C'_S C'^*_V)$ $\mathrm{Re}\,(C_T C_A^* + C'_T C'^*_A)$
$e\nu$	$(\mathbf{p}_e \mathbf{p}_\nu)$	$-\|C_S\|^2+\|C_V\|^2-\|C'_S\|^2+\|C'_V\|^2$ $-\|C_A\|^2+\|C_T\|^2-\|C'_A\|^2+\|C'_T\|^2$
je	$(\mathbf{J}\mathbf{p}_e)$	$\mathrm{Re}\,(C_S C'^*_T + C'_S C_T^* - C_V C'^*_A - C'_V C_A^*)$ $\mathrm{Re}\,(C_T C'^*_T - C_A C'^*_A)$
$j\nu$	$(\mathbf{J}\mathbf{p}_\nu)$	$\mathrm{Re}\,(C_S C'^*_T + C'_S C_T^* + C_V C'^*_A + C'_V C_A^*)$ $\mathrm{Re}\,(C_T C'^*_T + C_A C'^*_A)$
$je\nu$	$\mathbf{J}\,[\mathbf{p}_e \times \mathbf{p}_\nu]$	$\mathrm{Im}\,(C_S C_T^* - C_V C_A^* + C'_S C'^*_T - C'_V C'^*_A)$
σe	$(\boldsymbol{\sigma}_e \mathbf{p}_e)$	$\mathrm{Re}\,(C_S C'^*_S - C_V C'^*_V)$ $\mathrm{Re}\,(C_T C'^*_T - C_A C'^*_A)$
$\sigma\nu$	$(\boldsymbol{\sigma}_e \mathbf{p}_\nu)$	$\mathrm{Re}\,(C_S C'^*_V + C'_S C_V^*)$ $\mathrm{Re}\,(C_T C'^*_A + C'_T C_A^*)$
$\sigma e\nu$	$\boldsymbol{\sigma}_e\,[\mathbf{p}_e \times \mathbf{p}_\nu]$	$\mathrm{Im}\,(C_S C_V^* + C'_S C'^*_V)$ $\mathrm{Im}\,(C_T C_A^* + C'_T C'^*_A)$
$j\sigma$	$(\boldsymbol{\sigma}_e \mathbf{J})$	$\mathrm{Re}\,(C_S C_A^* + C_V C_T^* + C'_S C'^*_A + C'_V C'^*_T)$ $\mathrm{Re}\,(C_T C_A^* + C'_T C'^*_A)$
σje	$\boldsymbol{\sigma}_e\,[\mathbf{J} \times \mathbf{p}_e]$	$\mathrm{Im}\,(C_S C'^*_A + C'_S C_A^* - C_V C'^*_T - C'_V C_T^*)$ $\mathrm{Im}\,(C_T C'^*_A + C'_T C_A^*)$
$\sigma j\nu$	$\boldsymbol{\sigma}_e\,[\mathbf{J} \times \mathbf{p}_\nu]$	$\mathrm{Im}\,(C_S C'^*_T + C'_S C_T^* + C_V C'^*_A + C'_V C_A^*)$
$j_1 e j_2$	$\mathbf{J}\,[\mathbf{p}_e \times \mathbf{J}_2]$	$\mathrm{Im}\,(C_A C'^*_V + C'_A C_V^* - C_T C'^*_S - C'_T C_S^*)$

Table III. Experimental data on 0^+–0^+ transitions

β Transition	E_0	T, sec	ft	Reference
$O^{14}\,(\beta^+)\,N^{14}$	1812.6±1.4	71.00±0.13	3127±13	8
			3127±10	9
			3130±10	10
$Al^{26}\,(\beta^+)\,Mg^{26}$	3208.0±2.3	6.374±0.016	3084±17	8
			3086±8	9
			3088±12	10
$Cl^{34}\,(\beta^+)\,S^{34}$	4460.0±4.5	1.565±0.007	3137±28	8
			3138±19	9
			3140±20	10
$Sc^{42}\,(\beta^+)\,Ca^{42}$	5409.0±2.3	0.6830±0.0015	3112±12	8
			3122±9	9
$V^{46}\,(\beta^+)\,Ti^{46}$	6032.1±2.5	0.4259±0.0008	3117±12	8
			3131±8	9
			3139±25	10
$Mn^{50}\,(\beta^+)\,Cr^{50}$	6609.0±2.6	0.2857±0.0006	3106±12	8
			3125±9	9
$Co^{54}\,(\beta^+)\,Fe^{54}$	7228.8±4.8	0.1937±0.0010	3108±25	8
			3132±17	9
			3128±18	10

A comparison with the analogous quantity obtained from data on $\mu - e$ decay

$$G_F^{(\mu)} = (1.4350 \pm 0.0011) \cdot 10^{-49} \text{ erg-cm}^3 \text{ [11]} \tag{5}$$

shows that the difference amounts to about 2%, or more accurately

$$\frac{G_F^{(\mu)} - G_F^{(\beta)}}{G_F^{(\mu)}} \cdot 10^2 = \begin{cases} 2{,}04 \pm 0{,}12 \pm 0{,}5 \text{ [8]}, \\ 2{,}20 \pm 0{,}12 \pm 0{,}5 \text{ [9]}, \\ 2{,}30 \pm 0{,}12 \pm 0{,}5 \text{ [10]}. \end{cases} \tag{6}$$

The ratio of the constants determining the Gamow–Teller and the Fermi β transitions, G_{GT}/G_F, is determined most accurately from experiments on the neutral lifetime, performed by P. E. Spivak and co-workers.[12] From their experiment and from data on O^{14} it follows that[13]

$$\begin{gathered} \left|\frac{G_{GT}}{G_F}\right|^2 = \frac{|C_A|^2 + |C_A'|^2 + |C_T|^2 + |C_T'|^2}{|C_V|^2 + |C_V'|^2 + |C_S|^2 + |C_S'|^2} = 1.40 \pm 0.06, \\ |G_{GT}/G_F| = 1.18 \pm 0.025 \end{gathered} \tag{7}$$

with allowance for the Coulomb corrections.

Recently the experiments on the neutron lifetime were repeated by a group of Danish experimenters.[14] Their result

$$\left|\frac{G_{GT}}{G_F}\right| = 1.23 \pm 0.01 \tag{8}$$

is somewhat larger than the result of Spivak's group.

b) Investigation of the form of the spectra of allowed β transitions

Searches for deviations of the form of the spectra of allowed β transitions from the purely statistical form determined by the Kurie plot

$$W(E_e)\, dE_e = (F(Z, E_e)/4\pi^3)\, P_e E_e (E_0 - E_e)^2\, dE_e, \tag{9}$$

were performed many times, particularly for the nuclei P^{32} and In^{114}. The spectra of these nuclei were investigated in searches both for terms of the type bm_e/E_e, the so-called Fierz terms, and terms of the type aE_e/m_e, connected with the corrections that must be introduced in the β decay to take into account the vector-current conservation hypothesis. The employed transitions are of the pure Gamow–Teller type ($1^+\beta^-0^+$ and the Fierz terms in them are of the form

$$b_{GT} \cdot \frac{m_e}{E_e} = \frac{m_e}{E_e}\, \gamma\, \frac{2\,\mathrm{Re}\,(C_T C_A^* + C_T' C_A'^*)}{|C_A|^2 + |C_A'|^2 + |C_T|^2 + |C_T'|^2}. \tag{10}$$

Deviations of this type were observed in a number of earlier investigations, but the later and more accurate measurements did not confirm these results, and showed that the spectra of P^{32} and In^{114} are statistical. The experimental data for P^{32} show that[15-17]

$$b_{GT} \leqslant 0{,}02,$$

whereas the value obtained for In^{114} is[18]

$$b_{GT} = (0{,}5 \pm 2{,}2) \cdot 10^{-2}.$$

Similar estimates for the Fierz term were obtained from the experimental data on the ratio of the β^+ decay to the K capture in Na^{22} (1^+–0^+ transition); they are, however, somewhat contradictory. Thus, in [19] the value obtained for b_{GT} is

$$b_{GT} = -0.004 \pm 0.012,$$

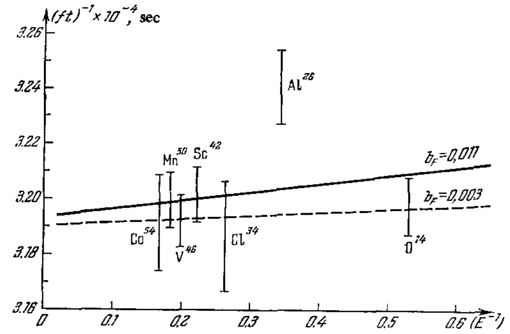

FIG. 1. Analysis of 0^+–0^+ transitions by the Gerhart method.

whereas in [20] there was observed a Fierz term

$$b_{GT} = -0.025 \pm 0.006.$$

Similarly, the results[21] on K capture for a number of nuclei V^{48}, Co^{58}, La^{134}, Pr^{140}, Nd^{141}, Sm^{143} yield the value

$$b_{GT} = -0.030 \pm 0.009.$$

On the whole, these data apparently make it possible to suggest the possibility of its existence in the spectrum of the Gamow–Teller β transitions, so that

$$b_{GT} = -0.02 \pm 0{,}01. \tag{11}$$

Let us examine the data on Fermi β transitions. Until recently, the best data were apparently those of Gerhart,[22] obtained from the reduction of experiments on 0^+–0^+ transitions in O^{14}, Al^{26}, and Cl^{34}:

$$b_F = 0.00 \pm 0.12.$$

Recently, Yu. S. Lyutostanskiĭ [77] used Gerhart's method to analyze all the known 0^+–0^+ transitions. The results of the analysis are shown in Fig. 1. As seen from the figure, all the transitions, with the exception of Al^{26}, fit with great accuracy the line y = const. The mean value is

$$b_F = 0.011 \pm 0.019. \tag{12}$$

Finally, in the case of mirror β transitions, the most accurate measurements were performed for the transition $N^{13}(\beta^+)C^{13}$,[23] and yielded the value

$$b = \gamma \cdot \frac{|M_F|^2\, 2\,\mathrm{Re}\,(C_S C_V^* + C_S' C_V'^*) + |M_{GT}|^2 \cdot 2\,\mathrm{Re}\,(C_T C_A + C_T' C_A')}{|M_F|^2 |G_F|^2 + |M_{GT}|^2 |G_{GT}|^2} = 0.0014 \pm 0.0237.$$

Using the data for the Gamow–Teller variant and the values of the matrix elements of the β transition from the ft data (see Table I), we obtain the following estimate of the Fierz terms of the Fermi variant:

$$b_F = \frac{2\,\mathrm{Re}\,(C_S C_V + C_S' C_V')}{|C_S|^2 + |C_S'|^2 + |C_V|^2 + |C_V'|^2} = 0.008 \pm 0.04.$$

c) Angular $e\nu$ correlation

The investigation of the $e\nu$ correlation, besides the investigation of the form of the spectrum and the electron polarization, was one of the main experiments for the determination of the interaction variants, and therefore, in spite of technical difficulties, has by now been performed for a number of nuclei: He^6, Ne^{19}, Ne^{23}, Na^{24}, Ar^{35}, and also for the neutron. In experiments of this

Table IV. Experimental data on the $e\nu$ correlation

β Transition	α_{exp}	Reference
$n_0^1\,(\beta^-)\,p_1^1$	$+0.05\pm0.12$	24
	-0.06 ± 0.13	25
	-0.091 ± 0.039	26
$He^6\,(0^+)\,(\beta^-)\,Li^6\,(1^+)$	-0.3343 ± 0.003	27
	-0.319 ± 0.028	28
$Ne^{19}\,(1/2^+)\,(\beta^+)\,F^{19}\,(1/2^+)$	0.00 ± 0.08	29
$Ne^{23}\,(5/2^+)\,(\beta^-)\,Na^{23}\,(5/2^+)$	-0.37 ± 0.04	29
	-0.41 ± 0.31	30
$Na^{24}\,(4^+)\,(\beta^-)\,Mg^{24}\,(4^+)$	-0.22 ± 0.12	31, 32
$Ar^{35}\,(3/2^+)\,(\beta^+)\,Cl^{35}\,(3/2^+)$	$+0.97\pm0.14$	29

Table V. Experimental data on the polarization of electrons in Gamow–Teller β transitions

Element	Transition	E_e, keV	$P_e/(-v/c)$	Reference
P^{32}	$1^+\,(\beta^-)\,0^+$	100	0.990 ± 0.025	33
		200–500	1.00 ± 0.01	34
		340	1.02 ± 0.03	35
		616	0.99 ± 0.01	36
		660–990	1.00 ± 0.02	37
Co^{60}	$5^+\,(\beta^-)\,4^+$	100	0.97 ± 0.016	38
		156	0.95 ± 0.002	39
		209	1.00 ± 0.02	39
		180	0.99 ± 0.02	39
In^{114}	$1^+\,(\beta^-)\,0^+$	261	0.97 ± 0.04	33
		310	0.97 ± 0.03	40
		340	0.93 ± 0.03	35
		540	1.01 ± 0.03	40
		1250	0.96 ± 0.015	41

type, the asymmetry coefficient is determined by the expression

$$a=\frac{(|C_V|^2+|C_V'|^2-|C_S|^2-|C_S'|^2)\,|M_F|^2+(|C_T|^2+|C_T'|^2-|C_A|^2-|C_A'|^2)\,\frac{1}{3}\,|M_{GT}|^2}{|M_F|^2\,|G_F|^2+|M_{GT}|^2\,|G_{GT}|^2}. \tag{13}$$

The results of the experiments are shown in Table IV.

As seen from the table, for the pure Gamow–Teller transitions the measurements have been performed only in He^6. It follows from them that

$$(|C_T|^2+|C_T'|^2)/(|C_A|^2+|C_A'|^2)=0.002\pm0.004. \tag{14}$$

An investigation of the Fermi β transitions from this point of view is difficult, since there are no data on the $e\nu$ correlation in 0^+–0^+ transitions. Thus, information on the ratio of the S and V variants can be obtained only from data on the $e\nu$ correlation of the neutron or in the mirror nuclei Ne^{19} and Ar^{35}. In the latter case, the errors are due both to the experimental errors on $e\nu$ correlation, and to errors in the determination of ft.

For the neutron, using the data of V. K. Grigor'ev et al.[26] and the estimates for the Gamow–Teller constants, we obtain

$$(|C_S|^2+|C_S'|^2)/(|C_V|^2+|C_V'|^2)=0.06\pm0.21.$$

In the case of Ar^{35}, using the experimental data of Allen et al.,[29] estimates of the matrix element of the Gamow–Teller type (Table I) and estimates of the Gamow–Teller constants, we obtain

$$(|C_S|^2+|C_S'|^2)/(|C_V|^2+|C_V'|^2)=-0.06\pm0.13.$$

The results for Ne^{19} are much more sensitive to errors in the determination of the asymmetry, and give a much rougher value

$$(|C_S|^2+|C_S'|^2)/(|C_V|^2+|C_V'|^2)=0.79\pm0.54.$$

Thus, the best data presently available are those on Ar^{35} and the neutron. From these, on the average, we obtain the following estimate of the contribution of the S variant relative to the V variant:

$$(|C_S|^2+|C_S'|^2)/(|C_V|^2+|C_V'|^2)=0.00\pm17. \tag{15}$$

As seen from this estimate, the accuracy of our knowledge of the absolute magnitude of the S variant is much lower than the average accuracy concerning other types of experiments. It is therefore of great interest to perform new experiments on $e\nu$ correlation in 0^+–0^+ or mirror β transitions, in order to refine these data.

d) Polarization of electrons and positrons in β decay

Experiments of this type yield information on the helicity of the particles that take part in the β interaction, i.e., on the relative sign of the constants C_i' and C_i. The polarization of the electrons (positrons) in the allowed β transition is determined by the quantity

$$P_{e\mp}=\mp\frac{v_e}{c}\cdot\frac{2\,\mathrm{Re}\,(C_VC_V'^*-C_SC_S'^*)\,|M_F|^2+2\,\mathrm{Re}\,(C_AC_A'^*-C_TC_T'^*)\,|M_{GT}|^2}{|M_F|^2\,|G_F|^2+|M_{GT}|^2\,|G_{GT}|^2} \tag{16}$$

and experimentally turns out to be close to v_e/c.

The most accurate data on the Gamow–Teller β transitions exists for P^{32}, Co^{60}, and In^{114} (Table V).

As seen from the table, in the nuclei P^{32} and Co^{60} the polarization of the electrons is equal to $-v_e/c$, with accuracy 1–2%. Using these data, we obtain

$$2\,\mathrm{Re}\,(C_A C_A'^* - C_T C_T'^*)/\,|\,G_{GT}\,|^2 = 0.995 \pm 0.02. \qquad (17)$$

The experimental data on In^{114} are less accurate and somewhat contradictory, but they apparently point to a possible deviation of the polarization from the values $-v/c \sim 2$–3%.

Further searches for such deviations are of great interest. An analysis of the possible causes of this deviation will be presented in Sec. 2.

In β transitions of the Fermi type, the experimental data are much less accurate (Table VI). Using experiments on O^{14}, we obtain the mean value

$$(2\,\mathrm{Re}\,(C_V C_V'^* - C_S C_S'^*))/(\,|\,C_S\,|^2 + |\,C_S'\,|^2 + |\,C_V\,|^2 + |\,C_V'\,|^2) = 0.85 \pm 0.18.$$

Here, as in the case of the data on the $e\nu$ correlation in mixed β transitions, the accuracy of the experiments is much lower than the mean value, pointing to a serious need for further refinement of these data.

e) Experiments of the Wu type

An investigation of the correlation between the directions of emission of the electron and the polarization of the nucleus in the initial (or final) state—the so-called Wu experiment—can be experimentally realized in two ways: directly or by investigating the $\beta\gamma$ correlation of the electrons of the decay and of the circularly polarized γ quanta emitted by the excited nucleus, occurring after β decay.

The correlation coefficient in both cases depends on the quantity

$$A = [\delta_{j_2 j_1} \sqrt{j_1 (j_1+1)}\, 2\,\mathrm{Re}\,(C_V C_A'^* + C_V' C_A^* - C_S C_T'^* - C_S' C_T^*)\, M_F M_{GT} \pm 2\,\mathrm{Re}\,(C_A C_A'^* - C_T C_T'^*)\,|\,M_{GT}\,|^2]/\,|\,G_F\,|^2\,|\,M_F\,|^2 + |\,G_{GT}\,|^2\,|\,M_{GT}\,|^2, \qquad (18)$$

and the correlation coefficient in the direct modification is given by

$$A_{\exp} = \mp \frac{v_e}{c} A \cdot [j_1 (j_1+1) + 2 - j_2 (j_2+1)]/2\,(j_1+1), \qquad (19)$$

while the coefficient of the $\beta\gamma$ correlation with the circularly-polarized ($\mu = \pm 1$) γ quantum of multipolarity L, emitted immediately after the β transition, is

$$A_{\beta\gamma} = \mu \cdot \frac{v_e}{c} \frac{j_2 (j_2+1) - j_3 (j_3+1) + L (L+1)}{4L (L+1)\, j_2 (j_2+1)} A \cdot [j_1 (j_1+1) + 2 - j_2 (j_2+1)]. \qquad (20)$$

As seen from the formulas, experiments on β transitions of the Gamow–Teller type give exactly the same information concerning the constants as measurements of the polarization of the electrons of the β decay. In the case of mixed β transitions, the correlation coefficient A includes a new combination of constants, containing the interference of the Fermi and Gamow–Teller terms.

$$\mathrm{Re}\,(C_V C_A'^* + C_V' C_A^* - C_S C_T'^* - C_S' C_T^*).$$

The Gamow–Teller β transitions have been well investigated by the method of the $\beta\gamma$ (circular) correlation (see Table VII).

The most accurate are the experimental data for Co^{60}, which yield for A the value

$$(2\,\mathrm{Re}\,(C_A C_A'^* - C_T C_T'^*))/|\,G_{GT}\,|^2 = +1.005 \pm 0.054, \qquad (21)$$

which does not contradict the data on the polarization of the electrons in Co^{60}.

There are at present no experiments on the $\beta\gamma$ (circular) correlation in mixed β transitions between analog states. However, the Wu experiment in its direct modification has been performed for the neutron, Ne^{19}, and Ar^{35} (see Table VIII).

If we use these data, estimates of A_{GT} from experi-

Table VI. Experimental data on the polarization of positrons in 0^+–0^+ transitions

Element	Transition	E_{β^+}, MeV	$P_e/(v/c)$	Reference
O^{14}	0^+—0^+	1,0	0,97±0,19	42
		1,2	0,73±0,17	43
Cl^{34}	0^+—0^+	3,0	0,64±0,39*)	44
		3,0	1,23±0,40**)	
Ga^{66}	0^+—0^+	2,6	1,00±0,16	
	($\Delta T \neq 0$)	3,0	0,95±0,12*)	44
		3,0	1,11±0,37**)	

*Thick target.
**Thin target.

Table VII. Experimental data on $\beta\gamma$ correlations in Gamow–Teller transitions

Element	Transition	$A_{\beta\gamma}$ = corr	A	Reference
Na^{22}	$3^+ (\beta^+)\, 2^+ (\gamma)\, 0^+$	0.377±0.046	1.131±0.144	45
Al^{28}	$3^+ (\beta^-)\, 2^+ (\gamma)\, 0^+$	−0.315±0.024	0.945±0.072	46
Mn^{56}	$3^+ (\beta^-)\, 2^+ (\gamma)\, 0^+$	−0.27±0.02	0.80±0.06	47
Co^{60}	$5^+ (\beta^-)\, 4^+ (\gamma)\, 2^+$	−0.335±0.018	1.005±0.054	48
Nb^{95}	$^9/_2{}^+ (\beta^-)\, ^7/_2{}^+ (\gamma)\, ^5/_2{}^+$	−0.49±0.08	0.98±0.16	49
		−0.56±0.09	1.12±0.18	50

Table VIII. Experimental data on the Wu experiment in mirror β transitions (je correlation)

Element	Transition	$A_{\exp}$	A	Reference
n^1	$^1/_2{}^+ (\beta^-)\, ^1/_2{}^+$	−0.11±0.02	+0.165±0.03	51
Ne^{19}	$^1/_2{}^+ (\beta^+)\, ^1/_2{}^+$	−0.033±0.002	−0.050±0.003	52, 53
Ar^{35}	$^3/_2{}^+ (\beta^+)\, ^3/_2{}^+$	+0.16±0.04	+0.40±0.10	53

ments in Gamow–Teller transitions, and also data on the ratios of the matrix elements of the Fermi and Gamow–Teller type from ft (Table I), then we can estimate experimentally the quantity

$$K = \mathrm{Re}\,(C_V C_A'^* + C_V' C_A^* - C_S C_T'^* - C_S' C_T^*)/|G_F|\cdot|G_{GT}|.$$

We then obtain for the neutron

$$K = -0.95 \pm 0.06, \qquad (22)$$

assuming that $M_{GT}/M_F = +\sqrt{3}$. For Ne^{19} we obtain the somewhat less accurate value

$$K = -0.96 \pm 0.13,$$

If we assume that $M_{GT}/M_F < 0$, with the main error occurring in ft_{exp}.

In the case of Ar^{35}, the errors in A_{exp} and ft_{exp} are too large to yield a reasonable value of K.

f) Experiments on the measurement of neutrino polarization

In experiments of this type one measures the angular correlation between the polarization of the nucleus in the initial (or final) state and the neutrino emission direction, and by the same token one measures the helicity of the neutrino (antineutrino) in the β decay. These experiments have been realized by now for Eu^{152}, the neutron, and Ne^{19}. They yield information concerning the quantity

$$B = [-\delta_{j_2 j_1}\sqrt{j_1(j_1+1)}\,2\,\mathrm{Re}\,(C_V C_A'^* + C_V' C_A^* + C_S C_T'^* + C_S' C_T^*)\,M_F M_{GT}$$

$$\pm 2\,\mathrm{Re}\,(C_A C_A'^* + C_T C_T'^*)\,|M_{GT}|^2]/|G_F|^2|M_F|^2 + |G_{GT}|^2|M_{GT}|^2,$$

$$B_{\mathrm{exp}} = B\,[j_1(j_1+1) + 2 - j_2(j_2+1)]/2\,(j_1+1). \qquad (23)$$

In the case of Eu^{152} (transition $0^-(K)1^-$), there occurs K capture with emission of a neutrino. If the neutrino is polarized, the produced nucleus is also polarized. The polarization of the final state is measured from the polarization of the succeeding γ quanta by the method of resonant scattering by Hg^{152} with subsequent detection of their circular polarization.[54] The experiment yields

$$2\,\mathrm{Re}\,(C_A C_A'^* + C_T C_T'^*)/|G_{GT}|^2 = 0.80 \pm 0.30, \qquad (24)$$

i.e., the neutrino is almost completely polarized in a direction opposite to the motion. In the case of the neutron, the β transition is mixed. An experiment performed by Novey[51] of the Argonne Laboratory yielded

$$A = +0.88 \pm 0.15.$$

Using the data of the matrix elements (Table I) and the result of the experiments with Eu^{152}, we obtain

$$L = \mathrm{Re}\,(C_V C_A'^* + C_V' C_A^* + C_S C_T'^* + C_S' C_T^*)/|G_F|\cdot|G_{GT}| = -1.01 \pm 0.69. \qquad (25)$$

A similar experiment was recently performed with Ne^{19}.[57] It yielded $A = -0.90 \pm 0.13$, which yields for L the value -1.02 ± 0.72.

Experiments of this type complete the group of the simplest β decay experiments performed presently and containing not more than two simultaneously measured quantities. Taken together, they yield information on 11 independent quadratic combinations of the constants C_i and C_i', and in particular, make it possible to determine uniquely the constants under the assumption that they are real.

Table IX. Experimental data on jeν correlations

Element	Transition	D_{exp}	Reference
n^1	$1/2^+ (\beta^-)\, 1/2^+$	0.00 ± 0.15	51
		0.04 ± 0.05	51, 55
		0.01 ± 0.01	56
Ne^{19}	$1/2^+ (\beta^+)\, 1/2^+$	0.002 ± 0.014	57

In the case of complex C_i and C_i', however, this information is insufficient and it is necessary to investigate more complicated triple correlations, in which one measures simultaneously three quantities, say two momenta and the polarization.

At the present time only two such experiments were performed: triple correlations of the jeν and of the $j_1 e j_2$ types (see Table II).

g) jeν correlation

Experiments of this type have been realized at present on the neutron and Ne^{19}. The experimentally investigated quantity was the asymmetry coefficient for the term of the type $(v/c)(\mathbf{j}/|\mathbf{j}|)[\mathbf{p}_e \times \mathbf{p}_\nu]/|\mathbf{p}_e|\cdot|\mathbf{p}_\nu|$:

$$D = \frac{2\,\mathrm{Im}\,(C_S C_T^* - C_V C_A^* + C_S C_T'^* - C_V' C_A'^*)\,|M_F|\cdot|M_{GT}|\sqrt{J/(J+1)}\,\delta_{JJ'}}{|M_F|^2|G_F|^2 + |M_{GT}|^2|G_{GT}|^2}. \qquad (26)$$

The results are given in Table IX. They yield the quantity of interest to us

$$\mathrm{Im}\,(C_S C_T^* - C_V C_A^* + C_S'^* C_T'^* - C_V' C_A'^*)/|G_F|\cdot|G_{GT}| = 0.022 \pm 0.022. \qquad (27)$$

This result makes use of the experimental data on D, recently obtained by the group of B. G. Erozolimskiĭ.[56]

If we use the data on Ne^{19}, then we obtain the somewhat less accurate value 0.007 ± 0.058, which does not contradict the results for the neutron.

h) $j_1 e j_2$ correlation

To measure such a correlation, they used in [50] a procedure involving the investigation of the angular distribution of the γ quanta accompanying the β decay of a polarized nucleus, relative to the direction of emission of the β electrons. The investigated β decay was that of Mn^{52}: $6^+(\beta^+)6^+(\gamma_1)4^+ \times (\gamma_2)2^+(\gamma_3)0^+$. The correlation coefficient of the term of the type $\mathbf{j}[\mathbf{p}_e \times \mathbf{p}_\nu] \times (\mathbf{j}\mathbf{p}_\gamma)$ was investigated; this coefficient contains the following combination of constants C_i and matrix elements:

$$\mathrm{Im}\,(C_A^* C_V' + C_A'^* C_V - C_T^* C_S' - C_T'^* C_S)\,M_{GT}^* M_F/|G_F|\cdot|M_F|^2 + |G_{GT}|^2|M_{GT}|^2. \qquad (28)$$

The β transition of Mn^{52} is not a β transition of the analog type, so that the ratio of the matrix elements M_{GT}/M_F cannot be obtained from the experimental data on ft and enters the experiment as a parameter. The authors formulate the results of the measurements, introducing the average phase shift of the constants of the Fermi and Gamow–Teller type from a relation equivalent to the following:

$$(C_A^* C_V' + C_A'^* C_V - C_T^* C_S' - C_T'^* C_S)\,M_{GT}^* M_F = e^{i\theta}|G_F|\cdot|G_{GT}|\cdot|M_F|\cdot|M_{GT}|.$$

The aggregate of the experiments performed by the authors (the Wu experiment, $\beta\gamma$ correlation, and $\beta\gamma$ correlation from an oriented nucleus) yields the region of

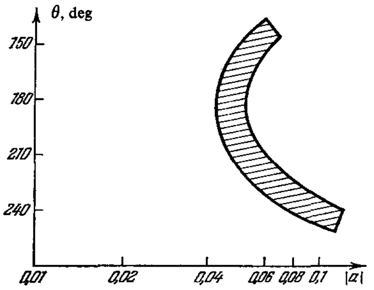

FIG. 2. Region of admissible values of the parameters in the analysis of the $\beta\gamma$ correlation in Mn^{52}.

admissible values of the angle θ as a function of $|a|$ (see Fig. 2), where

$$|a| = |G_F| \cdot |M_F|/|G_{GT}| \cdot |M_{GT}|.$$

Assuming that the matrix elements M_F and M_{GT} are real, we find that the quantity

$$N = \mathrm{Im}\,(C_A^* C_V' + C_A'^* C_V - C_T^* C_S' - C_T'^* C_S)/|G_F| \cdot |G_{GT}| = \sin\theta\,(M_F/|M_F|)\,(M_{GT}/|M_{GT}|)$$

lies within the angle interval $160° \leq \theta \leq 240°$. The relative sign of the matrix elements, from the data on $\beta\gamma$ correlation, is positive. Thus, the indicated quantity lies in the range

$$-0.85 \leqslant N \leqslant +0.65. \tag{29}$$

The set of experiments a)–h) accounts for all the experiments on the complete experiment in β decay, realized at the present time, and requiring no model estimates of the nuclear matrix elements for their analysis.

To complete the general picture, however, mention must also be made of two other important types of experiments, which are essentially connected with such estimates but yield interesting information on the Hamiltonian of the β interaction. These are the investigation of 0^+–0^- transitions and the investigation of RaE.

The study of 0^+–0^- transitions (spectrum and polarization of the electrons) gives information on the possible contribution of the pseudoscalar variant to the Hamiltonian (1). In particular, at the present time the 0^+–0^- transition in Pr^{144} has yielded the estimate[72]

$$|C_P/C_A| < 5.$$

A study of the spectrum and of the polarization of the electrons of RaE apparently offers an interesting possibility of estimating the relative phase shift of the constants C and C′, using the effect of mutual cancellation of the main matrix elements. Such a cancellation should lead to a strong sensitivity of the spectrum and of the correlation characteristics of RaE to small changes of the relative phase shift of the constants, and the experimental characteristics will depend on this phase shift and on the nuclear matrix elements. An analysis of the data on RaE make it possible to conclude that in (VA) two-component theory the relative phase shift of the constants C_V and C_A is smaller than 6°, which does not contradict the data on allowed transitions.

As already indicated, both experiments give information whose interpretation calls for the use of definite ideas concerning the structure of the nucleus. Following the general tendency of the present article to avoid the use of model considerations, we confine ourselves to an indication of the results of these experiments, but we shall not use them in the analysis of the complete experiments. They are described in greater detail, for example, in the reviews.[32, 72] A number of other experiments, not connected with the organization of the complete experiments, are reported in the article by Wu[74] (see also [75]).

2. ANALYSIS OF THE EXPERIMENTAL DATA ON THE COMPLETE EXPERIMENT

As already indicated, the general organization of the complete experiment on β decay should afford, in principle, a possibility of determining 15 of the 16 parameters C_i and C_i' in the Hamiltonian (1). Such a complete experiment calls for the organization of 15 independent experiments, of which only 13 were performed to data, and some of them, as will be shown, call for considerable improvement. The 16th parameter, which is not determined in pure β decay experiments, corresponds to the general phase of the Hamiltonian of the weak interaction, which can be determined only relative to some other type of interaction and in experiments in which interference takes place between the weak interaction and the chosen one. An example of such an experiment is the investigation of the weak scattering of nucleons, which interferes with their strong interaction.

Leaving aside the question of the relative phase shift of the weak interaction on the whole, we can state, however, that at the present time the general organization of a complete experiment consisting of 15 independent experiments has not yet been realized.

Besides such an organization of the complete experiment, which is aimed at an experimental determination of all the parameters C_i and C_i', there is also another possible formulation of the problem, which we shall call the limited complete experiment. In this case, an additional limitation is imposed a priori on the constants C_i and C_i'; this limitation is the consequence of one or several additional hypotheses that do not contradict the complete experiment. An experimental analysis of the complete experiments of this type makes it possible to carry out an additional refinement of the experimental limits of the quantities C_i and C_i'. Naturally, any contradiction in the interpretation of the data on the limited complete experiment would make it obligatory to review the limiting theoretical hypothesis.

Thus, there are different types of the limited complete experiment, which depend in principle on the structure of the proposed theory of β interaction.

The modern theory of weak interaction regards β decay of nucleons as one of the particular processes of the lepton-hadron type with strangeness conservation ($\Delta S = 0$). To construct the effective Hamiltonian of such a process it is convenient to start from the simplest processes of the lepton-lepton type, basic among which is the μ–e decay. It is assumed that the Hamiltonian of the μ–e decay has the V–A form:

$$H = (G/\sqrt{2})[\bar{\Psi}_4 \gamma_\mu (1+\gamma_5) \Psi_3][\bar{\Psi}_2 \gamma_\mu (1+\gamma_5) \Psi_1], \tag{30}$$

with a universal constant $G = G^{(\mu)}$. If particles 3 and 4 are not leptons but hadrons, the strong interaction of these particles can violate the V–A form, changing the relative weights and phases of the V and A variants, but the common (V, A) form of the Hamiltonian remains the same. Moreover, the absolute constant G for the hadron–lepton processes no longer coincides with the universal constant $G^{(\mu)}$. Its change is determined by the Cabbibo parameter θ_0,[67] so that for processes proceeding without a change of strangeness ($\Delta S = 0$) we have

$$G = G^{(\mu)} \cos\theta_0, \tag{31}$$

and for processes with change of strangeness ($\Delta S = 1$)

$$G = G^{(\mu)} \sin\theta_0. \tag{32}$$

Thus, in the case of β decay the predicted Hamiltonian form is

$$H_\beta = (G^{(\mu)} \cos\vartheta_0/\sqrt{2})\,[\overline{\Psi}_4\gamma_\mu(1+\lambda\gamma_5)\,\Psi_3]\,[\overline{\Psi}_2\gamma_\mu(1+\gamma_5)\,\Psi_1], \tag{33}$$

and contains two experimental parameters, $G = G^{(\mu)} \times \cos\theta_0$ and $\lambda = G_{GT}/G_F$. (We note that the parameter λ can also be obtained theoretically.[68]) The complete experiment reduces in this case to two experiments aimed at determining these parameters.

It is possible, however, to obtain the Hamiltonian (33) without directly using the theory of universal weak interaction, which imposes on the general form of the Hamiltonian (1) additional limitations with respect to the constants C_k and C'_k. Each of these limitations corresponds to a certain theoretical hypothesis on which the universal weak-interaction theory is based. Usually three such hypotheses are assumed:

1) the hypothesis of the V, A form of the weak interaction;

2) the hypothesis of a two-component neutrino;

3) the hypothesis of conservation of combined (CP) parity.

Each of these hypotheses can be used independently of the others and reduces the number of free parameters of the Hamiltonian (1) to one-half. Simultaneous utilization of all three leads to the form (33).

Such a subdivision of the theory into three fundamental hypotheses makes it possible to obtain different types of limited complete experiments. Thus, using the first hypothesis, we can arrive at a complete experiment with seven parameters C_k and C'_k (four moduli and three relative phases). Analogously, the limited complete experiment using the second hypothesis has seven parameters and that using the third has eight. Stronger limitations, naturally, are also possible. In such a formulation, the complete experiment on β decay now requires not 15 experiments, but fewer, and in many cases it has been realized by now. At the same time, it is possible to carry out an independent analysis of the validity of each of the foregoing hypotheses.

Let us analyze in detail each of the hypotheses, and let us formulate them in terms of the parameters N, θ, φ, and ψ, defined by the relations

$$C_k = N_k \cos\theta_k \exp[i\varphi_k], \quad C'_k = N_k \sin\theta_k \exp[i\psi_k],$$
$$N_k^2 = |C_k|^2 + |C'_k|^2, \quad 0 \leqslant \theta \leqslant \frac{\pi}{2}, \quad 0 \leqslant \varphi, \quad \psi < 2\pi. \tag{34}$$

Such parameters are more convenient than C_k and C'_k, since different hypotheses are described in this case in terms of different parameters.

1. V, A Interaction Hypothesis

According to this hypothesis, in a weak interaction, and particularly in β decay of nucleons, only the V and A variants are realized, so that

$$N_S = N_T = N_{PS} = 0. \tag{35}$$

This hypothesis was first formulated in [61, 62], and is particularly attractive from the point of view of theory because of the analogy that arises between weak interactions and electrodynamics. At the present time, it is assumed to be valid for any weak process.

In view of this universality of this hypothesis, the experimental limits of its applicability can be obtained in principle from any weak process by performing in it the same complete experiment as in β decay.

In this paper, however, we shall consider only the case of β decay. As to the other weak processes, it should be noted that until recently, no contradictions were observed in the reduction of the different experiments on the V and A theory, and the estimates of the possible contributions of other variants give results close to those for β decay.[73]

The V, A-interaction hypothesis can be verified with two groups of the experiments of the complete experiment. These are, first of all, the aggregate of experiments on the determination of the constants of the β decay and of the experiments on $e\nu$ correlation (see Sec. 1a, c). The experiments of this group depend only on the parameters N_k^2, and their reduction, by giving information on the constants $G^{(\beta)}$ and λ, yields simultaneously information on the parameters N_S^2/N_V^2 and N_T^2/N_A^2, making it possible to estimate the validity of the hypothesis in question. The other group is made up of experiments on the Fierz terms (Sec. 1b). Unlike the first group, they depend linearly on the parameters N_S/N_V and N_T/N_A, and give a negative result when the latter vanish. However, in addition to these parameters they also contain other parameters (θ, φ, and ψ), making their interpretation essentially ambiguous.

2. The Two-component Neutrino Hypothesis

This hypothesis was first introduced in [63, 64], and in terms of (34′) it takes the form

$$\varphi_k = \psi_k, \quad \theta_k = \frac{\pi}{4} \qquad (k = S, V, T, A, PS). \tag{36}$$

For the constants C_k and C'_k it corresponds to the relation

$$C'_k = +C_k. \tag{37}$$

Attention must be called to the fact that in practice this hypothesis includes two relations (36), the first of which ($\varphi = \psi$) is a part of a more general requirement that the combined parity be conserved, i.e., the third hypothesis, whereas the second ($\theta = \pi/4$) is independent of this relation. In this sense, the assumption that the hypothesis of the two-component neutrino is valid includes also the assumption of combined-parity conservation in each individual variant of the β interaction. It is possible to forgo the two-component neutrino by forgoing the condition $\theta = \pi/4$ without violating CP parity.

It is convenient to combine all the effects connected with the violation of CP parity, and to analyze jointly the experiments of the complete experiment, by determining first of all the degree of the possible violation of the condition $\theta = \pi/4$, assuming that CP parity is conserved. This group of experiments unifies the experiments on the measurement of the polarization of the electrons, experiments of the Wu type (je correlation) and experiments on the measurement of the neutrino polarization (see Sec. 1, d, e, f). As will be seen from the analysis, estimates of the parameters θ depend strongly on whether one considers the case of the complete or limited complete experiment, in the sense of the limitation in accordance with the first hypothesis We note also that experiments do not yield any limitations whatever on the parameters θ_S and θ_T.

3. CP-Parity Conservation

This hypothesis was proposed by L. D. Landau[65] immediately after the discovery of spatial parity violation in weak interactions. The possibility of introducing such a hypothesis follows directly from the Luders-Pauli theorem, according to which a weak interaction should be invariant against the product of the transformations of the charge conjugation (C), space reflection (P), and time reflection (T). If there exists a violation of spatial parity P, then it should be compensated in the product of the transformations CPT in such a way that CPT is conserved. Such a compensation can be obtained by forgoing the invariance of the theory with respect to charge conjugation C, but maintaining its invariance with respect to time reflection. Then the theory becomes invariant against the product of the transformations C and P (combined parity).

As already noted, the violation of this hypothesis has by now been observed in K^0-meson decay.[69, 76] The absolute magnitude of this violation, to be sure, is small ($\sim 0.2\%$), but this fact undoubtedly calls for an investigation of the limits of the possibility of such a violation also in the case of β decay.

The condition of combined-parity conservation in β decay leads to the requirement that all the constants of the Hamiltonian (1) be real. In the simplest case of the V–A variant of the theory, this corresponds to the following relation between the phases φ and ψ:

$$\varphi_V - \varphi_A = \pi, \quad \varphi_V = \psi_V, \quad \psi_V - \psi_A = \pi, \quad \varphi_A = \psi_A, \tag{38}$$

three of which are independent. Violation of CP parity conservation should lead to violation of these relations.

If we take into account the smallness of the expected effect ($< 1\%$), then two types of experiments sensitive to such violations are possible in principle.

In the experiments of the first type, the result depends linearly on the possible violations. Such experiments include experiments on the triple correlations $je\nu$ and j_1ej_2 (see Sec. 1g, h). In practice, the accuracy needed for such conclusions is possessed only by the former, the reduction of which yields information on the value of $\frac{1}{2}(\varphi_V - \varphi_A + \psi_V - \psi_A)$, i.e., on one linear combination of three independent parameters. To investigate the others it is necessary to resort to less accurate experiments, which depend on the possible violations not linearly but quadratically. These include experiments on electron polarization and experiments of the WU type in pure Fermi and Gamow–Teller β transitions (Secs. 1d, e), from which, as already indicated, such information is obtained concerning the parameters θ.

All these experiments contain, besides the parameters φ and ψ, also the parameters N and θ, the estimates of which depend, in particular, on the validity of the preceding hypothesis. Consequently, estimates of the validity of the combined-parity conservation hypothesis are different in different formulations of the complete experiment.

Proceeding now to a concrete analysis of the experiments of the complete experiment and to estimates of the parameters extracted from the experimental data, we note that, in accordance with the classification of the hypotheses, the experiments of the complete experiment also break up into two groups.

It is convenient to include in the first group experiments on the determination of the β decay constants and the $e\nu$ correlation (see Secs. 1a, c). They depend only on the parameters N_k^2 and make it possible to verify the hypothesis of the V, A variant independently of other hypotheses.

In the second group we can include experiments on electron polarization, experiments of the je type, and neutrino polarization (see Sec. 1d, e, f). Besides the parameters N_k, they depend on the parameters θ_k and make it possible to verify the hypothesis of the neutrino helicity. In addition, they depend quadratically on the possible violations of CP parity and afford estimates, albeit weak, of the parameters $\varphi_k - \psi_k$ for the V and A variants.

It is convenient to include in the third group experiments on triple correlations $je\nu$ and j_1ej_2, which depend linearly on CP violation (see Sec. 1g, h).

Finally, the fourth group includes experiments on the Fiert's terms, which yield information on the contributions of the S and P variants (see Sec. 1b), i.e., on the validity of the first hypothesis, which, however, depends in principle on the assumptions concerning the other parameters of these variants.

We now proceed to a concrete analysis of the experiments of the total experiment in the indicated groups.

A. Experimental limits of the parameters N_k. Estimates of the parameters N_k may be obtained from experiments of the first and fourth groups.

In the experiments of the first group, which include, as already indicated, experiments on the determination of the constants of the β decay and $e\nu$ correlation, we can obtain the value of the β decay constant $G^{(\beta)}$ and the parameters of the relative weights of the variants N_k^2.

The absolute value of the β decay constant

$$G^{(\beta)} = (1.4016 \pm 0.0022)\cdot 10^{-49} \text{ erg-cm}^3 \tag{39}$$

makes it possible to determine also the value of the Cabbibo parameter

$$\sin\theta_0 = 0.2095 \pm 0.0086, \tag{40}$$

which is close to data on K_{l_3} decays ($\Delta S = 1$, V variant):

$$\sin\theta_0 = 0.218 \pm 0.002.$$

It should be noted, however, that the K_{l2} decays ($\Delta S = 1$, = 1, A variant) give another value: $\sin\theta_0 = 0.2655 \pm 0.006$. The question of the reasons for this difference is not clear at present. It can be explained partially as being due to the influence of the electromagnetic corrections.[70]

The parameters of the relative weight of the variants are best analyzed in units in which

$$N_S^2 + N_V^2 = 1, \tag{41}$$

corresponding to the definition of the absolute constant $G^{(\beta)}$ as a constant of a Fermi transition. We then obtain from the experiments of the first group

$$N_T^2 + N_A^2 = \begin{cases} 1.40 \pm 0.06 \ [12], \\ 1.52 \pm 0.02 \ [14], \end{cases}$$

$$\frac{N_S^2}{N_T^2} = 0 \pm 0.17,$$

$$\frac{N_T^2}{N_A^2} = 0.002 \pm 0.004,$$

or

$$N_S/N_V = 0 \pm 0{,}41, \quad N_T/N_A = 0.04 \pm 0.06. \tag{42}$$

These estimates show that the hypothesis of the V, A variant of the theory has been better verified at the present time for the Gamow–Teller variant than for the Fermi variant. The experiment limits the possible admixture of the tensor variant to $\sim 4\%$, whereas the admixture of the scalar variant in the vector variant can reach 40% within the limits of errors. Contemporary experimental procedures apparently make it possible to improve the estimate for the Fermi variants, so that from the point of view of the direct verification of the hypothesis of the V, A variant it is of interest to perform new experiments on $e\nu$ correlation in β transitions of the mirror type or of the type 0^+–0^+.

Another group of experiments that yield information on the parameters N_S and N_T are those which depend on the combinations of constants of the Fermi-term type. Two such experiments have by now been realized (see Sec. 1b). In terms of the parameters (34), they yield the following relations:

$$\{N_S N_V/(N_S^2 + N_V^2)\}^{1/2} \{\cos(\theta_S - \theta_V)[\cos(\varphi_S - \varphi_V) + \cos(\psi_S - \psi_V)] + \cos(\theta_S + \theta_V)[\cos(\varphi_S - \varphi_V) - \cos(\psi_S - \psi_V)]\} = 0.01 \pm 0.02,$$

$$\{N_T N_A/(N_T^2 + N_A^2)\}^{1/2} \{\cos(\theta_T - \theta_A)[\cos(\varphi_T - \varphi_A) + \cos(\psi_T - \psi_A)] + \cos(\theta_T + \theta_A)[\cos(\varphi_T - \varphi_A) - \cos(\psi_T - \psi_A)]\} = -0.02 \pm 0.01. \tag{43}$$

The main feature of experiments of this group is their linear dependence on the parameters N_S and N_T. However, inasmuch as these expressions contain, besides these parameters, also other parameters of both the V, A and the S, T variants, it is clear a priori that the conclusions of the experiments of these groups will be essentially ambiguous. The main reason for this ambiguity is the absence of experimental limitations on the parameters θ, φ, and ψ of the S and T variants. The only way out of this situation is to introduce additional theoretical hypotheses concerning these parameters, i.e., to change over to a limited complete experiment. However, unlike in the V and A variants, where these hypotheses are experimentally confirmed in experiments of the other groups, arbitrary assumptions are possible here a priori.

Experience in the investigation of the V and A variants indicates first of all that the hypothesis of CP parity conservation is possible. This condition leads immediately to two possibilities for the S (T) variant, in each of which a relation is obtained between the parameters N_S/N_V (N_T/N_A) and θ_S (θ_T):

either $\varphi_S = \psi_S$, $N_S/N_V\,|\cos(\theta_S - \theta_V)| = 0.01 \pm 0.02$,
or $\varphi_S = \psi_S + \pi$, $N_S/N_V\,|\cos(\theta_S + \theta_V)| = 0.01 \pm 0{,}02$.

Analogously for the T variant

either $\varphi_T = \psi_T$, $N_T/N_A\,|\cos(\theta_T - \theta_A)| = 0.02 \pm 0.01$,
or $\varphi_T = \psi_T + \pi$, $N_T/N_A\,|\cos(\theta_T + \theta_A)| = 0.02 \pm 0.01$.

If we now add also the assumption of the helicity of the neutrino:

$$\theta_S = \theta_V = \theta_T = \theta_A = \pi/4,$$

then we obtain the alternative

either $\varphi_S = \psi_S$ and $N_S/N_V = 0.01 \pm 0.02$, (44)
or $\varphi_S = \psi_S + \pi$ and there are no limitations on N_S/N_V.

Analogously for the T variant:

either $\varphi_T = \psi_T$ and $N_T/N_A = 0.02 \pm 0.01$, (45)
or $\varphi_T = \psi_T + \pi$ and there are no limitations on N_T/N_A.

In terms of C_k and C_k', the appearance of limitations on the parameters N_S/N_V and N_T/N_A corresponds to the case when

$$C_S' = +C_S, \quad C_T' = +C_T.$$

Conversely, the condition

$$C_S' = -C_S, \quad C_T' = -C_T$$

causes the Fierz terms to vanish automatically, regardless of the values of the parameters N_S and N_T. Then the neutrino in the S and T variants should be polarized in the direction opposite to the direction, in which it is polarized in the V and A variants.

Thus, if CP parity is conserved and the neutrino has a helicity having the same sign for all variants, the experiments on the Fierz terms give additional limitations on the parameters N_S and N_T:

$$N_S/N_V = 0{,}01 \pm 0{,}02, \quad N_T/N_A = 0.02 \pm 0.01. \tag{46}$$

This conclusion, however, cannot be regarded as unambiguous, since the neutrino helicity in the S and T variants cannot be verified.

The considered experiments on the observation of the Fierz terms are not the only possible experiments that depend linearly on the parameters N_S and N_T. There exist in addition also other experiments of this class, of the correlation type, which however have not yet been realized. These include experiments on σj correlation, which contain in principle combinations of constants of the Fierz type (see Table II), and also experiments on correlations of the type σp_ν and $\sigma j p_e$. All these experiments call for a measurement of the electron polarization σ relative to the nuclear polarization j or the neutrino momentum p_ν, which at present is a complicated technical problem. For this reason, in particular, they have not yet been realized.

Before we proceed to the next groups of experiments, which yield limitations on the parameters θ, φ, and ψ, we make the following remark.

As already indicated, the parameters N_k enter in all types of experiments, particularly in the case of the complete experiment. Since the parameters N_k are known with definite errors, it follows that in order to be able to obtain any information at all from this experiment concerning the other parameters, it is necessary that its accuracy exceed the errors in the knowledge of the combinations of the parameters N_k which enter in the formulas that determine the experimental value. Otherwise the error in these experiments might be attributed entirely to the errors in N_k.

An examination of the experiments of the complete experiment shows that some of them do not satisfy this criterion and therefore, at the attained experimental accuracy, they do not yield any new information whatever concerning the parameters of the theory.

Thus, for example, owing to the low accuracy, experiments on the jν correlation in Gamow–Teller transitions yield no new information whatever compared with experiments on electron polarization, since the experimental accuracy for the quantity

$$2\,\mathrm{Re}\, C_T C_T'^{*}/|G_{GT}|^2 = [N_T^2/(N_T^2+N_A^2)]\cos(\varphi_T-\psi_T)\sin 2\theta_T = -0.09\pm 0.16$$

is worse than the independent estimates for the quantity

$$N_T^2/(N_T^2+N_A^2) = 0.002\pm 0.004.$$

Analogously, owing to the insufficient accuracy, no new information, compared with je correlation, is obtained from experiments on jν correlation in mixed transitions (see Sec. 1f) or experiments on triple correlation $j_1 e j_2$ (see Sec. 1h). We note that from now on we shall use weaker estimates for the parameters N_k (42), and not the stronger but ambiguous (46).

Thus, out of the seven remaining experiments of the complete experiment, which do not belong to the group in question, we can actually use only four for estimates of the remaining parameters φ, θ, and ψ. It is clear that in the best case it is possible to obtain from them the parameters of the A and V variants, and the remainder cannot be obtained in principle.

B. Experimental limits of the parameters θ_V and θ_A. As already indicated, the parameters θ should be estimated from the experiments of the second group. Only three of these have sufficient accuracy at present, namely experiments on electron polarization in Fermi and Gamow–Teller transitions and the Wu experiments for the mixed transitions. The Wu experiment in Gamow–Teller transitions yields nothing new compared with electron polarization, and experiments on jν correlations are insufficiently accurate, as indicated above. It should be noted that the main inaccuracy is connected in the latter with the contribution of the Gamow–Teller part, which affects considerably the reduction of the data in mixed β transitions, in spite of the experimental accuracy obtained in them.

In the case of the complete experiment, the reduction of the three indicated experiments leads to the relations

$$\left.\begin{aligned}
&\frac{N_A^2}{N_T^2+N_A^2}\cos(\varphi_A-\psi_A)\sin 2\theta_A - \\
&\qquad -\frac{N_T^2}{N_T^2+N_A^2}\cos(\varphi_T-\psi_T)\sin 2\theta_T = 0.99\pm 0.02,\\
&\frac{N_V^2}{N_S^2+N_V^2}\cos(\varphi_V-\psi_V)\sin 2\theta_V - \\
&\qquad -\frac{N_S^2}{N_S^2+N_V^2}\cos(\varphi_S-\psi_S)\sin 2\theta_S = 0.85\pm 0.18,\\
&\frac{1}{2}\frac{N_A N_V}{\sqrt{N_S^2+N_V^2}\sqrt{N_T^2+N_A^2}}\{\sin(\theta_V+\theta_A)[\cos(\varphi_V-\psi_A)+\\
&+\cos(\psi_V-\varphi_A)]+\sin(\theta_V-\theta_A)[\cos(\varphi_V-\psi_A)-\cos(\psi_V-\varphi_A)]\}-\\
&-\frac{1}{2}\frac{N_T N_S}{\sqrt{N_S^2+N_V^2}\sqrt{N_T^2+N_A^2}}\{\sin(\theta_S+\theta_T)[\cos(\varphi_S-\psi_T)+\\
&+\cos(\psi_S-\varphi_T)]+\sin(\theta_S-\theta_T)[\cos(\varphi_S-\psi_T)-\cos(\psi_S-\varphi_T)]\}=\\
&\qquad = -0.95\pm 0.14,
\end{aligned}\right\} \tag{47}$$

or, if we use the estimates (42) of the parameters N_k,

$$\left.\begin{aligned}
&\cos(\varphi_A-\psi_A)\sin 2\theta_A-(0{,}002\pm 0{,}004)\cos(\varphi_T-\psi_T)\sin 2\theta_T=\\
&\qquad =1.00\pm 0.02,\\
&\cos(\varphi_V-\psi_V)\sin 2\theta_V-(0\pm 0{,}17)\cos(\varphi_S-\psi_S)\sin 2\theta_S=\\
&\qquad =0.85\pm 0.38,\\
&{}^1/_2\{\sin(\theta_V+\theta_A)[\cos(\varphi_V-\psi_A)+\cos(\psi_V-\varphi_A)]+\sin(\theta_V-\theta_A)\times\\
&\times[\cos(\varphi_V-\psi_A)-\cos(\psi_V-\varphi_A)]\}-(0\pm 0.09)\,{}^1/_2\{\sin(\theta_S+\theta_T)\times\\
&\qquad\times[\cos(\varphi_S-\psi_T)+\cos(\psi_S-\varphi_T)]+\sin(\theta_S-\theta_T)\times\\
&\qquad\times[\cos(\varphi_S-\psi_T)-\cos(\psi_S-\varphi_T)]\}=-0.95\pm 0.23.
\end{aligned}\right\} \tag{48}$$

As seen from these relations, the experiment does not make it possible to draw any conclusions whatever on the terms containing the parameters of the S and T variants, since in all cases their contribution lies within the experimental error. Thus, the only information that can be obtained from them is information on the parameters of the A and V variants.

As noted above, it is convenient to investigate the experimental limits of the parameters θ under the assumption that CP parity is conserved, i.e., by changing over to the complete experiment limited in accordance with the third hypothesis, according to which Eqs. (38) are satisfied.

Under this assumption, the relations (48) take the form

$$\sin 2\theta_A = 1.00\pm 0.03,$$
$$\sin 2\theta_V = 0.85\pm 0.55,$$
$$\sin(\theta_V+\theta_A) = 0.95\pm 0.32,$$

whence we obtain for the parameters $\theta_{A,V}$ the limits

$$8.5^\circ\leqslant\theta_V\leqslant 81.5^\circ,\quad 37^\circ\leqslant\theta_A\leqslant 53^\circ. \tag{49}$$

In addition to limitations of the complete experiment in accordance with the CP-parity hypothesis, it is possible to have an even stronger additional limitation in accordance with the hypothesis (35). Naturally, in this case the errors decrease and the limits of the parameters are as follows:

$$21^\circ\leqslant\theta_V\leqslant 69^\circ,\quad 38^\circ\leqslant\theta_A\leqslant 52^\circ. \tag{50}$$

The obtained estimates show that in the case of the V variant the errors (in phase) are larger by two–three times than in the case of the A variant. The errors decrease strongly on going over from the general theory to the V, A variant. The neutrino helicity hypothesis is thus satisfied with accuracy (in phase) $\pm(24\text{–}36)^\circ$ for the V variant and $\pm(7\text{–}8)^\circ$ for the A variant. We see that further verification of this hypothesis calls for refinement of the experiments on the electron polarization, primarily in the cases of $0^+\text{–}0^+$ and mixed mirror β transitions.

C. Experimental estimates of CP-parity conservation. The estimates of the possible limits of violation of combined parity require in the general case a verification of three independent relations of type (38). These can be obtained in principle either in the experiments of the third group on triple correlations (first-order effects) or in experiments of the second group (second-order effects). Since the only third-group experiments with sufficient accuracy are those on jeν correlation, and yield only one parameter, the use of second-order effects is unavoidable for the time being.

Let us consider first the analysis of the experiment on jeν correlation. We obtain for it, in the case of the complete experiment, the relation

$$\frac{N_V N_A}{\sqrt{N_S^2+N_V^2}\sqrt{N_T^2+N_A^2}}\frac{1}{2}\{\cos(\theta_V-\theta_A)[\sin(\varphi_V-\varphi_A)+\sin(\psi_V-\psi_A)]$$
$$+\cos(\theta_V+\theta_A)[\sin(\varphi_V-\varphi_A)-\sin(\psi_V-\psi_A)]\}-$$
$$-\frac{N_S N_T}{\sqrt{N_S^2+N_V^2}\sqrt{N_T^2+N_A^2}}\frac{1}{2}\{\cos(\theta_S-\theta_T)[\sin(\varphi_S-\varphi_T)+\sin(\psi_S-\psi_T)]$$
$$+\cos(\theta_S+\theta_T)[\sin(\varphi_S-\varphi_T)-\sin(\psi_S-\psi_T)]\}=0.022\pm0.022 \tag{51}$$

or, if we estimate the contribution of the second term in accordance with (42),

$$\tfrac{1}{2}\{\cos(\theta_V-\theta_A)[\sin(\varphi_V-\varphi_A)+\sin(\psi_V-\psi_A)]$$
$$+\cos(\theta_V+\theta_A)[\sin(\varphi_V-\varphi_A)-\sin(\psi_V-\psi_A)]\}=0.022\pm0.11. \tag{52}$$

We see from this immediately the distinguishing features of the effects of first order in CP-parity violation. Indeed, putting

$$\varphi_V-\varphi_A=\pi+\Delta\varphi,\quad \psi_V-\psi_A=\pi+\Delta\psi,\quad \Delta\varphi,\ \Delta\psi\ll\frac{\pi}{2},$$

we readily obtain the preceding relation in the form

$$\Delta\varphi\cos\theta_V\cos\theta_A+\Delta\psi\sin\theta_V\sin\theta_A=0{,}02\pm0.11,$$

which in the case when the two-component neutrino hypothesis is satisfied goes over into the relation

$$\tfrac{1}{2}(\Delta\varphi+\Delta\psi)=\tfrac{1}{2}(\varphi_V-\varphi_A+\psi_V-\psi_A)-\pi=0.02\pm0.11. \tag{53}$$

Thus, an investigation of the jeν correlation makes it possible to obtain estimates for quantities of the type $\frac{1}{2}(\varphi_V-\varphi_A+\psi_V-\psi_A)$. In the case of a maximally limited experiment, this yields the relation

$$\tfrac{1}{2}(\varphi_V-\varphi_A+\psi_V-\psi_A)=\pi+1.4^\circ\pm1.4^\circ. \tag{54}$$

In other types of the complete experiment, with weaker limitations, these estimates naturally become much worse, and depend most strongly on the extent to which the hypothesis on the V, A variant is satisfied. It is convenient to introduce the reduction of the experiment on jeν correlation together with the reduction of the experiments on je correlation in mixed mirror β transitions. The latter pertains to second-order effects and yields information on a quantity of the type $\frac{1}{2}(\varphi_V-\varphi_A+\psi_V-\psi_A)$, so that jointly they make it possible to determine separately the two relative phases $\varphi_V-\varphi_A$ and $\psi_V-\psi_A$. The results of such an analysis in different types of complete experiments are given in Table X, where on the left side are indicated the limiting theoretical hypotheses of the experiment of the given type.

Let us proceed to the experiments of the second group. It is possible to find from them the limits of the parameters $\varphi_V-\psi_V$ and $\varphi_A-\psi_A$. The accuracy with

Table X. Analysis of experiments of the third group

Parameter \ Hypothesis		$\frac{1}{2}[\varphi_V-\varphi_A-\psi_V+\psi_A]$, deg	$\frac{1}{2}[\varphi_V-\varphi_A+\psi_V-\psi_A]$, deg
$S,\ T\neq0$	None	$\pi\pm67$	5 ± 37
	$\varphi=\psi$	π	4 ± 36
	$\theta=\pi/4$	$\pi\pm52$	2.5 ± 10
	$\left\{\begin{matrix}\varphi=\psi\\ \theta=\pi/4\end{matrix}\right\}$	π	2 ± 9.5
$S,\ T=0$	None	$\pi\pm56$	3.7 ± 3.7
	$\varphi=\psi$	π	3.5 ± 3.5
	$\theta=\pi/4$	$\pi\pm36$	1.5 ± 1.5
	$\left\{\begin{matrix}\varphi=\psi\\ \theta=\pi/4\end{matrix}\right\}$	π	1.5 ± 1.5

which these parameters are determined is low, since the effect is quadratic in the deviation of these quantities from zero. Indeed, in the complete experiment the electron polarization is determined by formulas (48), which yield the relations

$$\sin2\theta_A\cos(\varphi_A-\psi_A)=1{,}00\pm0.03,$$
$$\sin2\theta_V\cos(\varphi_V-\psi_V)=0{,}85\pm0.55,$$

which depend quadratically on $\varphi-\psi$. The situation is similar also in the case of the experiment on je correlation in mixed transitions, mentioned above in connection with the analysis of the jeν correlation. It is seen from (47) that it contains likewise only the cosines of the relative phases.

It is now easy to obtain estimates for the quantities $\varphi-\psi$ themselves:

$$-73^\circ\leqslant\varphi_V-\psi_V\leqslant73^\circ,\quad -15^\circ\leqslant\varphi_A-\psi_A\leqslant15^\circ. \tag{55}$$

These estimates correspond to the case of the complete experiment.

In the case of the maximal limitation (V, A theory with two-component neutrino) we obtain

$$-48^\circ\leqslant\varphi_V-\psi_V\leqslant48^\circ,\quad -13^\circ\leqslant\varphi_A-\psi_A\leqslant13^\circ. \tag{56}$$

Other possible cases of the use of the limited complete experiments for the estimate of the parameters $\varphi-\psi$ are gathered in Table XI together with estimates of the limits of the parameters θ_V and θ_A, which are extracted, as indicated, from an analysis of the same experiments of the second group. As follows from the table, the deviations in the relative phases of C_k and C'_k can reach, within the limits of experimental errors, 10° for the A variant and 40° for the V variant.

On the whole, combining the experimental data from both groups, we find that even in the case of the maximally limited complete experiment modern estimates yield

$$\varphi_V-\psi_V=0\pm48^\circ,\quad \varphi_A-\psi_A=0\pm13^\circ,\quad \tfrac{1}{2}(\varphi_V-\varphi_A+\psi_V-\psi_A)=\pi\pm2^\circ, \tag{57}$$

so that we obtain for the relative phases of the V and A variants, which are of greatest interest from the point of view of the theory,

$$\varphi_V-\varphi_A=\pi\pm31^\circ,\quad \psi_V-\psi_A=\pi\pm31^\circ. \tag{58}$$

This situation is due entirely to the fact that to derive the relative phases of the V and A variants it is

Table XI. Analysis of experiments of the second group

Parameter	Hypothesis	θ_V, deg	$\varphi_V - \psi_V$, deg	θ_A, deg	$\varphi_A - \psi_A$, deg
$S, T \neq 0$	None	$\pi/4 \pm 26$	0 ± 49	$\pi/4 \pm 8$	0 ± 19
	CP	$\pi/4 \pm 36$	0	$\pi/4 \pm 8$	0
	$\theta = \pi/4$	$\pi/4$	0 ± 73	$\pi/4$	0 ± 15
$S, T = 0$	None	$\pi/4 \pm 24$	0 ± 48	$\pi/4 \pm 6.5$	0 ± 13
	CP	$\pi/4 \pm 24$	0	$\pi/4 \pm 6.5$	0
	$\theta = \pi/4$	$\pi/4$	0 ± 48	$\pi/4$	0 ± 13

necessary to use not only effects of first order in CP-parity violation, but the use of second-order effects was also unavoidable. Then the experimental accuracy of the parameters is greatly lowered by the influence of the errors of the "poor" experiments.*

Thus, in connection with the problem of CP parity in β decay, the question arises of organizing new types of experiments, linear in this violation, and also the question of refining, in principle, the limits of the relative phase shifts of the constants C_k and C'_k in second-order experiments.

In the former case interest undoubtedly attaches to an investigation of the correlation of the type j_1ej_2 in mirror or analog mixed transitions. Such a correlation includes a different combination of constants than $je\nu$ correlation, and this should yield new information on the relative phase shifts of the V and A variants.

In the second approach, while remaining within the framework of the described experiments, it is necessary first to increase radically the accuracy of the experiments on electron polarization, especially in 0^+–0^+ transitions. It should be noted, however, that inasmuch as the expected effects on combined-parity violation are smaller than 10^{-2}, one can hardly expect any effects in experiments of this type without an accuracy of 10^{-4}–10^{-5}, which is hardly attainable at present. Much greater interest attaches apparently to searches for effects that depend linearly on $\varphi_k - \psi_k$.

Summarizing the analysis of the complete experiment, let us list briefly the conclusions.

1. Experiments of the first three groups (8 out of 13) make it possible to estimate within the framework of the complete experiment, without introducing any limiting theoretical hypotheses, all the parameters of the V and A variants of the interaction. In the case of S and T variants, they give only limitations on the parameters N_S and N_T, without imposing any limitations on the remaining parameters of these variants.

2. An analysis of the experimental data confirms the following three fundamental theoretical hypotheses: 1) the V, A form of the interaction, 2) the two-component character of the neutrino; 3) the conservation of combined parity in weak interactions.

Let us present experimental estimates of the feasibility of each of the hypotheses.

3. The hypothesis of the V, A form of the interaction is confirmed by estimates of the contributions of the S and T variants. The experiments of the first group show that

$$N_S/N_V = 0 \pm 0{,}41, \quad N_T/N_A = 0.04 \pm 0.06.$$

To improve these estimates it is necessary to carry out first of all new experiments on the $e\nu$ correlation in 0^+–0^+ or mixed mirror or analog β transitions.

Another but nonunique way of analyzing these parameters is to investigate the Fierz terms or to study fundamentally new types of correlations, namely σj, $\sigma\nu$, etc., which contain the electron spin σ. An analysis of these types of experiments on the basis of the assumption that $C'_S = +C_S$ and $C'_T = +C_T$ makes it possible to refine the estimates of the contributions of the S and T variants: $N_S/N_V = 0.01 \pm 0.02$, $N_T/N_A = 0.02 \pm 0.01$. In the case when $C'_S = -C_S$ and $C'_T = -C_T$, experiments of this type will give a negative result regardless of the values of the contributions of the S and T variants.

From the point of view of the investigation of the Fiert's terms, it is of interest to study ft in Al^{26} and C^{10}, and also to refine the experiments in Gamow–Teller β transitions.

4. An analysis of the feasibility of the hypothesis of the two-component character of the neutrino depends essentially on additional theoretical assumptions. Experimental estimates in the best case give for the parameters the values

$$\theta_V = \frac{\pi}{4} \pm 24°, \quad \theta_V = \frac{\pi}{4} \pm 7°.$$

An additional refinement is necessary primarily for the V variant, and calls for improvement of the experiment from electron (positron) polarization in 0^+–0^+ or in mirror β transitions. In Gamow–Teller transitions, besides the polarization of the electrons it is possible to study the je, $j\nu$, or $\beta\gamma$ (circular) correlation.

5. The hypothesis of combined parity (CP) conservation in weak interactions calls for the verification of at least three parameters in experiments of the second and third groups, which are quadratic or linear in the deviations. An analysis of the experiments depends strongly on additional theoretical assumptions and yields in the best case

$$\varphi_V - \psi_V = 0 \pm 48°, \quad \varphi_A - \psi_A = 0 \pm 13°,$$
$$\varphi_V - \varphi_A = \pi + 31.5°, \quad \psi_V - \psi_A = \pi + 31.5°.$$

The existing estimates thus do not make it possible to verify the violation of the CP parity and require considerable improvement. Such an improvement can be reached, first, by organizing new types of experiments on triple correlations, for example j_1ej_2 correlation in analog or mirror β transitions.

It is also of interest to improve the experiments on the polarization of the electrons in 0^+–0^+ or mirror transitions, and also searches for new experiments that are linear in the parameter $\varphi - \psi$—the relative phase shift of the constants C_k and C'_k of the same variant of the interaction.

6. At the present time in β decay there has actually been realized only a limited complete experiment with an additional assumption concerning the V, A variant of the interaction, which depends on seven parameters: four moduli of the constants C_V, C'_V, C_A, and C'_A, and

*A similar situation is noted in [71] for μ-e decay, where in the limited variant of the V, A theory with a two-component neutrino ($\varphi_A = \psi_A$, $\varphi_V = \psi_V$) an estimate $|\varphi_A - \varphi_A| \leq 16°$ was obtained.

three of their relative phase shifts and also a limited complete experiment with assumed CP conservation, depending on eight real parameters C_k and C'_k. The realization of the classical complete experiment would require not only refinement of all the already realized experiments, but also an organization of new types of experiments, for example σj, $\sigma\nu$, $j_1 e j_2$, and σje.

In this sense, the general situation with the realization of the complete experiment in β decay turns out to be analogous to the situation in $\mu - e$ decay, where, according to the analysis of I. I. Gurevich and B. A. Nikol'skii, it is possible at present to realize only a limited complete experiment, for example of the V, A type.[71] The realization of the complete experiment in the $\mu - e$ decay also calls for organization of new types of experiments—with detection of the decay neutrinos.

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