TYPES OF INTERACTION IN BETA DECAY. THE DECAY OF Na^{24}

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The electron-neutrino correlation in the β decay of Na^{24} was investigated using nuclear resonance scattering of the Mg^{24} γ rays that accompany the β decay of Na^{24}. A gaseous Na^{24} source was employed. The most probable value of the correlation constant was found to be $\lambda = -0.23 \pm 0.19$. It follows from these data that in the β decay of Na^{24} only the axial vector interaction should be involved, which corresponds to $\lambda = -1/3$.

INTRODUCTION

AN important problem in the theory of weak interactions is the determination of the type of interaction in β^- decay. The discovery of parity nonconservation has increased the number of experiments which involve the interaction constants. Nevertheless at this time the question of determining the interaction types has not been solved.

Prior to the discovery of parity nonconservation the established belief was that β decay is due to tensor and scalar covariants in the interaction Hamiltonian. This view was based on the electron-neutrino correlation experiments in He^6 (references 1, 2) and Ne^{19} (references 3, 4) as well as on the absence of Fierz interferences in the experimental determinations of β-decay spectrum shapes.

However, as was shown by Lee and Yang,[5] the absence of Fierz terms does not prove that only one of the covariants is present in transitions governed by Fermi selection rules (scalar S and vector V covariants). Neither can it be concluded that only one of the axial vector or tensor covariants, which are responsible for β decays governed by Gamow-Teller selection rules, is present.

The absence of Fierz terms requires only that the following expression vanish*

$$\mathrm{Re}\{(C_V C_S^* + C_V' C_S'^*)\,|M_F|^2 + (C_T C_A^* + C_T' C_A'^*)\,|M_{GT}|^2\}, \quad (1)$$

which will happen if $C_S = -C_S'$, $C_V = C_V'$, $C_T = -C_T'$, $C_A = C_A'$. This follows from data on polarization of β electrons.[6] Furthermore, the angular correlation between the electron and neutrino in Ar^{35} was measured recently.[7] There are reasons to believe that the β^+ decay of Ar^{35} is mainly due to the Fermi type of interaction.

As a result of this experiment the correlation constant was found to be $\lambda = 0.70 \pm 0.17$, which means a substantial contribution from the vector interaction.

The results of the Ar^{35} experiment can be satisfactorily explained by a combination of either vector and axial vector, or vector and tensor interactions. Thus a contradiction resulted, and the necessity arose for further measurements of the interaction constants responsible for β decay.

1. EXPERIMENTAL PROCEDURE

In all experiments[1-4,7] mentioned previously the electron-neutrino correlation was determined from observations of the nuclear recoil. One of the authors[8] has proposed a different method for determining the correlation, utilizing the nuclear-resonance scattering effect of the γ-rays that accompany β decay. This method consists in the following:

Suppose that the radioactive substance has a decay scheme as shown in Fig. 1, i.e., the β decay is followed by two γ-rays in cascade, with energies $E_{\gamma 1}$ and $E_{\gamma 2}$.

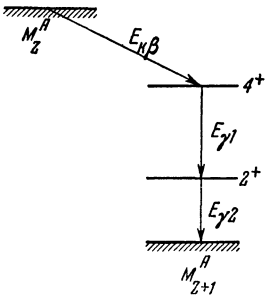

FIG. 1. Decay scheme.

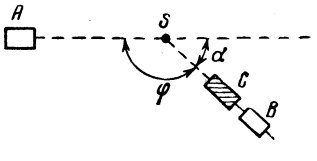

FIG. 2. Diagram of the setup.

In the experimental setup, shown schematically in Fig. 2, the detector A registers γ-rays of energy $E_{\gamma 1}$ and the detector B registers γ-rays of energy $E_{\gamma 2}$. A scatterer C is placed in the path of the γ-rays of energy $E_{\gamma 2}$, (corresponding to transitions to the ground state), consisting

*We use the notation of reference 5.

of M^{A}_{Z+1} nuclei resulting from the β^- decay of the M^{A}_{Z} nuclei of the source S. The detectors A and B are required to register in coincidence. The absorption of the γ-rays of energy $E_{\gamma 2}$ in the scatterer C is measured as a function of the angle φ between the directions of the observed γ-rays $E_{\gamma 1}$ and $E_{\gamma 2}$.

Beside the usual absorption of γ-rays due to the photo-effect, Compton effect, and pair production there is the additional absorption in C due to resonance scattering of γ-rays by the nuclei of the scatterer.

As was shown in reference 8, the average resonance scattering cross section depends not only on the width Γ of the level in which the scattering takes place but also on the quantity λ which characterizes the interaction type in β decay. The average cross section equals

$$\bar{\sigma} = \sigma_0 \frac{\pi}{4} \frac{\Gamma}{E_{\gamma 2}} \int_{p_0}^{p_{N\max}} \frac{m_1 c}{p_N} f(p_N)\, dp_N, \qquad (2)$$

where

$$p_0 = \left| \frac{E_{\gamma 1}}{c} \cos\alpha - \frac{E_{\gamma 2}}{c} \right|, \qquad \sigma_0 = 2\pi\lambda^2 (2j+1)/(2i+1), \qquad (3)$$

λ is the wavelength of the γ-ray of energy $E_{\gamma 2}$, divided by 2π; j is the spin of the excited level; i is the spin of the ground level; Γ is the natural width of the excited level; m_1 is the nuclear mass; $p_{N\max}$ is the maximum momentum that the nucleus can receive in the process of β decay; $\alpha = \pi - \varphi$ (φ is the angle between the directions of emission of the two γ-rays); $f(p_N)$ is the distribution function of the recoil nuclei. This function $f(p_N)$ is normalized according to

$$\int_0^{p_{N\max}} f(p_N)\, dp_N = 1 \qquad (4)$$

and depends on the correlation constant λ of the β decay. In deriving Eq. (2) it was assumed that the recoil nuclei are free, i.e., that their motion during the lifetime of the excited states is not perturbed by collisions with other nuclei.

It was further assumed that no correlation exists between the directions of emission of the β- and γ-rays.

A numerical calculation was performed of the cross section for Na^{24} whose decay scheme is similar to that pictured in Fig. 1.

The energies of the β- and γ-rays were taken as follows:

$$E_{k\beta} = 1.4 \text{ Mev}, \quad E_{\gamma 1} = 2.76 \text{ Mev}, \quad E_{\gamma 2} = 1.38 \text{ Mev}.$$

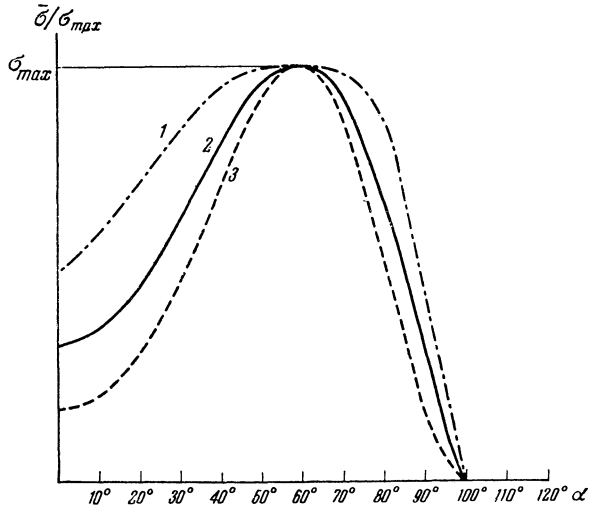

FIG. 3. Dependence of the cross section $\bar{\sigma}_r$ on the angle α: the curve labelled 1 corresponds to $\lambda = +1$, 2 – to $\lambda = 0$, 3 – to $\lambda = -1$.

The maximum of the cross section occurs for

$$\cos\alpha = E_{\gamma 2}/E_{\gamma 1}, \qquad (5)$$

i.e., for $\alpha = 60°$.

The dependence of the calculated cross section on the angle α is shown in Fig. 3 for the three values $\lambda = -1, 0, +1$. All curves are normalized to the same value at $\bar{\sigma} = \sigma_{max}$. As can be seen, the angular dependence of the cross section varies noticeably with the values of the correlation constant λ.

2. DESCRIPTION OF THE SETUP AND EXPERIMENT

In this work the experiments on electron-neutrino correlation were performed with a gaseous source of Na^{24}.

The experimental setup, the block diagram of which is shown in Fig. 4, is essentially similar to the setup described previously.[9]

As is well known, metallic sodium in the gaseous state is monoatomic, consequently molecular binding did not have to be considered. To create a source of sufficient intensity it was necessary to keep it at a temperature of ~900°C, which corresponds to a vapor pressure of metallic sodium in a hermetic container of stainless steel of the order of one atmosphere. At this pressure the time between collisions should be longer than 10^{-11} sec.

Preliminary measurements[9] performed with a liquid-sodium source had shown that the lifetime of the level $E_{\gamma 2} = 1.38$ Mev was less than 2×10^{-12} sec. Therefore, in the gaseous source used, the recoil nuclei may be treated as free. Part of the metallic sodium remains in the liquid phase when the source is heated and the γ-rays from

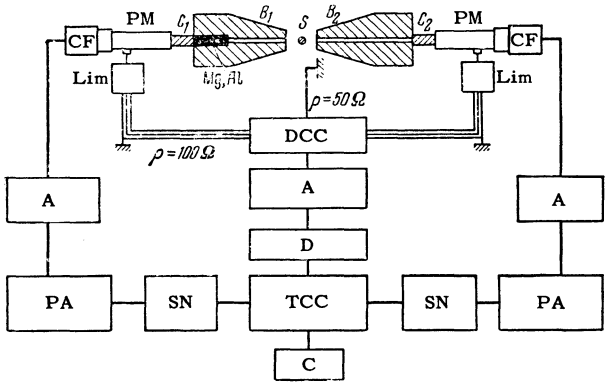

FIG. 4. Block diagram of the setup. S – γ-ray source, B_1 and B_2 – lead collimators, C_1 and C_2 – tolan crystals, PM – photomultiplier FEU-33, CF – cathode follower, Lim – limiters, DCC – double coincidence circuit ($2\tau = 2 \times 10^{-9}$ sec), A – amplifiers (K = 200, f = 3 Mc/sec), D – discriminator and tuning device to 10^{-6} sec, FU – shaping network for 10^{-6} sec, TCC – triple coincidence circuit ($2\tau = 10^{-6}$ sec), Ch – counter, PA – single channel pulse height analyzer.

the liquid phase were kept at < 1% of the γ-rays from the gaseous phase by blocking the lower part of the container with a lead shield.

The γ-rays were registered by scintillation counters consisting of FEU-33 photomultipliers and tolane crystals. The angle $\alpha = \pi - \varphi$ was varied by rotating one of the detectors around the axis of the source.

The pulse from each detector was fed into a "fast" coincidence circuit with a resolving time of 2×10^{-9} sec and, simultaneously, into a single-channel pulse-height analyzer so tuned as to pass only pulses from γ-rays of a single energy. From there the pulses were fed into a "slow" coincidence circuit of resolving time 10^{-6} sec and then were registered.

A scatterer composed of magnesium nuclei was placed in the path of the γ-rays headed for the counter registering γ-rays of energy $E_{\gamma 2} = 1.38$ Mev. Then α was varied from 0° to 100° and the additional absorption of γ-rays in magnesium due to resonant scattering was observed. In the aluminum scatterer no such resonant scattering should appear.

The magnesium scatterer was 80 mm long; the aluminum scatterer's length was so adjusted as to give the same absorption as magnesium in the absence of resonant scattering, i.e., at angles $\alpha >$ 100°.

3. EXPERIMENTAL RESULTS AND ANALYSIS OF THE MEASUREMENTS

To exclude from the calculations the usual absorption of γ-rays due to the photoeffect, Compton effect, and pair production the ratio of the transparency of the magnesium and aluminum samples

$$A_k = \frac{T_{Mg}}{T_{Al}} = \frac{N_{Mg}}{N} \Big/ \frac{N_{Al}}{N} = \frac{N_{Mg}}{N_{Al}} \qquad (6)$$

was measured for various angles α.

Here N_{Mg} is the number of true coincidences with the resonant scattering magnesium in place, N_{Al} is the number of true coincidences with the aluminum scatterer, N is the number of true coincidences without any scatterer, T_{Mg} and T_{Al} are the transparencies of the magnesium and aluminum absorbers.

However

$$T_{Mg} = T_{Mg,a}\, T_{Mg,r}; \quad T_{Al} = T_{Al,a}, \qquad (7)$$

where T_a is the transparency of the sample due to the usual absorption and scattering of γ-rays and T_r is the transparency due to the resonant scattering of γ-rays. Thus

$$\frac{N_{Mg}}{N_{Al}}(\alpha) = \frac{T_{Mg,a}}{T_{Al,a}} T_{Mg,r}(\alpha). \qquad (8)$$

The ratio $T_{Mg,a}/T_{Al,a}$ was determined experimentally without coincidences and found to be 1.0006 ± 0.0002, i.e., unity for all practical purposes. Therefore one may assume

$$T_{Mg,r}(\alpha) \approx N_{Mg}(\alpha) / N_{Al}. \qquad (9)$$

The experimentally determined absorption due to resonant scattering is shown in Table I for a few values of α.

TABLE I

α, °	$1-T_{Mg,r}(\alpha)$	α, °	$1-T_{Mg,r}(\alpha)$
0	0.011±0,004	40	0.036±0.007
10	0.015±0.006	60	0.052±0.004
15	0.017±0.004	85	0.026±0.009
30	0.032±0.005	120	0.001±0.004

Since the experimentally-determined transparency is near unity, one may write

$$1 - T_{Mg,r}(\alpha) = n_{Mg} \bar{\sigma}_{Mg,r}\, d_{Mg}, \qquad (10)$$

where $\bar{\sigma}_{Mg,r}$ is the resonant scattering cross section given by Eq. (2), n_{Mg} is the number of nuclei of the Mg^{24} isotope per unit volume of the scatterer, and d_{Mg} is the thickness of the magnesium scatterer.

From expression (10) we can calculate the maximum resonant scattering cross section. It is given by

$$\sigma_{max} = (1.93 \pm 0.15) \cdot 10^{-25}\ \text{cm}^2. \qquad (11)$$

If we denote by

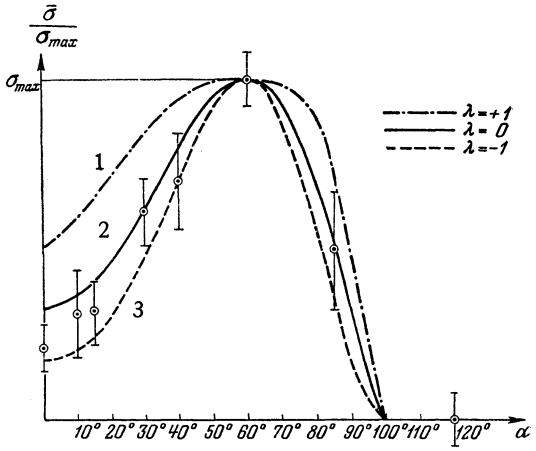

FIG. 5. Experimental results. 1 corresponds to $\lambda = +1$, 2 to $\lambda = 0$, 3 to $\lambda = -1$.

$$\overline{D} = \frac{\bar{\sigma}_{\mathrm{Mg},r}(\alpha)}{\sigma_{\max}(60°)} = \frac{1 - T_{\mathrm{Mg},r}(\alpha)}{1 - T_{\mathrm{Mg},r}(60°)} \qquad (12)$$

the quantities determined experimentally, and by D the ones calculated theoretically, we can obtain from Table I the ratios of the resonant scattering cross section to the maximum cross section for various angles α. The results are shown in Table II and plotted in Fig. 5.

TABLE II

α,°	$\overline{D}=\frac{\bar{\sigma}_{\mathrm{Mg},r}(\alpha)}{\sigma_{\max}(60°)}$	α, °	$\overline{D}=\frac{\bar{\sigma}_{\mathrm{Mg},r}(\alpha)}{\sigma_{\max}(60°)}$
0	0.21 ± 0.07	40	0.69 ± 0.14
10	0.29 ± 0.12	60	1.00
15	0.32 ± 0.09	85	0.50 ± 0.18
30	0.62 ± 0.10	120	0.00 ± 0.07

We included the root-mean-square errors in Table II and in Fig. 5. For each point the error $x = \overline{D} - D$, corresponding to a definite value of λ from +1 to −1, is characterized by the normal distribution law.

By multiplying the probabilities of all points referring to the same value of λ, we find the most probable distribution of $x = \overline{D} - D$ as a function of λ with the result

$$\lambda = -0.23 \pm 0.19. \qquad (13)$$

The error in measurement comes from the distribution of probabilities for λ, which lies in the indicated region with a probability of 67%.

From (2) and (11) we can determine the width, and therefore the lifetime of the excited level at 1.38 Mev. With $\lambda = -0.23$ we find

$$\tau = (2.6 \pm 0.2) \cdot 10^{-13} \text{ sec}. \qquad (14)$$

Measurements were performed with a solid Na^{24} source. The technique used was the same as for the gaseous source. The results of the measurements are compiled in Table III.

TABLE III

α,°	$1-T_{\mathrm{Mg},r}(\alpha)$
100	0.003 ± 0.008
90	0.000 ± 0.008
65	0.007 ± 0.008
62	0.010 ± 0.008
60	0.024 ± 0.006

TABLE IV

α,°	$1-T_{\mathrm{Mg},r}(\alpha)$
0	0.001 ± 0.004
40	0.000 ± 0.005
50	0.003 ± 0.005
60	0.001 ± 0.004
100	0.001 ± 0.004

In this experiment, as in the liquid source experiment,[9] additional resonant absorption was observed only in a narrow region near the angle $\alpha = 60°$.

The interpretation of the results for the solid source is analogous to that expounded in the paper dealing with the liquid source.[9]

The presence of the resonant scattering effect in a solid source indicates that the lifetime of the excited state with $E_{\gamma_2} = 1.38$ Mev is comparable to the time between collisions of the recoil nucleus in the solid (of the order 10^{-13} sec), which confirms the result (14).

In order to be assured that the measured resonant scattering effect was not due to some asymmetry in the apparatus we performed a control experiment using a Co^{60} source in place of Na^{24}. The decay scheme of Co^{60} is similar to that of Na^{24} except that the emitted γ-rays have energies $E_{\gamma_1} = 1.17$ Mev and $E_{\gamma_2} = 1.33$ Mev. The results of this experiment are shown in Table IV.

It is seen that there is no dependence of the absorption on the angle α, proving the absence of asymmetries in the apparatus.

4. DISCUSSION OF RESULTS AND CONCLUSIONS

In the process of β^- decay the Na^{24} nucleus of spin and parity 4^+ is transformed into the 4^+ level of the Mg^{24} nucleus. Thus, this is a $j \rightarrow j$ transition allowed by both the Fermi ($\Delta j = 0$, no) and the Gamow-Teller ($\Delta j = 0, \pm 1$, no, $0 \rightarrow 0$) selection rules.

However from a consideration of the isotopic spin T and the experiments on circular polarization of Na^{24} γ-rays* it will follow that the Fermi matrix element should be much smaller than the Gamow-Teller matrix element.

Experiments on the circular polarization of γ-rays from a number of emitters, including Na^{24}, are described in references 10 and 11. It is found that the polarization coefficient α is small, which allows the conclusion to be drawn that the β decay of Na^{24} is due to only Gamow-Teller or only Fermi interaction type. If both types were present

*We are grateful to A. I. Alikhanov, V. A. Liubimov, and K. A. Ter-Martirosian for calling these possibilities to our attention.

simultaneously, the interference term would increase greatly and α would be large.

In view of the importance of the question, one more experiment[12] on the circular polarization of Na^{24} γ-rays was performed.

The circular polarization of γ-rays was detected by using the method of transmission of γ-rays through a ferromagnetic alloy whose thickness was several radiation lengths for 2.76-Mev γ-rays. As result the sensitivity was somewhat higher than in other experiments[10,11] where the circular polarization was deduced from the dependence of the intensity of the scattered γ-rays on the direction of the magnetic field. The results of this work again indicate no significant interference term within the limits of experimental errors.

Consider next the isotopic spin T. Fermi type transitions are governed by the selection rule $\Delta T = 0$, Gamow-Teller type by $\Delta T = 0, \pm 1$.

The ground state of Na^{24} has $T_\xi = -1$. If the rule is invoked that the ground state has the smallest possible isotopic spin, the isotopic spin of Na^{24} ground state is expected to be $T = 1$ and of Mg^{24} ground state $T = 0$.

It is known that excited states of Mg^{24} with $T = 1$ appear only for excitation energies ~ 10 Mev; all lower levels have $T = 0$.

It has been shown[13] that the β^+ transition $Al^{24} \rightarrow Mg^{24}$ to the 9.35 Mev excited state is a super allowed ($\log ft = 3.35$) $\Delta j = 0$, $\Delta T = 0$, $T = 1$, $A = 4n$ type transition; consequently the 9.35-Mev level has $T = 1$.

Wilkinson calculated the first $T = 1$ level of Mg^{24}, excluding the Coulomb term from the binding energy, and found for its energy 9.45 Mev, which is in close agreement with experiment. Therefore the 4.14-Mev energy level will have isotopic spin $T = 0$. If that is the case, Fermi type transition can only amount to a small admixture to the Gamow-Teller type due to the inexactness of isotopic spin quantum numbers.

It may therefore be taken as established that the β decay of Na^{24} is due predominantly to the Gamow-Teller interaction type, i.e.,

$$|M_F|^2 \ll |M_{GT}|^2.$$

It then follows from the present work that in β-decay governed by Gamow-Teller selection rules the interaction type is axial vector, corresponding to the correlation constant $\lambda = -0.33$.

Taking into account the errors in the present experiment, the conclusion may be drawn that the tensor interaction is not the sole one, as would follow from the He^6 experiment,[2] but that it is present only as an admixture to the basic axial vector interaction.

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