PHYSICAL REVIEW C VOLUME 12, NUMBER 6 DECEMBER 1975

Second class interactions and the electron-neutrino correlation in nuclear beta decay*

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(Received 12 August 1975)

The electron-neutrino correlation for ^{6}He β decay is analyzed for possible second class effects. Existing data are found to be consistent with there being no second class form factor but the conclusion is somewhat model dependent. The $e\nu$ correlation for the ^{19}Ne decay is considered and it is shown that an improved measurement, comparable to that achieved for ^{6}He, would provide an unambiguous result concerning second class terms.

[RADIOACTIVITY ^{6}He; deduced second class form factor from the $e\nu$ angular correlation.]

I. INTRODUCTION

Recently there has been a new interest in the possible role of second class interactions[1] in nuclear β decay. On the negative side, there seems to be no evidence for second class effects in the Ft asymmetries of mirror Gamow-Teller decays.[2] Angular correlation measurements on the $A=12$ (Ref. 3) and $A=19$ (Ref. 4) systems, on the other hand, favor relatively large second class effects, while in related measurements on the $A=8$ nuclei[5] no second class effects are seen. In this article we comment on what may be learned from existing data on the $e\nu$ correlation.

The electron-neutrino correlation has the virtue, in common with other angular correlation measurements, of being relatively free of Coulomb effects, a source of difficulty in the analysis of Ft asymmetries. The $e\nu$ correlation is unique among correlations, however, in that its average over the β energy spectrum depends only on the tensor form factor of the axial vector interaction. This is in contrast to the other angular correlations cited above which always measure a combination of the weak magnetism and second class tensor form factors. For those correlations it is necessary to specify the weak magnetism form factor before anything can be deduced about the second class term. The virtual absence of Coulomb effects and the unique sensitivity to the tensor form factor make the $e\nu$ correlation particularly worthwhile as a probe of second class effects.

In the following we first examine the $e\nu$ correlation for the decay $^6\text{He}\rightarrow{}^6\text{Li}+e^-+\bar{\nu}$. This is one of the few cases already measured with sufficient accuracy to detect the tensor form factor. We then consider the $e\nu$ correlation for the ^{19}Ne decay and suggest that an improved measurement can be made to distinguish between a bona-fide second class effect and a violation of conserved vector current (CVC) theory, two possible explanations for the effect reported in Ref. 4.

II. $e\nu$ CORRELATION FOR ^{6}He DECAY

The ^{6}He decay is an allowed pure Gamow-Teller transition with the isospin-spin sequence $T=1, 0^+\rightarrow T=0, 1^+$. The branching ratio to the ground state of ^{6}Li is 100% and the half-life and kinetic end-point energy are 808.1 ± 2.0 msec (Ref. 6) and 3509.8 ± 3.7 keV (Ref. 7), respectively. With $Ft=815.7\pm4.2$ sec (Ref. 6) the decay is the fastest of the superallowed Gamow-Teller transitions, a property which has a natural explanation in the approximate validity of LS coupling.

In the "elementary particle" description of nuclear β decay, there are just three nuclear form factors needed to describe this transition to first order in recoil. Following the notation of Holstein and Treiman,[8] these are denoted by c, b, and d, corresponding to the Gamow-Teller, the weak magnetism, and the tensor form factors, respectively. It is important to understand how the second class interaction might manifest itself in these form factors. First, we note that the CVC theory rules out a second class vector interaction and thus all second class effects are restricted to the form factors of the axial-vector interaction, that is, c and d. Secondly, for $\Delta T=1$ transitions, such as the ^{6}He decay, we can expect to have first and second class contributions to both c and d, but, as inspection of the correlation formulas will reveal, it is only the second class part of d which we might hope to detect in a measurement of the angular correlation.

According to Holstein and Treiman, the decay rate for unpolarized nuclei, with electron and neutrino observed having relative angle θ, is given by the expression

$$d\lambda=\frac{G^2\cos^2\theta_c}{(2\pi)^5}F(Z,E)pE(E_0-E)^2\left[f_1(E)+f_2(E)\frac{p}{E}\cos\theta+f_3(E)\left(\frac{p}{E}\right)^2(\cos^2\theta-\tfrac{1}{3})\right]dEd\Omega_e d\Omega_\nu\ . \tag{1}$$

Here p and E refer to the electron momentum and energy, respectively, and the spectral functions $f_i(E)$ for Gamow-Teller decay and to first order in E/M ($M\sim$nuclear mass) are given by the following:

$$f_1(E)=c^2-\frac{2}{3}\frac{E_0}{M}(c^2+cb+cd)+\frac{2}{3}\frac{E}{M}(5c^2+2cb)-\frac{m_e{}^2}{3ME}[2c^2+c(d+2b)]\ , \tag{2}$$

$$f_2(E)=-\tfrac{1}{3}c^2+\frac{2}{3}\frac{E_0}{M}(c^2+cb+cd)-\frac{4}{3}\frac{E}{M}(3c^2+cb)\ , \tag{3}$$

$$f_3(E)=\frac{E}{M}c^2\ . \tag{4}$$

Both c and b can be specified independent of the $e\nu$ correlation data. For the c term we have the total rate of decay, or Ft value, which is related to the energy average of $f_1(E)$ by the expression

$$\langle f_1(E)\rangle=2\times Ft(\text{Fermi})/Ft\ . \tag{5}$$

Neglecting the recoil terms in f_1 and with $Ft(\text{Fermi})=3082.4\pm2.1$ sec (Ref. 9) we obtain

$$c\cong\left[\frac{2\times Ft(\text{Fermi})}{Ft}\right]^{1/2}=2.75\ . \tag{6}$$

This should be accurate to 1% because of the uncertainty in the recoil terms, but this is more than sufficient for our analysis of the ^{6}He decay. In the subsequent discussion of the ^{19}Ne decay we shall have to consider all recoil terms, however [see Eq. (25)].

The CVC theory relates the weak magnetism b term to the $M1$ matrix element for the analog transition in ^{6}Li (3562 keV$\rightarrow$ground state). Expressing the CVC relationship in terms of the $M1$ radiative width, Γ_{M1}, we have, with $\alpha\simeq1/137.04$, the expression

$$\Gamma_{M1}=\tfrac{1}{6}\alpha E_\gamma{}^3b^2/M^2\ . \tag{7}$$

The experimental radiative width is $\Gamma_{M1}=8.41\pm0.25$ eV (Ref. 10) and with $E_\gamma=3562\pm5$ keV we obtain for b the value

$$b=69.0\pm1.0\ . \tag{8}$$

We will use this value in the subsequent analysis, but as we shall see, the b term only weakly affects the value of d obtained from the data and to a first approximation it can be neglected altogether.

We now take up a discussion of the d term and in particular explore what we might hope to learn about second class interactions from a measurement of d. This is an important question for $\Delta T=1$ transitions because for these, d is made up of first and second class components and a measurement of d in itself implies nothing about second class effects. If d could be measured for mirror electron-positron decays it would be possible to separate first and second class parts by the relationship

$$d(e^\mp)=d^{\text{I}}\pm d^{\text{II}}\ . \tag{9}$$

Unfortunately, this type of separation is impossible for the mass-6 system since ^{6}Be, the mirror of ^{6}He, is an unbound system. What we will do is less satisfactory; we shall calculate d^{I} with nuclear wave functions. Given imperfect wave functions, this procedure in general would seem to be somewhat uncertain. What gives us optimism to pursue this line for the ^{6}He decay, however, is that d^{I} is approximately zero because of the special structure of the ^{6}He-^{6}Li states involved. This is a simple result and can be seen as follows. In the impulse approximation, the form factors d^{I} and d^{II} are given in terms of matrix elements of one-body operators by the following expressions[11]

$$d^{\text{I}}=Ag_A\left\langle{}^6\text{Li}\left\|\sum_{k=1}^{A}\tau_k^+ i\vec{\sigma}_k\times\vec{1}_k\right\|{}^6\text{He}\right\rangle\ , \tag{10}$$

$$d^{\text{II}}=Ag_{\text{II}}\left\langle{}^6\text{Li}\left\|\sum_{k=1}^{A}\tau_k^+\vec{\sigma}_k\right\|{}^6\text{He}\right\rangle\ . \tag{11}$$

Here A is the mass number, $g_A\cong1.25$ is the axial-vector coupling constant and g_{II} is a second class coupling constant. In a simple shell model the mass-6 states involve two valence nucleons in the p shell outside an inert ^{4}He core. In LS coupling the ^{6}He and ^{6}Li states are denoted as $^1S_0$ and $^3S_1$, respectively. According to this description the β decay involves the transition $L=0$ to $L=0$; this implies that d^{I} is zero because the operator $\vec{\sigma}\times\vec{1}$ cannot couple states with $L=0$. On the other hand d^{II}, as given, is not hindered by this selection rule.

The simple S structure of the mass-6 states explains the superallowed character of the β decay and also explains why the electric quadrupole moment of ^{6}Li is so small; $Q=-8\times10^{-4}$ b, the smallest quadrupole moment known. We can expect more realistic wave functions to produce a nonzero d^{I}, bit since d^{I} is small we do not need to demand much of the wave functions to obtain a useful value. Barker's wave functions, for example, are the following[12]

$$|{}^6\text{He}\rangle = 0.934|{}^{31}S_0\rangle - 0.358|{}^{33}P_0\rangle \ , \tag{12}$$

$$|{}^6\text{Li}\rangle = 0.992|{}^{13}S_1\rangle + 0.120|{}^{11}P_1\rangle - 0.028|{}^{13}D_1\rangle \ . \tag{13}$$

These are obtained by adjusting the Hamiltonian to fit the energy levels and support the assertion that the dominant components are the S states. Barker calculates, for the analog β and γ transitions, the values $ft = 813$ sec and $\Gamma_\gamma = 8.4$ eV in very good agreement with the experimental values of 815.7 ±4.2 sec and 8.41 ±0.25 eV, respectively. Using these wave functions we calculate for d^{I} the value

$$d^{\text{I}} = 2.4 \tag{14}$$

or

$$\frac{d^{\text{I}}}{Ac} = 0.12 \ . \tag{15}$$

We now proceed to analyze the $e\nu$ correlation data and begin by casting the correlation formula in a form consistent with that used in quoting experimental results. Accordingly we write

$$W(\theta) = 1 + A\,\frac{v}{c}\cos\theta + B\left(\frac{v}{c}\right)^2(\cos^2\theta - \tfrac{1}{3}) \ . \tag{16}$$

The correlation parameters, specified by $A = f_2/f_1$ and $B = f_3/f_1$, are given to first order in E/M by the expression

$$A = -\frac{1}{3} + \frac{4}{9}\frac{E_0}{M}\frac{d}{c} + \frac{4}{9}\frac{E_0 - 2E}{M}\frac{b}{c} + \frac{2}{9}\frac{2E_0 - 13E}{M} + \frac{16}{81}\,\alpha ZR(E - E_0) - \frac{\alpha Z}{\sqrt{6}\,MR}\left(\frac{2b}{c} + \frac{d}{c}\right) , \tag{17}$$

$$B = +E/M \ . \tag{18}$$

We have included the recoil terms of f_1 as well as those of f_2 and f_3. In addition we have added to Eqs. (2) and (3) the Coulomb corrections proportional to αZR and $\alpha Z/MR$ as given in Ref. 11, to obtain the complete expression given in Eq. (17). We note that the value $A = -\frac{1}{3}$ is expected for a pure Gamow-Teller decay in the allowed approximation; recoil order corrections alter this simple result and introduce the $\cos^2\theta$ dependence.

To interpret the data it is important to understand how the $e\nu$ correlation is measured. The method, which is the basis of the experiment we quote, consists of measuring the *energy spectrum* of the recoil $^6\text{Li}^+$ ion. In particular, the recoil energy spectrum is measured without detecting the β particle. Clearly, the recoil spectrum is sensitive to the $e\nu$ correlation; if the electron and neutrino have a tendency to be emitted in the same direction ($A > 0$) the ion spectrum will have an excess of high energy events; with $A < 0$ there is an abundance of low energy ions. For our purpose the important feature of the method is that the β particle is not detected. This means that one obtains an average of the $e\nu$ correlation over the electron energy spectrum. Thus it is the energy average of the correlation parameter which is measured; this is given with $\langle E\rangle \approx \frac{1}{2}E_0$ by the expression

$$\langle A\rangle = -\frac{1}{3} + \left(\frac{4}{9}\frac{d}{c} - 1\right)\frac{E_0}{M} - \frac{8}{81}\,\alpha ZRE_0 - \frac{\alpha Z}{\sqrt{6}\,MR}\left(\frac{2b}{c} + \frac{d}{c}\right) . \tag{19}$$

Except for the small Coulomb correction term we see that the energy average $e\nu$ correlation is independent of the weak magnetism b term, apparently a unique result for angular correlations since generally b and d are inseparable. The ion spectrum is fitted assuming an $e\nu$ correlation of the form $W(\theta) \simeq 1 + \text{constant} \times \cos\theta$. That is, the energy dependence of A and the $\cos^2\theta$ dependence are neglected. This procedure yields for the constant, designated as "$\langle A\rangle$" to emphasize the assumptions, the value[13]

$$\langle A\rangle = -0.3343 \pm 0.0030 \ . \tag{20}$$

At the present level of accuracy it is safe to ignore the $\cos^2\theta$ term since this contributes to $W(\theta)$ at at most an amount $\sim 10^{-4}$, well below the error in A. On the other hand, the energy dependence of A may or may not be important. With the values of b and c given above we expect $dA/dE \approx -[8(b/c) + 26]/(919) = -0.44\%\ \text{MeV}^{-1}$. That is, A changes by -0.015 over the β spectrum; this is a 4.6% variation in A, a big effect considering that A is measured with a relative error of 0.9%. To a first approximation it is only the energy average which affects the ion spectrum. The energy dependence should have no effect because the β energy spectrum is approximately symmetric about its midpoint and because the energy dependence of A is essentially linear. A proper reanalysis of the ion energy spectrum should be made but for the present, and for the reasons just mentioned, it may not be too far off the mark to interpret the experimental result as given in Eq. (20) in terms of the energy average, given by Eq. (19). We proceed on this assumption but at the same time we emphasize that, for a more definite result, the ion energy spectrum should be reanalyzed allowing for the energy dependence of the correlation parameter and for the $\cos^2\theta$ term, as well.

Using Eq. (19) and the experimental value of Eq. (20) we calculate

$$\left(\frac{d}{c}\right)_{\text{exp}} = +12 \pm 9 \tag{21}$$

or

$$\left(\frac{d}{Ac}\right)_{\text{exp}} = +2.0 \pm 1.5 \ . \tag{22}$$

It is interesting to note that the b term, specified by CVC, contributes 3×10^{-3} to $\langle A\rangle$, a small but nonnegligible amount. Because of the Coulomb corrections we are apparently still slightly dependent on the CVC prediction of the b term.

We observe that the data, as presently analyzed, are more or less consistent with $d=0$. It is useful to compare the value $d/Ac = +2.0 \pm 1.5$ with the CVC weak magnetism term $b/Ac = +4.18$, calculated with the values of Eqs. (6) and (8). The ^{6}He result is very interesting because the β-spin angular correlations on the $A=12$ and $A=19$ systems favor a second class d term with $d^{\mathrm{II}} \approx -b$ and $d^{\mathrm{II}} \approx -1.7$ b, respectively. On purely statistical grounds, the ^{6}He $e\nu$ correlation data argue strongly against the result $d \approx -b$, a 6 standard deviation effect. If we interpret our value of d as a measure of d^{II} we conclude that the data are definitely inconsistent with the value $d^{\mathrm{II}} \approx -b$. Aside from the possibility of faulty experimental methods we offer the following possible explanations:

(1) The energy dependence of the $e\nu$ correlation affects the determination of the energy average of the correlation parameter, and our determination of d for ^{6}He is incorrect. The ion energy spectrum should be reanalyzed.

(2) Other first class effects, not described by the impulse approximation, contribute to d^{I} and cancel d^{II}. Such first class terms have not been calculated but there is no reason, *a priori*, to expect that they will be small.

(3) The value of d^{II}/Ac varies from one nucleus to another. In particular, off-mass shell and meson-exchange effects,[15] not described by Eq. (11), conspire to enhance d^{II} for $A=12$ and $A=19$, but reduce d^{II} for $A=6$.

(4) The mass-12 and mass-19 experiments have not measured a second class term, but instead have detected a violation of CVC theory. This is difficult to understand since for $A=12$ the weak magnetism b term has been measured and found to agree with CVC.[14]

We conclude that the absence of any evidence in the ^{6}He $e\nu$ correlation for a second class d term with $d^{\mathrm{II}} \approx -b$ is difficult to explain. To improve on our present result there are obvious refinements in the analysis of the recoil spectrum and one can make an effort to fit all experiments into a framework of second class effects such as advocated by Rho and his co-workers (Ref. 15). It is quite likely that a clear picture of recoil effects will not emerge, however, until a variety of other experiments has been done. With this objective in mind we next propose a new measurement of the $e\nu$ correlation.

III. $e\nu$ CORRELATION FOR ^{19}Ne DECAY

We now turn to a discussion of the $e\nu$ correlation for the decay $^{19}\mathrm{Ne} \to {}^{19}\mathrm{F} + e^+ + \nu$. The $e\nu$ correlation has been measured[17] for this decay but the accuracy is inadequate for our purposes, and the point of our discussion is to propose a refined measurement. The choice of the ^{19}Ne decay was made in recognition of the feasibility of such a measurement but also the choice is based on the importance of having another independent, and complementary, measure of recoil effects on a system which already displays evidence for a second class interaction.[4]

To begin we observe that the ^{19}Ne decay is a superallowed mirror transition between members of a common isospin doublet. We must therefore include in our considerations a fourth form factor, denoted by a, which is equivalent to the Fermi matrix element. An important property of mirror decays is that all form factors are either first class or second class. By CVC the a and b form factors are first class, but in addition, and because of mirror symmetry, c and d are also definite, that is, first and second class, respectively. A nonzero value of d for the ^{19}Ne decay therefore definitely implies the existence of a second class weak interaction. We note for later use that the spin sequence is $\frac{1}{2}^+ \to \frac{1}{2}^+$, the kinetic end-point energy is 2216 ± 1 keV, and $Ft = 1733 \pm 4$.

For the ^{19}Ne decay the $e\nu$ correlation is again given by Eq. (16), but the correlation parameters now also include the Fermi form factor a. Keeping only the leading terms in $A = f_2/f_1$ and including the Coulomb corrections of order αZR and $\alpha Z/MR$ yields the following expression:

$$A(E) = \frac{a^2 - \frac{1}{3}c^2}{a^2 + c^2} - \frac{2}{3}\frac{E_0}{M}\frac{cb + cd}{a^2 + c^2} + \frac{4}{3}\frac{E}{M}\frac{3c^2 + cb}{a^2 + c^2} + \tfrac{2}{9}\,\alpha ZR\left[4E\,\frac{2a^2 - c^2}{a^2 + c^2} + E_0\right] - \frac{\alpha Z}{3\sqrt{6}\;MR}\,\frac{cd + cb}{a^2 + c^2} \ . \tag{23}$$

We consider again the energy-average of A. With $\langle E\rangle \approx \frac{1}{2}E_0$ we obtain

TABLE I. Form factors and the $e\nu$ correlation for ^{19}Ne β decay.

a	b	d	c	dA/dE	$\langle A\rangle$ [a]
1.00	−148.6	+250(100)	−1.609(3)	−0.0049 MeV^{-1}	+0.0495(10)
1.00	−148.6	0	−1.583(3)	−0.0049 MeV^{-1}	+0.0433(10)
1.00	0	0	−1.597(3)	≈ 0	+0.0428(10)
1.00	−280(60)	0	−1.573(3)	−0.0094 MeV^{-1}	+0.0429(10)

[a] The present experimental value is $\langle A\rangle = 0.00 \pm 0.06$ (Ref. 17).

$$\langle A\rangle = \frac{a^2 - \frac{1}{3}c^2}{a^2 + c^2} - \frac{2}{3}\frac{E_0}{M}\frac{cd}{a^2+c^2} - \frac{\alpha Z}{3\sqrt{6}\,MR}\frac{cd+cb}{a^2+c^2} + \frac{2}{9}\alpha Z R E_0\left[\frac{2(2a^2-c^2)}{a^2+c^2}+1\right] . \qquad (24)$$

To detect the d term from a measurement of $\langle A\rangle$ it is necessary first to specify the quantity $(a^2 - \frac{1}{3}c^2)/(a^2+c^2)$. The a term is just the overlap of the ^{19}Ne-^{19}F states and is unity except for a small Coulomb effect, estimated to reduce a by 0.02%.[16] The c term, on the other hand, must be taken from experiment and for this purpose we have two independent data, the Ft value and the β-spin asymmetry parameter.[4] Both of these quantities depend on all four form factors a, b, c, and d and though the dependence on b and d is weak, it is still important to include these terms in determining c. For example, the Ft value determines the energy average of $f_1(E)$ [see Eq. (5)] and writing this explicitly we have

$$\langle f_1\rangle = a^2 + c^2 + \frac{2}{3}\frac{E_0}{M}cd + \frac{\alpha Z}{\sqrt{6}\,MR}c(d+2b) = 2\times Ft(\text{Fermi})/Ft. \qquad (25)$$

With the Ft values given earlier we obtain

$$\langle f_1\rangle = 3.557 \pm 0.008 . \qquad (26)$$

In Table I we present the values of c calculated from $\langle f_1\rangle$ assuming $a=1$ and four sets of values of b and d. The value $b = -148.6$ is the CVC prediction[8] based on the experimental magnetic moments of the ^{19}Ne-^{19}F mirror pair

$$b_{\text{CVC}} = 19\sqrt{3}\,[\mu(^{19}\text{Ne}) - \mu(^{19}\text{F})] . \qquad (27)$$

The energy dependence of the electron-spin angular correlation has recently been measured[4] and some of the entries of Table I are based on the results of this measurement. To summarize the measurement we simply note that the angular distribution functions of positrons emitted from polarized nuclei is given by

$$W(\theta) = 1 + A'\hat{J}\cdot\vec{p}/E , \qquad (28)$$

where the energy dependence of this correlation parameter has the approximate form

$$dA'/dE \approx -\frac{2}{9M}\left[\frac{(\sqrt{3}\,a + 5c)b + (\sqrt{3}\,a - c)d}{a^2+c^2}\right]. \qquad (29)$$

The slope was measured to be $dA'/dE = (-0.65 \pm 15)\%\ \text{MeV}^{-1}$ and with $b = b_{\text{CVC}}$ this yields the value $d = +250 \pm 100$. These values of b and d are the first entry of Table I. Alternatively, assuming $d=0$ the slope yields $b = -280 \pm 60$, that is a substantial violation of the CVC prediction and this combination of b and d is the last entry of the table. The value of c is determined for each set of b and d by means of Eq. (25).

Also given in Table I are the energy average $e\nu$ correlation $\langle A\rangle$, calculated by Eq. (24), and the slope dA/dE, calculated with Eq. (23). Note that $\langle A\rangle$ is virtually independent of b but that between $d=0$ and $d=+250$ the quantity $\langle A\rangle$ changes by approximately 0.006. This is our main result. If the energy average of the electron neutrino correlation could be measured to an accuracy of 0.002 or better (the ^{6}He correlation is now known to 0.003), it would be possible to detect the postulated d term.

Note that the energy average gives nothing on b but that a measurement of the slope of the $e\nu$ correlation, dA/dE, would uniquely determine b and thus provide a test of CVC. The b term can also be determined, again free of d, by measuring the shape of the β energy spectrum, that is, the energy dependence of $f_1(E)$. A direct measurement of b would also be highly desirable to provide a complete set of measurements on the ^{19}Ne decay.

IV. SUMMARY

The $e\nu$ correlation provides a unique means to determine the tensor form factor d. For the ^{6}He decay d consists of first and second class parts but because of the peculiar nuclear structure the first class component is small. A preliminary analysis of the ^{6}He data yields no evidence for a second class d term, more specifically, the value $d^{II} \approx -b$ seems clearly to be inconsistent with the data. However, the analysis of the ion recoil spectrum should properly account for the energy dependence of the correlation parameter.

A prime candidate for a precise measurement of the $e\nu$ correlation is the ^{19}Ne decay. A measurement comparable in accuracy to the ^{6}He experiment could detect the second class d term which has been suggested to explain the correlation parameter for polarized ^{19}Ne decay (Ref. 4).

The assistance of N. Andrei on the calculation of d^I is gratefully acknowledged.

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*Work supported in part by the National Science Foundation under Grant No. MPS71-03445.
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