thermal and epithermal neutron capture was therefore negligible. It is reasonable to assume that the $Li^7(n,\gamma)$ reaction also gives a negligible contribution for 14-Mev neutrons, since at these energies particle emission from the compound nucleus is generally much favored over gamma emission. This assumption is borne out by the fact that even at the resonance peak of about 10 barns in the total cross section at 0.256-Mev neutron energy the $Li^7(n,\gamma)$ cross section is less than 0.1 millibarn.[10]

The authors are pleased to acknowledge the helpful interest of Dr. J. H. Coon and Dr. E. R. Graves throughout this investigation.

[10] Rose, Bayly, and Freeman, AERE, Harwell (private communication).

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The Beta-Decay Interaction*

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The recent identifications of two beta-decays as 0-to-0 transitions proves that the beta-decay interaction must contain a component obeying Fermi selection rules. Evidence is presented regarding the relative strengths of the Fermi- and Gamow-Teller interactions, and experiments are suggested to improve our knowledge of these strengths. It is pointed out that the He^6 *ft* value does *not* give significant information about the beta-decay interaction. An experiment is proposed to determine the nature (scalar or polar vector) of the Fermi interaction.

THERE are now two cases known of allowed and favored 0-to-0 transitions. One is a branch of the C^{10} decay;[1,2] the second is the decay of O^{14}.[1,3,4] Hence, the beta-decay interaction must contain a part leading to Fermi selection rules, i.e., an admixture of either the scalar or the polar vector interaction, or of both interactions.[5]

We wish to call attention to the fact that the O^{14} decay allows us to get more specific information about this Fermi component. First, we may ask for the relative strength of the Fermi and Gamow-Teller interactions. Let M_0^2 be the square of the nuclear matrix element for the Fermi interaction, M_1^2 be the corresponding quantity for the Gamow-Teller interaction (these quantities are often referred to as $(\int 1)^2$ and $(\int \boldsymbol{\sigma})^2$, respectively). We restrict ourselves to transitions for which these matrix elements can be computed theoretically without detailed knowledge of the nuclear wave functions.[6] For transitions within the same isotopic spin multiplet, between nuclei with neutron excesses T_ζ and T_ζ', respectively, we get

$$M_0^2 = T(T+1) - T_\zeta T_\zeta', \tag{1}$$

where T is the quantum number for the total isotopic spin. Formula (1) depends only upon the assumed charge independence of nuclear forces. In particular, it holds even in the presence of strong spin-orbit coupling, i.e., under conditions where the full supermultiplet theory of Wigner[7] is inapplicable.

Unfortunately, the determination of M_1^2 is not as clean-cut since the presence of spin-orbit coupling leads to appreciable corrections. For example, the 4 percent admixture of $^4D_{\frac{1}{2}}$ state to the $^2S_{\frac{1}{2}}$ ground state of H^3 leads to a 5 percent correction in M_1^2.[6,8,9] Since the D-state admixture is not very well known (it could be anywhere between 1 and 10 percent, if one takes into account the possibly quite large relativistic corrections to the magnetic moments of H^3 and He^3) the value of the beta-decay matrix element M_1^2 is correspondingly

* Work assisted by the joint program of the ONR and AEC.
[1] Sherr, Muether, and White, Phys. Rev. **75**, 282 (1949).
[2] R. Sherr and J. Gerhart, Phys. Rev. **86**, 619 (1952).
[3] Hornyak, Lauritsen, Morrison, and Fowler, Revs. Modern Phys. **22**, 291 (1950).
[4] The identification of the final state (a 2.3-Mev excited level of N^{14}) as having spin zero was made by Adair (private communication) by an ingenious application of the charge independence of nuclear forces, leading to a selection rule for the isotopic spin quantum number. In particular, Adair's argument shows that there cannot be an excited $^3S_1$ state of N^{14} close (in energy) to the $^1S_0$ "partner" of the O^{14} ground state. Previously the possibility (and even theoretical likelihood) of such a $^3S_1$ state close to the $^1S_0$ state had made it impossible to identify the beta-decay of O^{14} as a 0-to-0 transition. Dr. N. Kroll has kindly informed the writer that a weaker assumption about nuclear forces suffices to get the selection rule in the cases discussed by Adair. However, the identification of the 2.3-Mev level of N^{14} as a spin 0 state is not appreciably weakened by Kroll's argument; in particular, a $^3S_1$ state close by would have been observed in Adair's experiment even under Kroll's assumptions about nuclear forces.
[5] E. J. Konopinski, Revs. Modern Phys. **15**, 209 (1943).
[6] E. P. Wigner, Phys. Rev. **56**, 519 (1939); J. M. Blatt, Phys. Rev. **89**, 86 (1953), following paper.
[7] E. P. Wigner, Phys. Rev. **51**, 106 (1937).
[8] E. Gerjuoy and J. S. Schwinger, Phys. Rev. **61**, 138 (1942); and experimental evidence from the magnetic moments of H^3 and He^3. A recent theoretical calculation by Pease and Feshbach (private communication) indicates an admixture of 3 percent rather than 4 percent.
[9] E. Feenberg, quoted by G. Trigg, Phys. Rev. **86**, 506 (1952). An error of sign in the value quoted there was corrected in a private communication from Professor Feenberg to the writer. At the time Trigg's paper was written there was no experimental identification of the spins in the O^{14} decay. Thus Trigg's argument for the presence of a Fermi interaction was based primarily upon comparative half-lives rather than upon selection rules.

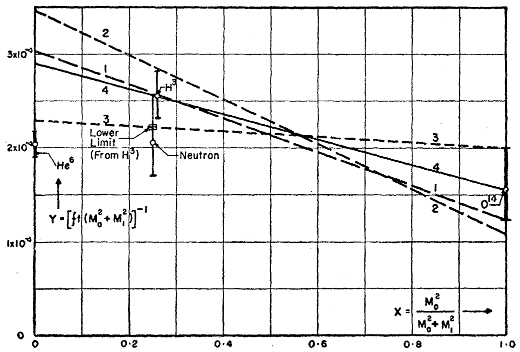

FIG. 1. Ordinate: $y=[ft(M_0^2+M_1^2)]^{-1}$, in (seconds)$^{-1}$. Abscissa: $x=M_0^2/(M_0^2+M_1^2)$. In principle, all points should lie on a straight line, with $y=G_1^2$ (strength of Gamow-Teller interaction) at $x=0$, and $y=G_0^2$ (strength of Fermi interaction) at $x=1$. The He^6 point is too low, indicating that the simple theoretical value $M_1^2=6$ is a bad overestimate. The H^3 value shown assumes a 4 percent admixture of ^4D state. Since the amount of this admixture is not well known at all, this point may be in error. However, M_1^2 for H^3 is certainly less than or equal to 3, giving the "lower limit" also indicated on the figure. Line 4 is considered the present "best" line, while lines 2 and 3 give reasonable extreme values of the ratio G_0^2/G_1^2.

uncertain. The situation is even worse in the He^6 decay, since the initial and final states do not even belong to the same isotopic spin multiplet. However, we can still use the H^3 and He^6 decays to establish upper limits for M_1^2ft, since in both cases M_1^2 is surely no larger than the theoretical value.[6] The only decay for which M_1^2 can be determined with high accuracy is the decay of the neutron.

A convenient way to plot the data is as follows: for each decay we determine (from theory) the nuclear matrix elements M_0^2 and M_1^2 and (from experiment) the comparative half-life (ft value). We then plot $y=[ft(M_0^2+M_1^2)]^{-1}$ against $x=M_0^2/(M_0^2+M_1^2)$. The result should be a straight line satisfying the equation

$$y=G_0^2x+G_1^2(1-x), \tag{2}$$

where G_0 and G_1 are the interaction constants for the Fermi and Gamow-Teller interactions, respectively. G_0^2 and G_1^2 can be read off directly as the values of y at $x=1$ and at $x=0$, respectively.

In order to minimize uncertainties arising from the theoretical calculation of matrix elements, we shall restrict ourselves to the simplest possible decays: those of the neutron, of H^3, of He^6, and of O^{14}. We shall adopt the following values for the lifetimes and maximum energies:

$$\text{Neutron: } E_0=0.783 \text{ Mev}, \quad t_{\frac{1}{2}}=12.5\pm2.5 \text{ minutes}; \tag{3}$$

$$\text{Triton: } E_0=18.0\pm0.5 \text{ kev}, \quad t_{\frac{1}{2}}=3.93\times10^8 \text{ sec}; \tag{4}$$

$$He^6\text{: } E_0=3.50\pm0.05 \text{ Mev}, \quad t_{\frac{1}{2}}=0.823 \text{ sec}; \tag{5}$$

$$O^{14}\text{: } E_0=1.8\pm0.1 \text{ Mev}, \quad t_{\frac{1}{2}}=76.5 \text{ sec}. \tag{6}$$

These values were taken primarily from the review article by Hornyak *et al.*[3] The lifetime of the neutron is not very well known, and the error stated here may be too optimistic. A recent measurement of the end-point energy in the triton decay by Langer (private communication) agrees with the value adopted here, but has a significantly smaller claimed error. No error is given here on the lifetimes of the triton, He^6, and O^{14}, since in all three cases the error in the ft value comes predominantly from the error in E_0. The end-point energy of He^6 differs from the value quoted in reference 3 because of two new measurements.[10]

The f values for all these decays were computed by numerical integration of the Fermi function; they check against previously stated values. The matrix element M_0^2 was taken from formula (1); the matrix element M_1^2 was taken to be 3 for the neutron, and 6 for the He^6 decay. The latter is probably an overestimate. In the case of H^3 we have used $M_1^2=2.84$, which follows if we assume a 4 percent admixture of the ^4D state. In view of the results of the following paper, however, we have also made use of the fact that M_1^2 cannot exceed 3. $M_1^2=0$ for O^{14}, of course.

The resulting plot of y *vs* x is shown in Fig. 1. In this figure we have also drawn in the lower limit for y determined from the H^3 decay by taking the values $M_1^2=3$ and $E_0=18.5$ kev. We see that this lower limit lies above the "best" value from the neutron decay. Hence it is very probable that the true lifetime of the neutron is somewhat less than 12.5 minutes. Next we observe that the dotted line number 3, drawn through the upper limit of the O^{14} point and the lower limit from H^3, falls above the He^6 point. We conclude that the matrix element of He^6 is almost certainly less than 6, and furthermore (since the matrix element is practically impossible to compute with any accuracy) that the *ft value of He^6 does not give any significant information about the beta-decay interaction.* This conclusion is sharply at variance with earlier work.[11] However, the difference is entirely due to the new value of the maximum energy in the He^6 decay. From the theoretical point of view the new value is much more acceptable, since the old ft value would have implied a practically perfect overlap between the wave functions of the $^1S_0$ ground state of He^6 and the $^3S_1$ ground state of Li^6. This was rather difficult to believe, especially since the magnetic moment of Li^6 deviates somewhat from the value expected for a pure $^3S_1$ state. While the situation now is more in accordance with theoretical expectations, it is of course unfortunate that the He^6 ft value no longer gives significant information.

If we accept Langer's measurement of the H^3 end point, the error on the H^3 point is decreased by a factor of 5, and the lower limit on the value of y at $x=0.25$ would move up to $y=2.42$, implying a neutron lifetime shorter than about 11 minutes.

[10] Dewan, Pepper, Allen, and Almquist, Phys. Rev. **86**, 416 (1952); Wu, Rustad, Perez-Mendez, and Lidofsky, Phys. Rev. **87**, 1140 (1952).
[11] S. A. Moszkowski, Phys. Rev. **82**, 155 (1951).

We now try to draw straight lines through the points of Fig. 1 (ignoring the He^6 point, of course). Dotted line number 1 is drawn as if the neutron lifetime were certainly longer than 10 minutes, and the value of E_0 for O^{14} certainly smaller than 1.9 Mev. Both assumptions are questionable at present, and we feel that a line such as dotted line number 2 gives a more adequate lower limit for the ratio G_0^2/G_1^2. An upper limit for this ratio is obtained from dotted line number 3, drawn as if E_0 of O^{14} were certainly greater than 1.7 Mev, and E_0 of H^3 less than 18.5 Mev. The latter of these assumptions is probably not too far off, but the former may be in error. Thus *it is not possible at present to exclude a ratio* $G_0^2/G_1^2=1$ (which corresponds to a horizontal straight line). However, a precision measurement of E_0 in the O^{14} decay would settle this question. The present "best" value of G_0^2/G_1^2 is derived from line 4. We thus obtain

$$G_0^2/G_1^2=0.54_{-0.25}^{+0.5}. \qquad (7)$$

The best value of the ratio (7) agrees very well with Trigg's[9] best value; this agreement is somewhat fortuitous because Trigg based his best value in considerable part upon the old *ft* value of He^6. We also agree with other recent analyses of decays of mirror nuclei.[12] However, we feel that our decision not to incorporate decays for which the value of M_1^2 is doubtful allows us to fix more definite limits on the permissible range of the ratio (7) than can be obtained from a statistical analysis of a larger number of decays, all of which have uncertain matrix elements.

It might be worth while to point out that, in our opinion, a careful measurement of the lifetime of the neutron (with special attention given to establishing a *lower limit* for the lifetime) is more important than a measurement of the beta-neutrino angular correlation in the decay of the neutron.

The data discussed so far do not determine the nature of the Gamow-Teller or of the Fermi interaction. However, the decay of Cl^{36} strongly suggests the tensor interaction,[13] and so does the beta-neutrino angular correlation in He^6.[14] Thus, the Gamow-Teller part of the interaction is very probably of the tensor type. A theoretical conjecture can then be made as to the nature of the Fermi part, based upon the symmetry principle of Tolhoek and deGroot.[15] According to this symmetry principle, the Fermi interaction must be of the polar vector type.

We would like to point out that this theoretical conjecture can be checked experimentally by a measurement of the beta-neutrino angular correlation in the O^{14} decay.[16] This is a more unequivocal test than the beta-neutrino angular correlation in the neutron decay because, unlike the neutron decay, *only* the Fermi interaction is effective in O^{14}. While the 0-to-0 transition of C^{10} is equally good in principle, it is useless practically because it is only a minor branch.

At first sight, the beta-neutrino angular correlation in O^{14} seems hard to measure because the subsequent 2.3-Mev gamma-ray gives rise to a recoil momentum comparable to the recoil momentum from the beta-emission. However, we can use the gamma-ray to good advantage by requiring triple coincidences between positron, gamma-ray, and (delayed) recoil ion. Not only does this allow correction for the recoil momentum from the gamma-ray emission, but even more important, the experiment can be set up in such a way that observation of the gamma-ray limits the effective source volume. Since the gamma-ray is so energetic, it can be distinguished easily from the annihilation gamma-rays by pulse-height discrimination. Since the intermediate state has spin zero, there is no beta-gamma correlation[17] to confuse the beta-neutrino angular correlation.

Finally, Professor Teller has kindly pointed out to the writer that a beta-decay interaction which is a mixture of tensor and polar vector interactions is inconsistent with the view that the pi-meson (assumed to be pseudoscalar) appears in an intermediate state during the beta-decay. The absence of any direct interaction between pi-mesons and the electro-neutrino field had already been inferred from considerations based upon the lifetime of the pi-meson against μ-decay and electron decay and upon nuclear beta-decay lifetimes.[18]

We would like to thank Dr. Adair and Dr. Kroll for letting us see their work on isotopic spin selection rules before publication; Dr. Feenberg, Dr. Lauritsen, and Dr. Wu for calling to our attention the changed value of the He^6 end point, and Dr. Wu for communication of her recently determined value before publication; Dr. Teller and Dr. Lee for theoretical discussions; Dr. Allen for communication of results on the beta-neutrino angular correlation in He^6 prior to publications, and Dr. Allen, Dr. Frauenfelder, and Dr. Jentschke for discussions about the proposed beta-neutrino angular correlation experiment.

[12] R. Nataf and R. Bouchez, Phys. Rev. **87**, 155 (1952); R. Bouchez and R. Nataf, Compt. rend. **234**, 86 (1952); O. Kofoed-Hansen and A. Winther, Phys. Rev. **86**, 428 (1952), and unpublished work by the same authors.

[13] C. S. Wu and L. Feldman, Phys. Rev. **76**, 693 (1949); **82**, 457 (1951); H. W. Fulbright and J. C. D. Milton, Phys. Rev. **82**, 274 (1951). For the spin of Cl^{36} see: C. H. Townes and L. C. Aamodt, Phys. Rev. **76**, 691 (1949); Johnson, Gordy, and Livingston, Phys. Rev. **83**, 1249 (1951). The conclusion of Longmire *et al.*, Phys. Rev. **76**, 695 (1949) that the Cl^{36} spectrum *necessitates* a mixed interaction is no longer accepted.

[14] Allen, Paneth, and Morrish, Phys. Rev. **75**, 570 (1949) and later measurements by Professor Allen (private communication).

[15] S. R. deGroot and H. A. Tolhoek, Physica **16**, 456 (1950). However, a recent argument by Konopinski (to be published), based upon the spectrum shapes of once-forbidden beta-transitions, appears to rule out the tensor-polar vector combination.

[16] D. R. Hamilton, Phys. Rev. **71**, 456 (1947).

[17] D. L. Falkoff and G. E. Uhlenbeck, Phys. Rev. **79**, 334 (1950).

[18] J. Tiomno and J. A. Wheeler, Revs. Modern Phys. **21**, 144, 153 (1949); Lee, Rosenbluth, and Yang, Phys. Rev. **75**, 905 (1949).